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A Hybrid Modelling Approach for Maintenance and Rehabilitation Treatment Effectiveness of Asphalt Pavements in Texas

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Abstract

Analysis tools in pavement management systems are critical to assist transportation agencies in developing the most adequate maintenance and rehabilitation program. The significant elements are not only the type of treatment selected and its cost, but also the quantification of its short-term and long-term effectiveness and the timing of intervention. Methodologies with complex statistical approaches and performance model theories have been previously implemented in their derivation, but they may not be suitable or accurate. Therefore, it is imperative to factor in engineering experience in their assessment. In this thesis, a hybrid modelling approach was presented to systematically introduce expert knowledge in the statistical processes for quantifying the maintenance and rehabilitation short-term and long-term effectiveness, performance models, and optimal treatment times. The approach was applied to asphalt pavements using historical performance information from the Texas Department of Transportation (TxDOT) located in the Pavement Management Information System (PMIS). Furthermore, the hybrid approach was validated in the quantification of the short-term effectiveness of different construction treatments, under changing pavement characteristics, through extensive state-wide field performance monitoring. The presented hybrid model better reflected the treatment's effectiveness measures observed in the field when compared to the previous recommendations.

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Chapter 1: Introduction

Today's transportation agencies are facing severe challenges to preserve the existing roadway infrastructure at a satisfactory level (Tasai et al.). The U.S. Department of Transportation estimates that $85 billion would need to be invested in the nation's highways in the next 15 years. Budget shortfalls and growing traffic has forced the agencies to maximize the allocation of available resources when developing their maintenance and rehabilitation (M&R) programs. To assist decision-makers in selecting the most effective treatments, agencies have implemented pavement management systems (PMS). The PMS implements pavement performance prediction models, cost analysis, optimization algorithms, decision trees and impact analysis for network-level planning, programming, and budget optimization. The most critical elements that aid this process are the type of treatment selected, their short- and long- term effectiveness, the cost and, the timing of the intervention.

In Texas' 190,570 lane mile network, of which 90% are asphalt pavements, the annual maintenance and rehabilitation (M&R) budget reached $2.7 billion annually (Persad et al. 2010). To aid in the management of the large pavement network, the Texas Department of Transportation (TxDOT) uses the Pavement Management Information System (PMIS) created in 1993. The PMIS is used for storing, retrieving, analyzing and reporting pavement related information at the network level (Zhang and Machemehl 2004). The analysis tool is used in the process of "providing, evaluating, and maintaining pavements in a serviceable condition according to the most cost-effective strategy" (Zhang and Machemehl 2004). The current system was established over 20 years ago. During this time, there have been many new treatment types, improvements to construction practices and implementation of new specifications that have resulted in changes to the short- and long-term M&R improvements. Therefore, extensive research has been performed in this thesis to develop a methodology to quantify the treatment effectiveness.

1.1 Treatment Effectiveness

An integral part of the treatment selection process is to determine the effectiveness of M&R treatments. Treatment effectiveness should be measured in the short- and long-term. Short-term effectiveness measures include condition improvement jump (CIJ), deterioration reduction level (DRL), "holding" the condition, and deterioration rate reduction (DRR) (Zaghloud et al., 2006; Dong and Huang, 2012; Labi and Sinha, 2012; Haider and Dwaikat, 2011; Peng and Ouyang, 2011; Ong et al., 2010). On the other hand, the long-term effectiveness measures include extending the service life and area bounded by the treatment performance curve or "benefit" (Zaghloud et al., 2006; Dong and Huang, 2012; Chou et al., 2008; Haider and Dwaikat, 2011; Peng and Ouyang, 2011; Ong et al., 2010; Peshkin et al., 2004). Besides the dependency on short-term effectiveness, an important consideration of the long-term effects is the requirement of pavement performance models which vary from simple deterministic regression models to complex probabilistic Markovian or Bayesian Models (Hamdi, 2012; Flintsch, 1997; Wolters and Zimmerman, 2010). These models can be empirical, mechanistic or a combination of the two (Hajek et al. 1985).

The treatment performance is greatly dependent on the condition of the pavement at the time of the application, meaning different M&R strategies will be most effective at certain times in a pavement's life (Peshkin et al., 2004). This translates into an optimal timing for applying the treatment. Under a "Needs Estimate" where the budget constraints are ignored, the optimal time is based on the ability of the treatment to address the functional and structural condition of the pavement (California DOT, 2007).When the budget constraints are introduced, feasible projects must be prioritized and the optimal timing becomes closely related to cost-effectiveness. At the end, the optimal timing information aids to establish M&R strategy evaluation and prioritizing the funding allocation over the planning horizon.

The accuracy of the effectiveness modelling relies heavily on the quality and quantity of pavement data available (Hajek et al. 1985). Furthermore, it relies on the accuracy of the predicted future condition by the deterioration models. There are many sources of error in

performance models, which affect their reliability; for example the introduction of bias and the absence of key information such as unobserved heterogeneity and pavement construction dates. The effectiveness calculation and optimal timing of treatments is also affected by the difficulty in combining static, new to failed, deterioration models with the observed incremental condition changes in maintenance-effectiveness models.

1.2 Thesis Objective and Scope

The objective of this thesis is to provide a reliable method in the quantification of effectiveness and the optimum treatment timing. This process will provide pavement managers with more robust and reliable support in the preservation of the roadway infrastructure. A hybrid modelling approach is developed to systematically merge expert judgment with historical data to quantify the short-term effectiveness. This hybrid approach can be applied to any transportation agency's M&R program. The hybrid approach presented in this thesis was validated for the short-term effectiveness in the State of Texas. Furthermore, the method was expanded to adopt the hybrid techniques for the calculations of long-term effectiveness and the optimum treatment timing under budget and non-budget constraints.

1.3 Thesis Organization

The thesis will present the results and conclusions of this research in the following Chapters.

- Chapter 1 will introduce the importance of identifying the treatment effectiveness and its optimal timing application, in addition to the measures that are used in their quantification. The objective and scope of this thesis is also provided herein.
- Chapter 2 presents an extensive literature review of the relevant effectiveness measures, the performance models that compliment them and the techniques available to implement expert knowledge.
- Chapter 3 will demonstrate the hybrid methodology implemented in the short-term effectiveness calculations in the state of Texas and its expansion to include long-term effectiveness and optimal treatment timing.

- Chapter 4 describes an overview of the database PMIS and the process to link it to other Texas perpetual databases.
- Chapter 5 will show the steps taken in updating and establishing the PMIS treatment levels that include Preventive Maintenance (PM), Light Rehabilitation (LRhb), Medium Rehabilitation (MRhb) and Heavy Rehabilitation (HRhb).
- Chapter 6 demonstrates the statistical process to derive final short-term treatment effectiveness recommendations from historical, field data and expert knowledge, as well as the impact caused by climate, traffic and pavement types,.
- Chapter 7 describes the steps taken in the creation of pre- and post-treatment performance models and their usage to quantify long-term effectiveness.
- In Chapter 8, the optimal times for treatment application based on benefit and cost-effectiveness can be found.
- Chapter 9 summarizes the research, provides concluding remarks and offers recommendations.

Chapter 2: Literature Review

2.1 Introduction

There is an extensive body of work related to the different measures used to quantify short- and long-term effectiveness, as well as the derivation of the optimal treatment timing. The measures have been implemented across transportation agencies using different condition indices, mathematical approaches and performance model theories. In addition, there is a wide variety of techniques used to implement expert knowledge. For this reason, a comprehensive literature review was performed to identify the best techniques for quantifying treatment effectiveness and the implementation of expert knowledge.

2.2 Short-Term Effectiveness

Past research efforts on treatment effectiveness have been predominantly focused on certain preventive maintenance treatments. The focus of this measure lies in the immediate impact due to the treatment. This might be taken as the condition improvement jump (CIJ), the deterioration reduction level (DRL), and the deterioration reduction rate (DRR). The CIJ is the difference between two condition points, one pre-treatment and one post-treatment. The CIJ is illustrated in figure 1 as the ΔC_4 or the change between D and F. The smaller the time interval between the pre- and post-condition measurements and the construction activity, the higher the accuracy of the performance jump (Ong et al., 2010). The deterioration reduction level (DRL) entails the estimation of condition increase over a 1-year period (Labi and Sinha, 2012). To derive this measurement a condition reading is needed one year before treatment and another measurement right after or vice versa and their respective deterioration is calculated. This is illustrated as the deterioration difference along ΔC_1 and ΔC_2 in figure 1. The calculation can also be accomplished with three readings, one taken one year before the project begins, another right before the project begins and the third taken after the project has been completed. It has been widely stated that deriving this measurement is problematic because of the timing between the condition monitoring and the application of the treatment. The deterioration reduction rate

(DRR) refers to the change of the pavement deterioration before and after the M&R project. The deterioration of the pavement is observed to be

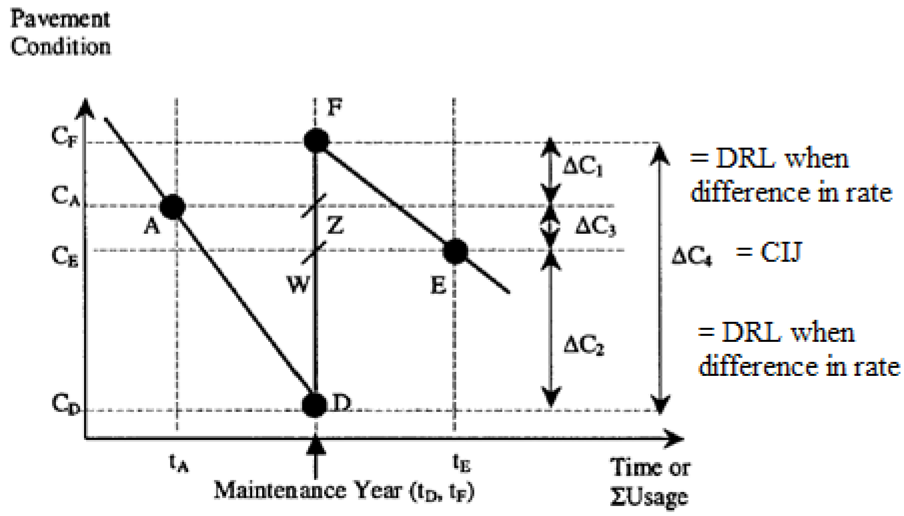

Figure 1: Concept of Deterioration Reduction Level in Short-Term Effectiveness (Modified from Ong et al., 2010).

reduced once a treatment has been applied, meaning a steep deterioration in condition over time will slope more gently. A major construction activity will have a greater impact on the deterioration making the slope more positive as is illustrated in figure 2. The figure shows the expected deterioration before the treatment is applied according to the condition of the pavement and the expected deterioration slope after the treatment is applied depending on the treatment intensity. The slope is assumed to linear because the effectiveness is viewed over a short time and at least 3 data points are needed.

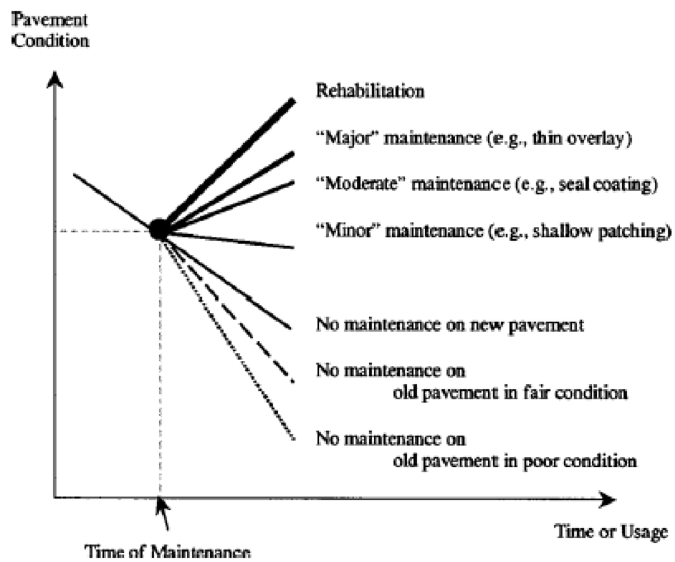

Figure 2: Concept of Deterioration Reduction Rate in Short-Term Effectiveness (Ong et al., 2010).

Labi and Sinha (2012) conducted testing on various linear and non-linear functional forms using annual Seal Coating condition data starting from year 1995 and 1966. The paper focused on the measures of CIJ and deterioration rate reduction in terms of the International Roughness Index (IRI) converted to Pavement Serviceability Index (PSI). In addition, the models developed were validated with sections treated with seal coating in both lane directions. Labi and Sinha (2012) concluded that for performance jump models, the initial condition as opposed to pavement family (traffic level, subgrade properties and pavement layers), was the most important factor. Pavements in poor initial condition reflected higher performance improvement jumps than pavement in good condition. In the case of DRR, Labi and Sinha concluded that the initial condition index, traffic level and subgrade properties had the most impact on the models. On the contrary to performance jump, pavements in good condition showed a greater deterioration reduction rate than when poor pavements were treated. In Ong et al. (2010), short-term effectiveness models for thin overlay, microsurfacing, crack seal and patching were created based on the condition index before the treatment was applied. The condition indices used in the study included the IRI, the pavement condition index (PCI) and the rut depth. It was conclude,

that in the cases of crack sealing and patching there was no discernable performance jump, but a deterioration reduction rate was introduced in its place. Furthermore, both of those treatments had no effect on rut depth. For the thin overlay and microsurfacing, the paper proposed performance jumps and performance resets for the three condition indices.

The Arizona DOT Pavement Management System recommends the lighter construction treatments which are the general and localized maintenance activities, to have a small immediate CIJ (Zaghloud et al., 2006). The improvement is followed by holding the condition constant for a period of time. The rehabilitation and construction activities are to reset to a newly construction condition.

In the state of Texas for the Texas Department of Transportation, Stampley et al. (1993) provided CIJ based on engineering judgment since there was not enough available historical data. The condition indices used are the ride score (RS) and the distress score (DS). Table 1 provides the recommended increase based on the severity of the construction activity. The medium and high rehabilitation treatments show a score reset instead of a finite CIJ for RS. Also, all treatment levels show a DS reset.

Table 1: Current Gain of Rating Values for TxDOT PMIS Treatment Level Categories (Stampley et al., 1993).

Treatment Type	Gain in Distress Score	Gain in Ride Score
Preventive Maintenance	Distresses reset to 95	Ride Score increases 0.5
Light Rehabilitation	Distresses reset to 100	Ride Score increases 1.5
Medium Rehabilitation	Distresses reset to 100	Ride Score resets to 4.8
Heavy Rehabilitation	Distresses reset to 100	Ride Score resets to 4.8

2.3 Performance Models

The importance of performance models in the long-term effectiveness has led to the development of extensive methodologies for their creation. The models vary from deterministic to stochastic. Furthermore they can be empirical (site-specific), where the dependent variable (condition) is related to one or more independent variables (age, cumulative traffic, environment and pavement structure characteristics); mechanistic, where the response parameter is dependent

on stress, strain and deflection or a combination of the two (mechanistic-empirical) (Ong et al., 2010). Deterministic models predict a precise value from one or more independent variables (Wolters and Zimmerman, 2010). Most deterministic models use regression analysis to predict the dependent variable as a function of the independent variables. Stochastic models consider probability through a transition probability matrix to predict future condition (Huang and Dong, 2009). This technique predicts a range of values for example the likelihood that the pavement condition will change to the next state. The models include Markov Chains, survivor curves, and Bayesian models (Hamdi, 2012).

The most used network-level pavement deterioration models are site-specific based on the "windows" method. The "windows" method aggregates pavement historical condition data based on climate, subgrade, traffic and pavement family (Gallegos et al., 2013). In Zaghloud et al. (2006), pavement section condition based on the Present Serviceability Rating (PSR) were grouped on the basis of last rehabilitation activity, pavement type, environment conditions, traffic, subgrade condition and structural thickness. Once the sections were filtered using pre-establish thresholds values, a sigmoidal, S-shape, model was fitted with non-linear regression. Other very similar examples of the same procedure can be found in Hamdi (2012) and, Huang and Dong (2009) but the deterioration function is exponential. As previously stated there are sources of inaccuracy in deterministic models in which stochastic models have been introduced as an alternative to better describe the possible deterioration scenarios for pavements. Eun (2008) stated that errors are introduced when prediction curves are based on the latest condition observation and not on the all past observations. To counter this fallback, Eun (2008) introduced a Bayesian analysis tool using the sigmoidal longitudinal cracking equation used by the Texas Department of Transportation. The longitudinal propagation model demonstrated that the Bayesian approach can be used effectively to model deterioration. Chu and Durango-Cohen (2008) provided a PSI deterioration model with Markovian transition probabilities, in order to incorporated maintenance-effectiveness models. The conclusion of the work stated that adequate estimates of performance were observed. Gao et al. (2011) proposed a Bayesian approach to

capture the real deterioration without filtering out pavement sections that had previously received maintenance. Using pavement deterioration in terms of IRI, Hong and Prozzi (2010), investigated a nonlinear hierarchical Bayesian model to add unobserved heterogeneity which includes material properties, quality control and pavement structure.

Stampley et al. (1993) created performance models for TxDOT based on the "windows" model. They were recalibrated in Gharaibeh et al. (2012). The pavements are aggregated based on the climate and subgrade zone, traffic levels, pavement family and, treatment levels. Gharaibeh et al. (2012) used non-linear regression to fit the sigmoidal curve. The independent distresses are modeled independently based on equation 1. Factor A replaced several of the original factors due to the extensive combinations possible. The factors were *ε*, factor that controls the effect of rainfall and freeze-thaw cycles, *χ,* factor that controls the effect of an 18-k ESAL, *σ,* factor that controls the effect of the subgrade strength, and *ρ,* factor that controls how steeply distress is lost in the middle of the curve.

$$L_i = \alpha e^{-[\left(\frac{A}{Age}\right)^{\beta}]} \qquad \text{Equation 1}$$

L_i = level of distress in a pavement section. The level of distress is obtained by "normalizing" the extent of the asphalt distress in the section.

α = horizontal asymptote factor that represents the maximum range of distress growth.

β = a slope factor that controls how steeply utility is lost in the middle of the curve.

A = prolongation factor controls the time it takes before significant increases in distress occur. In addition it replaced the other regression factors as previously stated.

The distress extent or ride quality lost (Li) are used as the predicting condition index and derived into Distress Score (DS) and Ride Score (RS) based on utility sigmoidal equation 2 (Stampley et al. 1993).

$$U_i = 1 - \alpha e^{-(\frac{\rho}{L_i})^{\beta}} \qquad \text{Equation 2}$$

U_i = Utility value.

e = base of the natural logarithm.

α = alpha, a horizontal asymptote factor that controls the maximum amount of utility that can be lost.

β = beta, a slope factor that controls how steeply utility is lost in the middle of the curve.

ρ = rho, a prolongation factor that controls how steeply utility is lost in the middle of the curve.

L_i = level of normalized distress.

2.4 Long-Term Effectiveness

The development of long-term effectiveness differs with the immediate performance improvement because it is concerned with the performance of the treatment over the entire life of the pavement. The long-term effectiveness in essence ties the performance jump with the pavement deterioration models (Peng and Ouyang, 2011). Common measurement for long-term effectiveness is the treatment influence in extending the service life. A subrogate measure to determine the treatment effectiveness is using the area under the performance curve to consider the pavement condition improvement, deterioration rate, and service life extension (Ong et al., 2010). It is defined by the area bounded by the post-treatment performance curve and either the "do-nothing" curve or the pre-treatment curve or a predefined threshold value (Peshkin et al., 2004). The treatment service life is achieved by extrapolating the post-treatment performance curve to the point at which the condition reverts to the established threshold (Haider and Dwaikat, 2011).This threshold is the same as the boundary for the benefit. Figure 3 illustrates the long-term effectiveness concept.

Dong and Huang (2012) conducted an investigation on the evaluation of different overlay treatments' benefit with the condition index, IRI. With multiple regression analysis, the paper also focused on the impact of milling, overlay thickness, and traffic level on the effectiveness and cost-effectiveness. It was concluded that pavement with thick overlay and high rate of deterioration before rehabilitation has greater benefit. Milling was observed to have a greater

impact on the cost-effectiveness. Chou et al. (2008) the area under the curve and the extended service life for thin overlays was studied. Moreover, the effect of traffic level, condition before, overlay thickness and snowfall complimented the study. The benefit was calculated as

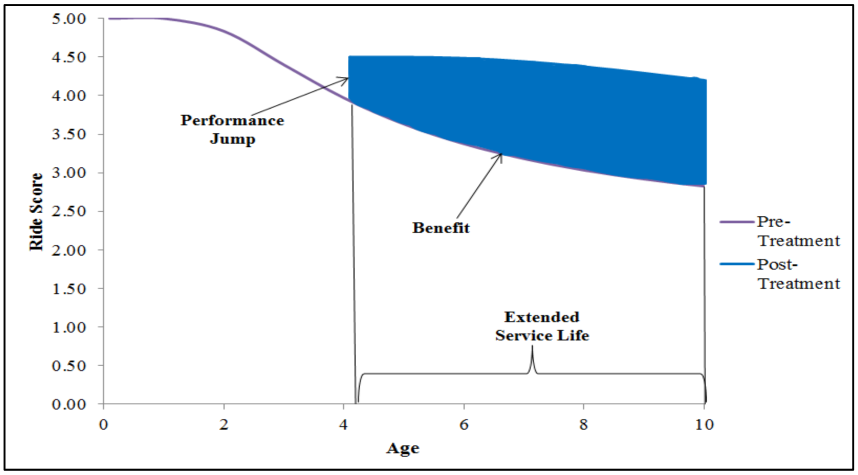

Figure 3: Long-Term Effectiveness Concept.

the area between the pavement condition rating (PCR) vs. age curve and the terminal PCR threshold line. The extended life was calculated as the difference in years between the pre and post PCR curves starting from the same year and condition. The difference of years was taken at a predefined condition value. Chou et al. (2008) concluded that while overlay thickness and traffic had an effect on benefit, snowfall and PCR before the thin overlay had the largest influence over the benefit.

The long-term effectiveness measure the Texas Department of Transportation has implemented in Texas is the benefit or the area between the "untreated" pavement performance curve and the "treated" performance curve. PMIS uses the heavy rehabilitation curve for the "untreated" curve but it's essentially a "do-nothing" curve. The "treated" curve corresponds to the treatment suggested in the PMIS, meaning the current condition of the sections first passes through the decision tree. Certain treatment levels may not be sufficient to remove all distresses. The same process is conducted for the ride score. Moreover, there are guidelines for the

boundaries of the area. They include boundaries set by the failure criteria of 60 for DS and 3.0 for RS (Figure 4), the age the upper and lower curves cross (Figure 5) and if the curves never cross each other the age is set at 20 years. The distress benefit and the ride benefit are then added and divide by 100. There are no weight factors currently in use. Another long-term effectiveness term used and calculated in this step is the effective life, which is the smallest boundary condition in years between the ride and distress score.

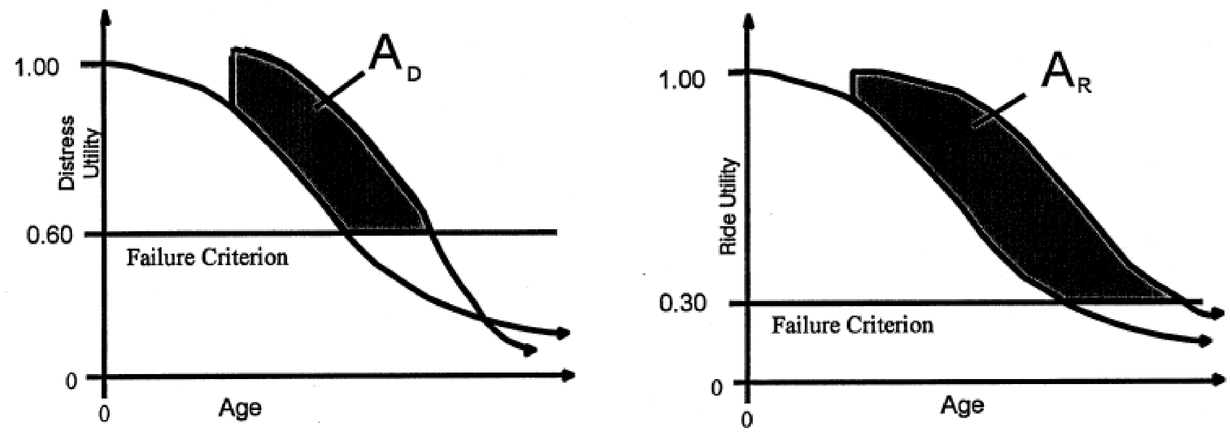

Figure 4: PMIS Boundary Conditions Using Failure Criterion (Stampley et al., 1993).

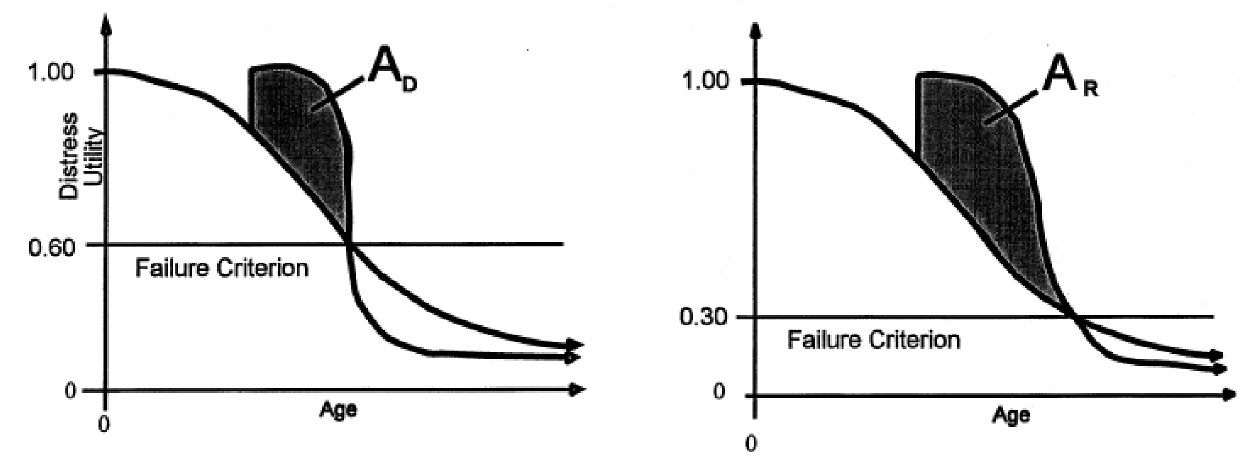

Figure 5: PMIS Boundary Conditions When Upper and Lower Curve Cross (Stampley et al., 1993).

2.5 Cost-Effectiveness

In order to prioritize among different projects with budget constraints, the cost required to obtain the benefit must be achieved. The most desirable treatment is the treatment that results in greatest benefit for the lowest costs (California DOT, 2007). Although any long term effectiveness measure may be used, Peshkin et al. (2004) has used the "benefit", or the area under the curve, as the principal criteria for finding the cost-effectiveness. In Peshkin et al. (2004) the cost effectiveness of preventive maintenance for five different highway agencies was investigated with the calculation of the area under the curve, bounded by the "do-nothing" curve, in terms of rutting, cracking and friction. When more than one condition index is used the paper uses a method to combine the independent values with a weighting factor and a normalization process. The cost-effectiveness measure is the benefit-to-cost ratio which is simply the benefit divided by the cost. The conclusion of the study is that the methodology discussed is capable of prioritizing among different projects. In addition to the benefit, cost effectiveness methodologies have implemented the remaining service life in the long-term effectiveness measure. Hicks et al. (2000) and California DOT (2007) presented a cost-effectiveness ratio by dividing the cost by the remaining life. The treatment with the lowest ratio is the selected project.

In the state of Texas for TXDOT, Stampley et al. (1993) implemented a cost-effectiveness ratio which not only uses the benefit and cost but also the remaining service life. It first requires the cost to be adjusted to the year of the actual treatment based on inflation with equation 3. Then the unit cost is annualized over the effective life of the treatment with equation 4. Finally the uniform annual cost and the long-term effectiveness are combined with equation 5. The ratios are ranked with high value projects prioritized above the lower ones.

$$TCost = UCost * (1 + InfRate)^n \qquad \text{Equation 3}$$

TCost = Treatment Cost of the Needs Estimate treatment, in dollars.

UCost = Unit Cost of the Needs Estimate treatment, in dollars.

InfRate = Inflation Rate, in percent year.

n = Number of years that the Unit Cost has been projected.

$$UACost = TCost * \frac{DRate(1+DRate)^{EffLife}}{(1+DRate)^{EffLife}-1} \qquad \text{Equation 4}$$

UACost = Uniform Annual Cost of the Needs Estimate treatment, in dollars.

TCost = Treatment Cost (current or future) of the Needs Estimate treatment, in dollars.

DRate = Discount Rate, in percent years.

EffLife = Effective Life of the Needs Estimate treatment, in years.

$$CERatio = 10000 * \frac{LM*B}{EffLife*UACost} * log_{10}VMT \qquad \text{Equation 5}$$

CERatio = Cost-Effectiveness Ration.

LM = Lane Miles.

B = Benefit.

EffLife = Effective Life of Needs Estimate Treatment, in years.

UACost = Uniform Annual Cost of the Needs Estimate treatment, in dollars.

VMT = Vehicles Miles Traveled.

2.6 Optimal Treatment Timing

The application of different M&R treatments will also be directly related to the time of its application. If the treatment is applied too early, it may not maximize its effectiveness, if applied too late it may not be as effective as another strategy. Furthermore, the cost of the treatment impacts the decision. This means that it is not feasible to rehabilitate or reconstruct a pavement at an early age due to the high cost. This is the definition of the optimal time of treatment application. Figure 6 describes the optimal time based on total construction cost and age. The age in this case is a subrogate measure of condition index; the younger pavements are always in better condition than older ones.

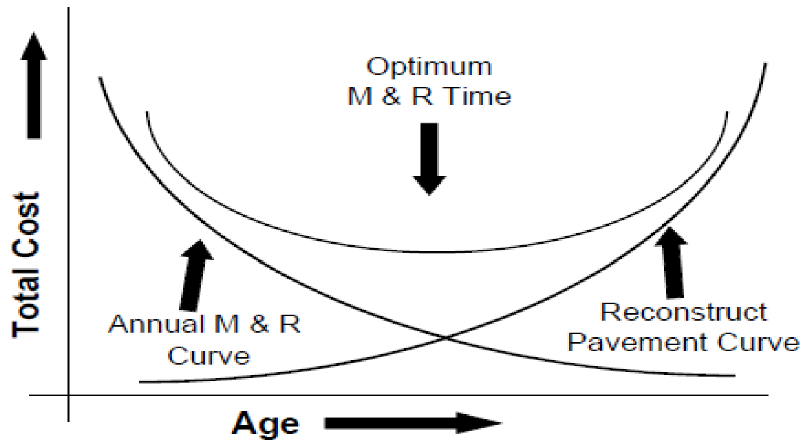

Figure 6: Optimal Treatment Timing Based on Age and Cost (Hicks et al., 2000).

Haider and Dwaikat (2011), created a methodology to estimate the optimum preventive maintenance timing in the state of Texas, Kansas and Minnesota. The research used the IRI condition index found in the long-term pavement performance database SPS-3. The process included determining the best time based on the benefit and the condition improvement jump but no cost was taken into consideration. The result for the optimum treatment time for Kansas was 4 to 6 years and for Minnesota 3 to 4 years. The conclusion expressed that the methodology was capable of deriving the best treatment time and cost may be incorporated to analyze the life-cycle cost. Hicks et al. (2000) provided recommendations of the best time to perform preventive maintenance projects such as Fog Seals, Chip Seals and Thin Overlays. In Wu et al. (2010) a synthesis of state highway agencies' construction practices was performed. This study contained the most detailed information on the timing of M&R applications across state agencies. There were no actual models but just synthesis of the state of practice. The lack of mathematical derived optimal timings shows how much it relies on expert judgment.

2.7 Techniques for Incorporating Expert Knowledge

The many challenges in the quantification of effectiveness and optimal treatment timing have led to the development of many different models. The models are not perfect and rely on many assumptions, robust statistical processes, and data quality and quantity. Techniques for

gathering and quantifying expert's knowledge have been created and implemented in order to complement models and arrest their modelling shortfalls. The techniques include utility theory, Delphi technique, rational factorial and fuzzy set theory. The utility theory involves the estimation of a scalar utility function. This utility function is estimated through the quantification of engineering judgment. The process includes the structuring of the problem, the assessment of utility function, identification of uncertainties and the selection of best alternative (Ordonez and Vinson, 1988). Fuzzy sets theory offers a systematic process to transform ambiguous and fuzzy or vague information into numerical data (Wolters and Zimmerman, 2010). The theory allows the processing of ambiguous information in a logical fashion. The information includes the rating pavement condition in terms of good, bad, fair, etc. The process includes first representing the fuzzy information into a membership function, processing the information and interpreting the fuzzy output (Fwa and Shanmugan, 1998). The Delphi technique is an iterative procedure that tries to get a consensus among a group of experts with cycles of questioning with controlled feedback (Turoff and Linstone, 2002). The procedure takes into consideration the statistical response. The first step is filling out a survey and then feedback is provided on the results. The experts are asked to revise their answers until a reasonable agreement is achieved. In the case of rational factorial, expert opinion is obtained by using a designed experiment or a survey. The survey must first define the factors that influence the topic under investigation (Wolters and Zimmerman, 2010). Once the factors have been established, a questionnaire is created and sent to participating experts. The questionnaire must contain detailed filling instructions and clear definitions. The results of the questionnaire can then be analyzed with regression analysis.

Gallegos et al. (2013) presented a hybrid technique for the calibration of continuously reinforced concrete pavements (CRCP) in Texas. The hybrid technique combines the use of a rational factorial experiment with utility theory. A panel of experts is surveyed on the utility of pavement sections at different deterioration levels. The compiled opinion is then analyzed with non-linear regression. Gallegos et al. (2013) concluded that the hybrid technique was successful in capturing real pavement deterioration and was key in the implementation of the CRCP

recalibrated performance models. In Gharaibeh et al. (2012) a similar approach was taken for the implementation of recalibrated asphalt pavement deterioration models in Texas. Detailed questionnaires were distributed across experts with special attention on the influencing factors such as traffic levels, treatment levels and subgrade zones. Experts who largely disagreed on the models were provided feedback and asked for pavements sections representative of the condition deterioration. In the end, Gharaibeh et al. (2012) concluded that this methodology provided sufficient confidence for the implementation of the recalibrated asphalt deterioration models.

2.8 Summary

- The short-term effectiveness measure the immediate effect any treatment has on the pavement condition. There have been many short-term effectiveness measures implemented and include the condition improvement jump (CIJ), the deterioration reduction level (DRL), and the deterioration reduction rate (DRR). Most of these measures are dependent on the time of condition monitoring as well as the time the treatment is applied and require at least three data points.
- The derivation of long-term effectiveness measures relies heavily on the performance deterioration models. The models can be stochastic or deterministic. Stochastic models are probability dependent and predict a wide range of values. The deterministic only predicts one value based on different characteristics such as environmental facts, cumulative traffic and pavement structure. In addition, these models can me site-specific, mechanistic or a combination of the two.
- The most common long-term effectiveness measures include the benefit and the extended service life. The benefit is the area under the pre-treatment and post-treatment performance curves. There are several boundary conditions for the area but the most common are starting the year of treatment an ending when the pavement curves reach a pre-defined threshold value or when the performance

curves intersect. The extended service life is the difference in years between the area boundaries.

- The cost-effectiveness ratio is a variable which incorporates the short-term and long-term effectiveness of the treatment and the unit cost. This is done because state transportation agencies have limited funds. There are a wide variety of equations to derive this ratio. The Texas Department of Transportation incorporates the benefit and the extended service life in their cost-effectiveness derivation. The goal of the cost-effectiveness ratio is to prioritize among different competing projects.
- The optimal treatment time placement is the year where treatment application maximizes effectiveness and minimizes the cost. The optimal treatment time can be calculated based on benefit alone or including cost with the cost-effectiveness ratio. The optimal treatment time concept is that if a treatment is applied too early to a pavement such as reconstruction, the treatment is highly expensive for the small amount of benefit achieved. On the other hand, if preventive maintenance is added to a highly deteriorated pavement, it will not be costly but it will not beneficial either.
- To address the many challenges in effectiveness modelling, there have been many established techniques for incorporating expert knowledge into useful information. The utility theory and the fuzzy set theory rely heavily on pre-defined mathematical formulations. The Delphi technique and the factorial design are other techniques but they focus on the creation of questionnaires to survey expert knowledge. All of these techniques have been proven to be efficient in the quantification of engineering knowledge in the pavement management industry.

Chapter 3: Overview of Hybrid Methodology for Quantifying Treatment Effectiveness

3.1 Challenges in Quantifying Effectiveness

The accuracy of the effectiveness modelling approach relies heavily on the quality and quantity of pavement data. It is a challenge to collect and maintain performance data for all pavement sections in the network due to limited resources and funding (Gallegos et al., 2013). Consequently, agencies have to compromise the extent and quality of condition surveys. This means that at most, agencies can only survey a small sample size and cannot provide important pavement information such as structural indices. Furthermore, it forces transportation agencies to use less accurate performance monitoring such as visual surveys. Visual surveys have many beneficial aspects but it also introduces data inaccuracies. The inaccuracies may be in the subjective nature of the monitoring as well as errors prone to occur during the manual data entry of large amounts of information. These sources of error can also create uncertainties in the accuracy of the predicted future condition by the deterioration models. Sources of error in performance models have been recorded as:

- Biased estimation while filtrating maintenance work in Gao et al. (2011).
- Basing the prediction curve on the latest condition observation and not on the past observations in Eun (2008).
- Ignoring unobserved heterogeneity such as construction quality control and material characteristics in Hong and Prozzi, (2010).
- The use of separate deterioration and maintenance-effectiveness models Chu and Durango-Cohen (2008).
- The use of self-selected samples as opposed to random, which add selective bias in (Madanat and Mishalani 1998).

In the TxDOT PMIS other challenges were observed which included:

- The absence of defined treatments in each level

- No maintenance or rehabilitation information available
- The date of assessment for the two condition indices, Ride Score (RS) and Distress Score (DS) did not correspond. This is because the visual surveys for DS and the profiler data measurement of RS are taken at different times and do not provide detail date information only fiscal year

3.2 Overcoming Difficulties

To overcome the difficulties in the quantification of effectiveness and the optimum treatment timing a hybrid modelling approach was developed. The approach seeks to systematically integrate expert knowledge into the model. The methodology combines Delphi and rational factorial techniques to systematically complement the short- and long-term effectiveness of asphalt pavement treatments statistically inferred from historical condition information.

3.3 Hybrid Methodology

There are four major areas in which the methodology was adapted and they are in defining the treatment levels, the short-term effectiveness, the creation of pre- and post-construction models for the calculation of long-term effectiveness, and the optimal treatment time. In essence the same techniques were used across the different measures to implement expert's opinion.

3.3.1 Treatment Levels

The hybrid technique implemented to define the treatments for each level included a combination of rational factorial and Delphi techniques. Extensive surveys were created using all available past research attempts and distributed among experts throughout the state (Chang et al., 2013). From the collected answers, statistical analyses were performed and used to create a preliminary list of treatments found in each treatment level. This preliminary list was the guide put in place to categorize each project. It was later found that the description of construction projects in the preliminary list was not detailed enough to classify the descriptions found in the

databases. To overcome this obstacle another round of surveys was implemented but in this case they were tailored for each District. This iterative process described in figure 7 resulted in a final consensus among Districts in the construction projects found in each treatment level. Table 20 provided in chapter 5 shows the construction activities categorized by treatment level.

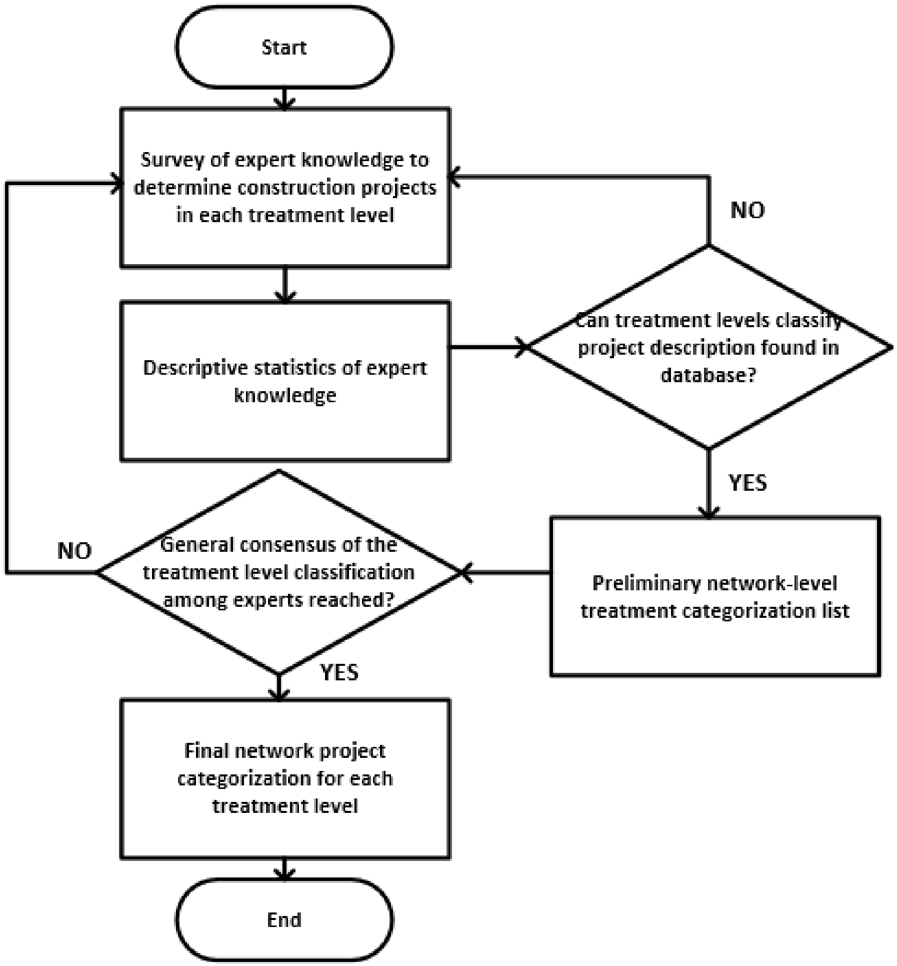

Figure 7: Methodology to Define Treatment Levels.

Figure 7 first starts with surveying the experts to determine the different construction activities in each treatment level. The data was analyzed with the use of descriptive statistics and resulted in a preliminary list. This preliminary list was used to categorize the different project using the layman's description found in the database. Some descriptions were not sufficient to categorize these projects. If the list was not sufficient another round of surveys was created but

this time it was tailored for each independent district. Finally after aggregating all different survey answers a final list was created, this list was send across the state to reach consensus. The final network-level categorization for each treatment was not finalized until this consensus was reached.

3.3.2 Short-Term Effectiveness

The following hybrid methodology to achieve the CIJ is as follows:

1. The condition improvement jump (CIJ) first began with meticulous statistical analyses that included descriptive statistics, histograms, cumulative plots and condition increase vs. condition before plots based on their treatment level. The main observations of the investigation were that the PM and LRhb ride score had a finite increase, whereas the MRhb and HRhb showed a ride score reset. The distress score and condition score showed a complete reset across all levels. These preliminary results were consistent with the initial recommendations found in (Stampley et al. 1993). To account for the limitations in the assumptions, agency experts were consulted with the preliminary results and their judgment was implemented. Some observations were that the ride score increase for light rehabilitation as well as the ride score reset for medium and heavy rehabilitation was low.
2. It was also important to find the effect of traffic, climatic and subgrade characteristic zones, and pavement families on the ride score increase per treatment level. The investigation included grouping certain characteristics within their respective treatment level and using hypothesis testing between the increases. ANOVA was the main hypothesis test used and post-hoc multiple comparisons complemented the testing to find which groups differed within the ANOVA. Mann-Whitney hypothesis testing was also needed in some instances where the distribution did not follow a normal distribution. Box-whisker plots were found helpful in illustrating the different score increases. The effect of the pavement characteristics for preventive maintenance and light rehabilitation

condition improvement jump in ride score were not significant which is consistent with the results found in Labi and Sinha (2012). The ride score reset in the case of MRhb and HRhb was also not sensitive to the pavement characteristics. None of the characteristics were found to be sensitive on the distress score reset across all treatment levels. Expert knowledge was again implemented to check for the accuracy of the results.

3. An extensive field experiment was conducted in which condition surveys right before the placement of treatment and right after treatment were taken. The treatments were selected across the state of Texas to find a satisfactory distribution among different treatment levels, traffic levels, climatic and subgrade characteristic zones, and pavement families. Again statistical hypothesis testing was performed, in this instance between the historical data and the field data. The field data demonstrated that the distress score in fact did reset across all treatment levels. It also reinforced the ride score reset for MRhb and HRhb. Expert opinion was checked in the final recommendations to arrive at a consensus between pavement experts.

The hybrid methodology implemented a factorial experiment in the first phase of the preliminary calculations, after the conclusion on the effect of pavement properties and an iterative process to achieve consensus on the final recommendations. The survey always provided a starting point based on both existing recommendations in literature and the ones derived from historical data. It also provided specific instructions for answering the questions as shown in the following example.

Qquestion.1 Please insert the number that most represents your expert opinion. The preliminary ride and distress score increase or reset derived from historical data is reasonable (1), over predicts (2) or under predicts (3) the observations in your district?

Table 2: Survey of Preliminary Recommendations of Short-Term Effectiveness for Flexible Pavement in Texas.

Treatment Level	Ride Score					Distress Score		
	Current PMIS	Historical Data Analysis		Expert knowledge		Current PMIS	Historical Data Analysis	Expert knowledge
		Increase	Reset	Increase	Reset		Reset	Reset
PM	Increase by 0.5	0.4	-			Reset to 95	100	
LRhb	Increase by 1.5	0.8	-			Reset to 100	100	
MRhb	Reset to 4.8	-	4.5			Reset to 4.8	100	
HRhb	Reset to 4.8	-	3.8			Reset to 4.8	100	

Question.2 Please insert the number that most represents your expert opinion. More than one number is acceptable. Which of the following factors impacts the ride score reset or increase: traffic level (1), climatic and subgrade characteristics zone (2) or pavement family (3)?

Table 3: Survey of Factors that Impact the Short-Term Effectiveness for Flexible Pavement in Texas.

Treatment Level	Ride Score					Distress Score		
	Current PMIS	Historical Data Analysis		Expert knowledge		Current PMIS	Historical Data Analysis	Expert knowledge
		Increase	Reset	Increase	Reset		Reset	Reset
PM	No Impact	No Impact	-		-	No Impact	No Impact	
LRhb	No Impact	No Impact	-		-	No Impact	No Impact	
MRhb	No Impact	-	No Impact	-		No Impact	No Impact	
HRhb	No Impact	-	No Impact	-		No Impact	No Impact	

In the last stage of the calculation of the condition improvement jump and the effect the different pavement characteristics have, a consensus must be reached based on controlled feedback. The feedback would be based on the final recommendations of the condition improvement jump and it would be dynamic, meaning that in every iteration the values recommended would be compared to the expert opinion. The flow chart in figure 8 shows the hybrid technique presented for incorporating expert knowledge in the calculations of condition improvement jump and the effect the different pavement characteristics have on it.

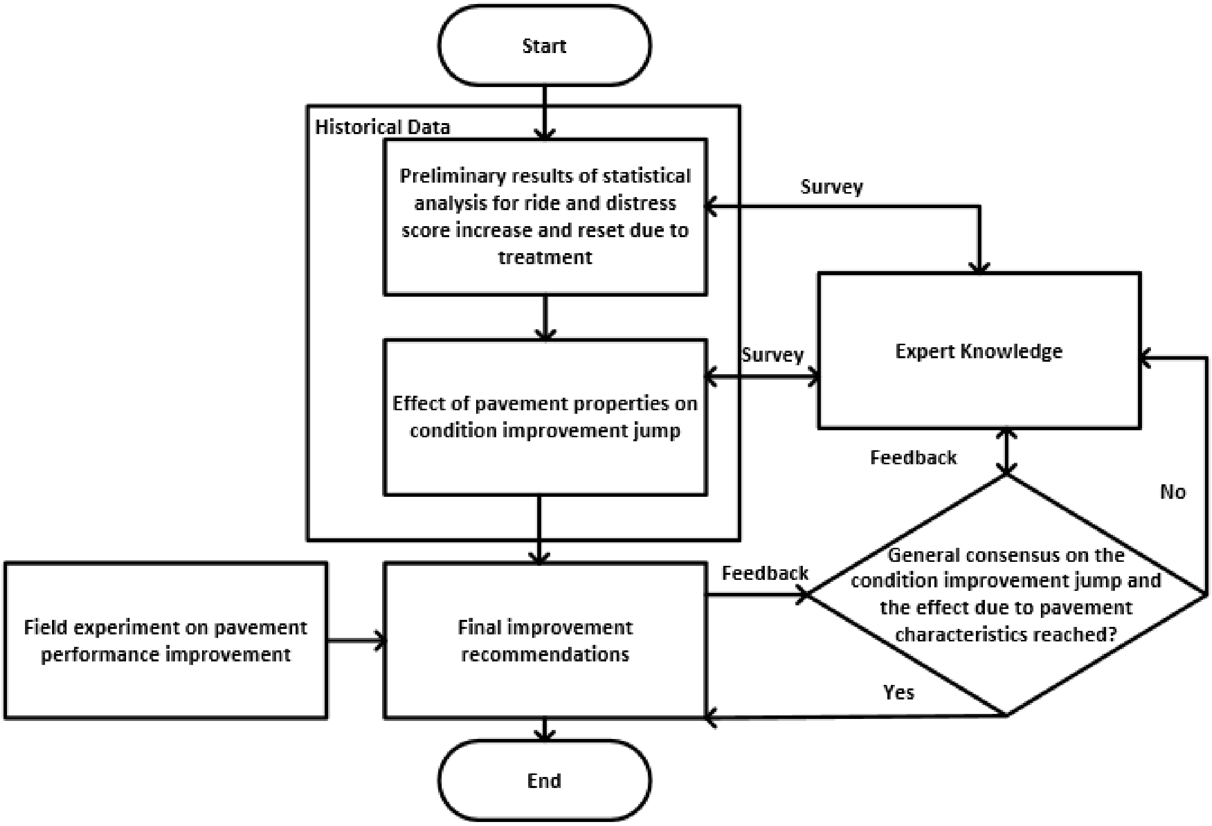

Figure 8: Methodology to Incorporate Expert Knowledge in Short-Term Effectiveness.

3.3.3 Long-Term Effectiveness

The following methodology describes the hybrid technique proposed to integrate the pre-treatment and post-treatment models derived from the historical data and expert engineering judgment. The difficulty in deriving the models and the many different combinations of the pavement characteristics will not allow for engineering opinion to be harnessed for all combinations of characteristics. Furthermore, the benefit and extended service life is dependent on the time of treatment.

1. The long-term effectiveness needs historical data for many years, for this reason data for 10 years before and 10 years after was acquired. In the creation of the deterioration models, it was important to filter the data which was affected by past or future M&R treatments applied, relative to the current treatment levels under investigation. Also, the "windows" method was used in the filtering of the data. This method aggregates

pavement sections based on pavement characteristics. These characteristics are climatic and subgrade characteristics zone, pavement family, treatment level and traffic level. The data was summarized per year and prepared for the non-linear regression. Since TxDOT uses a hierarchical decision trees based on independent distresses to select the needs estimate and since the distress score resets to 100 after any treatment level, a modelling equation based on equation 1 and equation 2 found in Stampley et al. (1993) was implemented. It is common for agencies to use the "do-nothing" curve or in the case of TxDOT the HRhb curve.

2. The non-linear regressions were created based on climatic regions, pavement, families, traffic, and treatment levels. The different traffic and treatment levels introduce constraints in the deterioration slope. The deterioration in the case of treatment levels and pre-construction must have follow the trend HRhb>MRhb>LRhb>PM. On the contrary, post-treatment deterioration must follow the trend with PM having a higher slope and HRhb having the lowest slope. In the case of traffic levels the higher the traffic level, the higher the deterioration slope. For the historical data the deterioration constraint was not achievable for the pre-construction ride score deterioration model due to the bias introduced in M&R activities where higher traffic levels trigger treatment with higher ride scores. The MATLAB algorithm "lsqcurvefit" or least-squares curve-fitting was used in the model fitting. Figure 9 demonstrates the pre-construction ride score curves fitted for dry-warm climate and good subgrade zone; thick (> 5.5" thick), intermediate (2.5-5.5" thick) and overlaid asphalt pavements; 20-year projected equivalent single axle load (ESALS) of 1.0 million to less than 10 million; and all treatment levels.

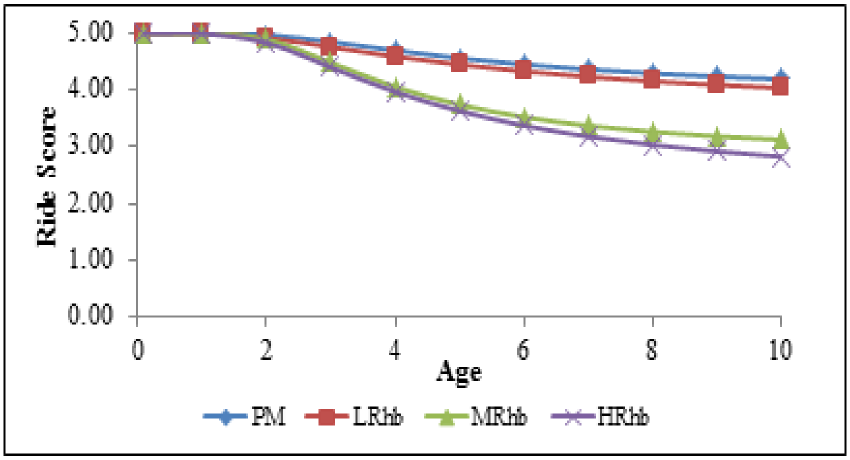

Figure 9: Ride Score Deterioration Curves for Pre-Construction.

Figure 10 demonstrates the post-construction ride score curves fitted for dry-warm climate and good subgrade zone; thick (> 5.5" thick), intermediate (>2.5-5.5" thick), and overlaid asphalt pavements; 20-year projected equivalent single axle load (ESALS) of 1.0 million to less than 10 million; and all treatment levels.

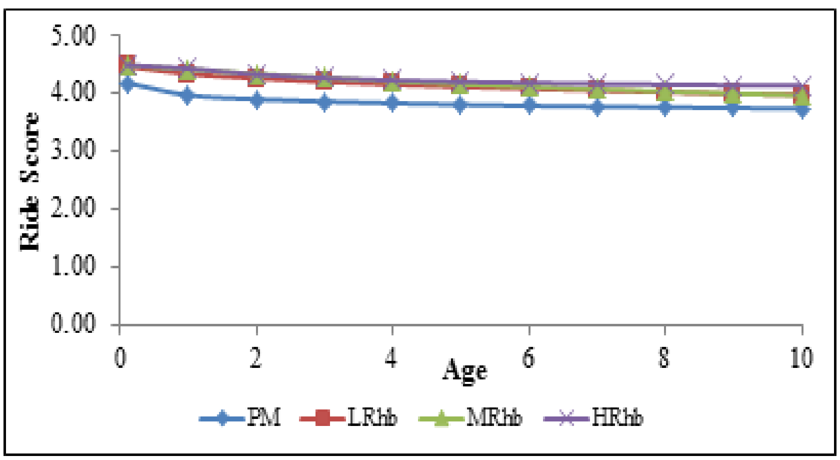

Figure 10: Ride Score Deterioration Curves for Pre-Construction.

3. To validate the fitting quality, the root mean squared error was calculated for each curve fitting. The RMSE is the summation of the difference between the predicted and the observed value which is then squared and divided by the number of observations. Then the square root of the value is taken. This value represents the average distance of a data

point from the fitted line, measured along a vertical line, in the same units as the variable (Miles and Sheylin, 2001). The smaller the RMSE the better the model fit to the data.

The hybrid methodology to implement the expert knowledge into the forecasting of ride score or distress score over time for each treatment level requires the creation of detailed surveys because of the great variability the data introduces. The surveys will have to state what pavement characteristics the engineer has experience with. There are many combinations between the different pavement characteristics and some are not achievable. For example there are no utility coefficients in Gharaibeh et al. (2012) when using HRhb and grouping across different pavement families and 20-year projected traffic equal to 10 million ESALS or greater, considered high traffic. Another important factor to determine is the use of the HRhb curve for the pre-construction curve as a "do-nothing" curve. In the creation of the post-treatment curve the same process is followed. An example of the survey is as follows:

Question.1 Is it feasible to use the HRhb deterioration curve as the pre-construction curve? or should each treatment level have its own curve?

This answer may then tailor the next question, meaning if most engineers answer as a "yes" for the use of HRhb, then only HRhb curve input is necessary. For simplicity it will be assumed that most engineers answer "yes".

Question.2 Please state the pavement family, treatment level, and climatic and subgrade zone you have most experience with in you District.

Again, depending on how the engineer answers, the information provided to the engineer on the next question can be tailored to his personal experience. Creating dynamic surveys is not complicated when using survey software such as Survey Monkey, which was used for determining the treatment levels discussed earlier in this thesis. As an example let's assume the engineer answered dry-warm climate and good subgrade zone denominated 4; thick (> 5.5" thick), intermediate (2.5-5.5" thick), and overlaid asphalt pavements shown as pavement family A; 20-yer projected equivalent single axle load (ESALS) of 1.0 million to less than 10 million denominated medium traffic; and the treatment level of heavy rehabilitation. It may not be

feasible to ask the expert, the score deterioration over a large span of time, therefore the last year of deterioration will be 5 years. On the contrary, it can be expected for the engineer to have experience in determining when the treatment is expected to hit the PMIS threshold values. The information derived from the historical data should be provided alongside.

Question.3 Please provide the expected ride score deterioration for the first 5 years. Also provide the year that the ride score reaches the threshold value of 3.0 and the year that the distress score reaches a threshold value of 60.

Table 4: Survey to Incorporate Expert Knowledge in the Development of Pre-Treatment Performance Curve.

Treatment Level	Traffic Level	Climatic and Subgrade Zone	Pavement Family	Years	Ride Score		Distress Score	
					Historical Data	Expert Input	Historical Data	Expert Input
HRhb	High	4	A	0	5		100	
				1	4.8		90	
				2	4.4		78	
				3	4.1		71	
				4	3.9		67	
				5	3.7		64	
Expected year that ride score = 3.0 distress score = 60					20 Years	Years	7 Years	Years

Table 5: Survey to Incorporate Expert Knowledge in the Development of Post-Treatment Performance Curve.

Treatment Level	Traffic Level	Climatic and Subgrade Zone	Pavement Family	Years	Ride Score		Distress Score	
					Historical Data	Expert Input	Historical Data	Expert Input
HRhb	High	4	A	0	5		100	
				1	4.5		100	
				2	4.5		99	
				3	4.4		98	
				4	4.3		97	
				5	4.3		96	
Expected year that ride score = 3.0 distress score = 60					30 Years	Years	45+ Years	Years

From the responses it is feasible to use non-linear regression to fit the sigmoid equation to the expert knowledge. In addition, the RMSE between the historical and engineer information can

also be calculated. To further refine the information, with the Delphi technique, the finished performance curves may be sent back to the engineers to assess how well the pavement deterioration fits the real deterioration observed in the field.

Question.4 In your opinion, is the model of the curve deterioration reasonable (1), over predicts (2) or under predicts (3) the observations in your district?

If the engineer determines the curve needs to be calibrated further, the table in question 3 can be reconstructed with the information from the updated performance curve. This interactive process may continue until the experts reach a consensus in the applicability of the curve created.

Figure 11 summarizes the hybrid methodology for the creation of the pre-treatment performance curve. The same methodology is used in the post-treatment curves but the question about the use of a "do-nothing" curve is omitted.

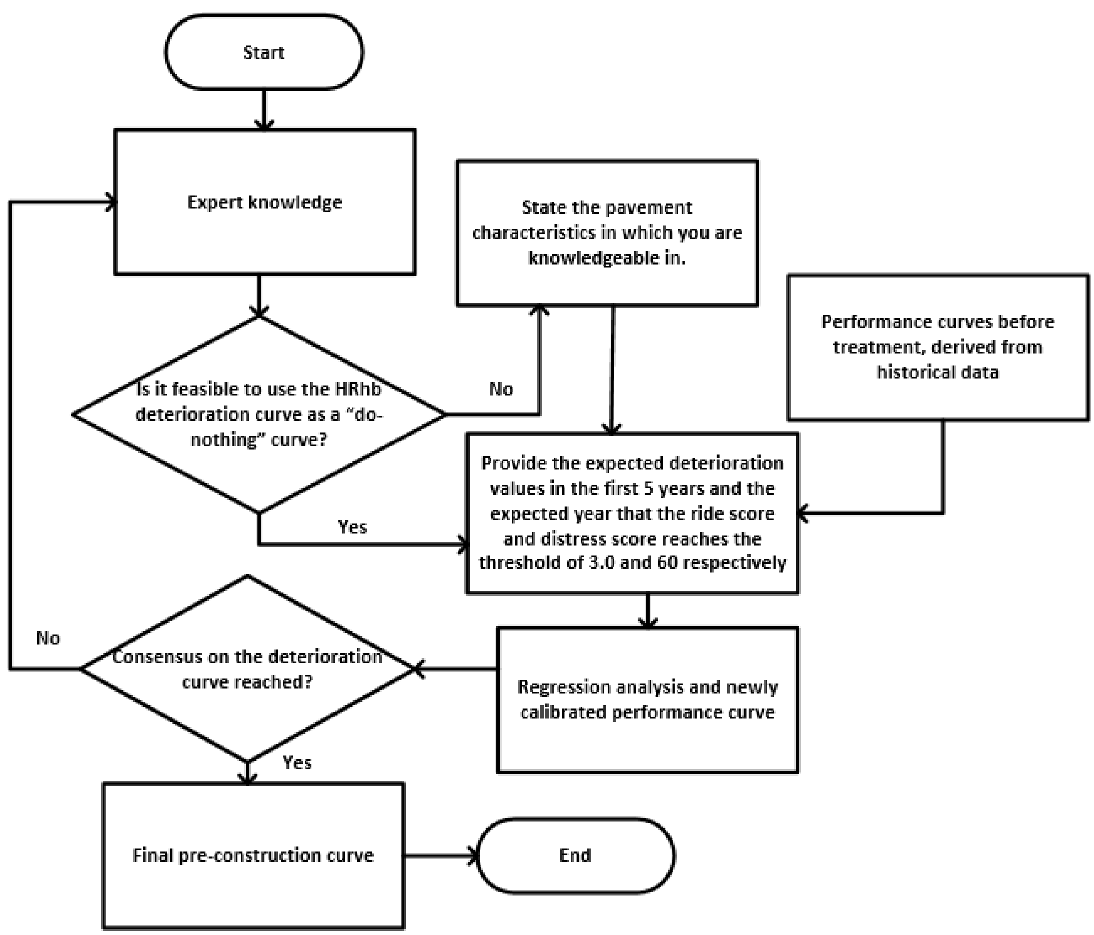

Figure 11: Methodology for Pre-Treatment Performance Curve Calibration.

3.3.4 Optimal Time for Treatment Application

The long-term effectiveness is highly dependent on the time of application. There is an optimal time of treatment, meaning if the treatment is applied too early or too late the treatment effectiveness is affected. This dependency of the time the treatment is applied is the reason why the long-term effectiveness calculations were left for this section. This last section ties together the short-, long- and cost-effectiveness as well as the optimal time to apply a treatment. To calculate the long-term effectiveness the following steps were taken.

1. The starting point for the deterioration post-treatment curves is shifted vertically according to the condition value in the pre-construction deterioration curve, at the year of application and the performance jump. The post-treatment curves are also shifted horizontally.
2. The benefit is the area under the curve between the pre- and post-treatments. The area under the curve is calculated by subtracting the integral of the post-treatment curve by the pre-treatment curve which was modelled with the equation based on equation 1 and equation 2 found in Stampley et al. (1993). The extended service life may also be derived in this step as the difference in years between the integral boundary conditions. Table 6 shows the ride score area under the curve and the extended service life calculated for the preventive maintenance; dry-warm climate and good subgrade zone denominated 4; Thick, intermediate and overlaid asphalt pavements denominated family A; 20-yer projection of 1.0 million to less than 10 million ESALS or medium traffic. The table also demonstrates that the optimal time of treatment in this situation is 5.5 years.
3. The next step is to derive the cost-effectiveness ratio based on the smallest extended service life between the ride and distress score. The equations 3-5 currently in use by TxDOT in PMIS and presented in Stampley et al. (1993) were implemented to achieve this calculation. Table 6 shows an example of cost-effectiveness calculated for the preventive maintenance, climate and subgrade zone 4, asphalt pavement family A, and medium traffic.

Table 6: Optimal Time of Treatment to Maximize the Ride Effectiveness.

Year	Benefit	Extended Service Life	Cost-Effectiveness
3.0	0.0	0.0	0.00
3.5	0.0	0.0	0.00
4.0	4.8	20.0	2.58
4.5	5.1	20.0	2.77
5.0	5.4	20.0	2.93
5.5	5.7	20.0	3.08
6.0	5.0	20.0	2.69
7.0	3.6	20.0	1.95
8.0	2.6	20.0	1.40
9.0	1.9	20.0	1.03
10.0	1.4	20.0	0.74
11.0	0.8	20.0	0.43
12.0	0.4	20.0	0.22

Engineering judgment will need to reinforce the extended service life, the optimal treatment time and the treatment cost. It would not be feasible to have static recommendations of benefit or cost-effectiveness since they are surrogate factors of the prediction models and costs. As the other techniques shown earlier in this thesis, the first step would be to create a comprehensive survey with examples derived from the historical data. The extended service lives found in the literature do not differentiate between the pavement characteristics, although it has been stated that traffic, climatic and subgrade zones, and treatment types do play a role in the measure. This will impact the way the question is formulated. The treatment guidelines in Chang et al. (2013) and Wu et al. (2010) have vast information in the service life extension and will be used in the following example. The pavement characteristics were expanded for all traffic levels. The ride or distress score value at the end of the life might also give an idea of the accuracy of the post-construction performance curve.

Question.1 Based on your knowledge, please provide the extended service life for the different traffic levels and corresponding attributes. Also, provide the ride score at the end of the extended service life. You may use the historical data values and literature values as a reference. You may use the same values for all traffic levels, pavement families, and climatic and subgrade zones.

Table 7: Survey to Incorporate Expert Knowledge in the Expected Service Live.

Treatment Level	Traffic Level	Climatic and Subgrade Zone	Pavement Family	Extended Service Life (years)			Ride Score Value at end of Extended Life	
				Literature	Historical Data	Engineer Expert	Historical Data	Engineer Expert
PM	High	4	A	1 to 15	7		3.7	
PM	Medium	4	A		20		3.7	
PM	Low	4	A		20		3.1	

The next survey question is very similar to question 1 but instead of service life, it will concentrate on the optimal treatment placement. In Wu et al. (2010) a synthesis of state highway agencies provided the treatment timing of different M&R as used in the example.

Question.2 Based on your knowledge, please provide the optimal treatment placement for the different traffic levels and corresponding attributes. You may choose one answer for all three traffic levels, climatic and subgrade zones and pavement families. You may use the historical data values and literature values as a guide.

Table 8: Survey to Incorporate Engineering Knowledge in the Optimal Treatment Time.

Treatment Level	Traffic Level	Climatic and Subgrade Zone	Pavement Family	Optimal Treatment Time (years)		
				Literature	Historical Data	Engineer Expert
PM	High	4	A	1 to 15	4.5	
PM	Medium	4	A		5.5	
PM	Low	4	A		8	

The following question will focus on the unit cost of treatments. There are a wide range of factors that affect the cost, even inflation or the discount rate. In this instance, the factors that affect the cost the most are the treatment itself, the climatic and subgrade zones, and the pavement family. To avoid confusion and achieve a higher level of consensus among widely varying costs around the state, this question will focus on a more general answer. The costs used for the implementation in Gharaibeh et al. (2012) will serve as the literature backdrop.

Question.3 In your opinion, what is the feasible max, min and average unit construction cost for the different treatment levels in your state? You may use the literature unit costs as a guide.

Table 9: Survey to Incorporate Engineering Knowledge in the Unit Cost.

Treatment Level	**Unit Cost ($/lane-mile)**			
	Literature	**Engineer Expert**		
		Min	**Average**	**Max**
PM	29,000			
LRhb	173,000			
MRhb	237,000			
HRhb	442,000			

The last questions will serve to bring a level of consensus in the optimal treatment timing and the unit cost per treatment. It's important to create the factorial experiment with intent to arrive at a consensus from the experts at the end. This is the main objective and requirement of the Delphi technique. For this reason less detail was incorporated in the wide variable answers such as the unit costs.

Question.4 In your opinion, is the optimal treatment timing, reasonable (1), over predicts (2) or under predicts (3) the observations in your district?

Question.5 In your opinion, is the unit cost per treatment, reasonable (1), over predicts (2) or under predicts (3) the observations in your district?

The flow chart shown in figure 12 summarizes the hybrid methodology to incorporate expert opinion into the optimal treatment timing and unit costs. Since the optimal treatment time links the short- and long-term effectiveness, the figure is a summary of the hybrid methodology which systematically adds expert opinion throughout the quantification of effectiveness. The sub-processes shown for the treatment levels, short-term effectiveness and pre- and post-treatment performance curves have been shown in figures 7-9.

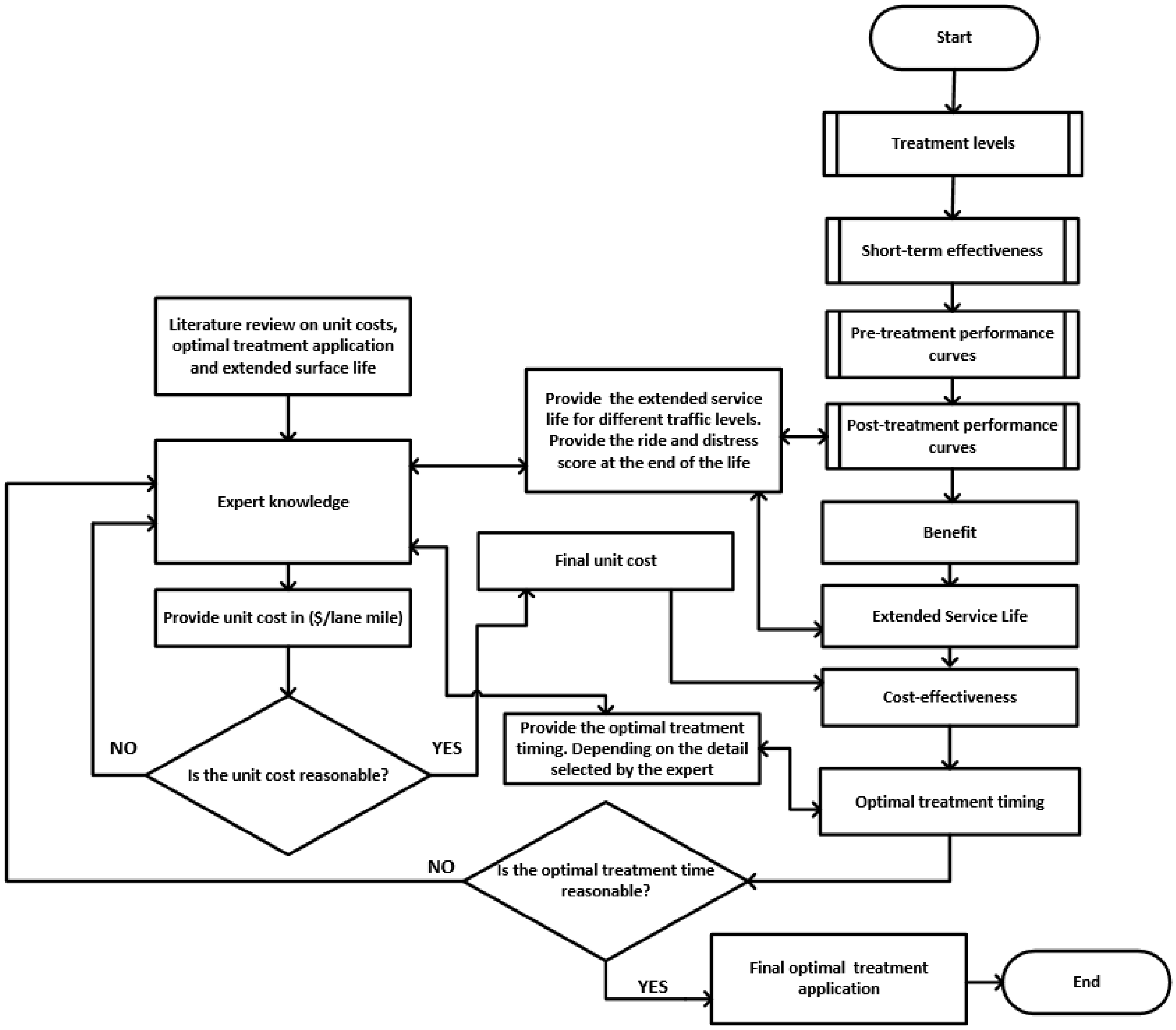

Figure 12: Summary of the Hybrid Methodology Proposed in this Thesis.

3.4 Validation of Methodology

The methodology presented for the establishment of treatment levels and the short-term effectiveness was used to improve the recommendations found in the PMIS. The results were validated further with the field experiment. The positive acceptance by TxDOT experts motivated this research to expand the hybrid methodology to encompass the long-term treatment effectiveness and the optimal treatment timing. The next chapters will describe in detail the use of this hybrid methodology and how the historical values were derived.

3.5 Conclusion

There are many challenges in the quantification of short-term and long-term effectiveness, and the optimal treatment application. They include the quality and quantity of performance data available as well as the accuracy of the models in use. The hybrid methodology proposed, systematically merges statistical analyses of historical data, literature and expert knowledge to create a robust and reliable decision support system. Furthermore, the methodology is able to account for factors that although not measured directly can affect the management of the network.

The hybrid approach is highly adaptable due to its ability to draw expert knowledge using diverse techniques. Therefore, the approach can be implemented using a wide range of pavement management evaluation tools, pavement condition indices and management philosophies.

Overall, the hybrid method presented in this thesis can create reliable decision-making support due to its simplicity and capability to add outside unpredictable factors such as economic downturns and the availability of new technology.

Chapter 4: Pavement Performance Historical Data Acquisition

In February 1989, the Federal Highway Agency Administration (FHWA) introduced a pavement management system design policy required by the State Highway Agency (SHA) (TxDOT Construction Division, Materials and Pavement Section 2010). The system based on the basic concepts provided in the Association of State Highway and Transportation Officials (AASHTO) publication Guideline on Pavement Management from 1985. TxDOT implemented the Pavement Management Information System (PMIS) in 1993.

4.1 Overview of TxDOT's Pavement Management Information System (PMIS)

The PMIS contains large amount of pavement evaluation data. The data is used by TxDOT to monitor statewide trends in pavement condition. The PMIS subdivides the flexible broad pavement types in different pavement types, based on the thickness of the pavement and past maintenance and rehabilitation activities. Table 10 shows the different pavement types available within the asphalt pavement broad type.

Table 10: PMIS Pavement Types for Asphalt Broad Type.

Pavement Type	Description
4	Thick Asphalt Concrete Pavement (greater than 5.5" thick)
5	Intermediate Asphalt Concrete Pavement (2.5-5.5" thick)
6	Thin Asphalt Concrete Pavement (less than 2.5" thick)
7	Composite Pavement (heavily-stabilized asphalt-surfaced pavement)
8	Overlaid or Widened Old Concrete Pavement
9	Overlaid or Widened Old Flexible Pavement
10	Thin-surface Flexible Base Pavement (surface treatment or seal)

The pavement evaluation data collected, stored and reported on is Distress, Ride Quality, Deflection and Skid Resistance. Surface distress data indicates the poor or unfavorable pavement performance or signs of impending failure. The rating helps in determining the current condition of the pavement's surface. The data is collected on the entire maintained highways using the visual roadside survey method by trained raters. The only ratings that are not measured by the raters are the Shallow Rutting and Deep Rutting. These distresses are measured using calibrated

profilometers such as the Rutbar. Table 11 shows the twelve distress types that are measured for asphalt pavements and the units of the measurement.

Table 11: PMIS Pavement Distress Types and Rating Method.

ACP Distress Types	Rating Method
Shallow Rutting (0.25" -0.5")	percent of wheelpath length (0-100)
Deep Rutting (0.5"-1")	percent of wheelpath length (0-100)
Severe Rutting (1"-1.99")	percent of wheelpath length (0-100)
Failure Rutting (>2")	percent of wheelpath length (0-100)
Patching	percent of lane area (0-100)
Failures	total number (0-99)
Block Cracking	percent of wheelpath length (0-100)
Alligator Cracking	length per 100' station (0-999)
Longitudinal Cracking	number per 100' station (0-99)
Transverse Cracking	none, low, medium, or high
Raveling	none, low, medium, or high
Flushing	none, low, medium, or high

The ride quality is used to describe the pavement roughness. The measurements are made hundreds of times per foot by the calibrated TxDOT profiler. The profiler uses lasers, accelerometer and inertial distance measuring for each wheelpath. The roughness data is recorder as IRI values and turned into Serviceability Index (SI) values.

TxDOT uses the utility theory which is defined as the "measure of relative satisfaction from or desirability of consumption of various goods and services". What this means is that the utility measures the usefulness of the pavement at different levels. This utility is dependent on the PMIS distress rating and ride quality lost demonstrated with L_i. The L_i for the various distress types is the normalization of the rating since a 0.1 mile section and a 0.5 miles section cannot have the same number of distress. For example, 5 failures on a 0.1 mile section have a larger impact on the quality than the same amount of failures on the 0.5 mile section. All distress types have equal L_i to the measured distress quantity in the field except for failures, raveling and flushing. Table 12 shows the computing of these values.

Table 12: Computing Li for PMIS Pavement Distress Types.

ACP Distress Types	**PMIS Rating**	Computing Li
Shallow Rutting (0.25" -0.5")	percent of wheelpath length (0-100)	same
Deep Rutting (0.5"-1")	percent of wheelpath length (0-100)	same
Patching	percent of lane area (0-100)	same
Failures	total number (0-99)	rating divided by length
Block Cracking	percent of wheelpath length (0-100)	same
Alligator Cracking	length per 100' station (0-999)	same
Longitudinal Cracking	number per 100' station (0-99)	same
Transverse Cracking	none, low, medium, or high	same
Raveling	none, low, medium, or high	none
Flushing	none, low, medium, or high	none

The PMIS Distress Score (DS) describes the amount of visible surface deterioration by combining the utility values for each distress type into a single index. Equation 6 is used in the calculation of the distress score.

$$DS = 100 \times U_{SRut} \times U_{DRut} \times U_{Patch} \times U_{Fail} \times U_{Block} \times U_{Alg} \times U_{LCrack} \times U_{TCrack} \quad \text{Equation 6}$$

DS = Distress Score

U_{SRut} = Utility value for Shallow Rutting

U_{DRut} = Utility value for Deep Rutting

U_{Patch} = Utility value for Patching

U_{Fail} = Utility value for Failures

U_{Blcok} = Utility value for Block Cracking

U_{Alg} = Utility value for Alligator Cracking

U_{LCrack} = Utility value for Longitudinal Cracking

U_{TCrack} = Utility value for Transverse Cracking

The PMIS Ride Score (RS) is the measure of the pavement roughness. The measure is the length-weighted arithmetic mean of all SI values in a data collection section. Equation 7 is used to calculate the RS.

$$RS = \frac{\sum_{i=1}^{n} d_i SI_i}{\sum_{i=1}^{n} d_i} \quad \text{Equation 7}$$

RS = Ride Score

n = number of SI values in the Data Collection Section

d = length of pavement, in miles, covered by the SI value

SI = Serviceability Index (from profiler)

TxDOT defines five treatment level categories: Needs Nothing (NN), Preventive Maintenance (PM), Light Rehabilitation (LRhb), Medium Rehabilitation (MRhb), and Heavy Rehabilitation or Reconstruction (HRhb). These treatment levels are meant to correct surface distresses and ride quality problems. PM, LRhb, MRhb, and HRhb treatments may lead to a certain amount of improvement in PMIS distress and ride scores (Stampley et al., 1993).

PMIS assigns the treatment levels using decision trees with a “hierarchical” scheme without budget constraints also called “Needs Estimate”. The factors used in the hierarchical scheme for the PMIS needs estimate process are extent of normalized distress (L_i), ride score, ADT, number of lanes, functional class, and date of last surface. Trigger criteria are used in the decision trees based on reason codes related to the factors influencing the treatment level recommendations. Severe deep rutting, alligator cracking and poor ride quality usually trigger medium and heavy rehabilitation.

4.2 Combination of Performance and Construction Databases

One of the major drawbacks of the Pavement Management Information System (PMIS) is the absence of historical M&R records. This challenge required the need to merge different construction TxDOT legacy databases such as the Decision Construction Information System (DCIS) and The Decision Support System (DSS) with the performance database PMIS. The pavement data was extracted from the following thirteen Districts: Amarillo, Atlanta, Austin, Brownwood, Bryan, Childress, Dallas, El Paso, Houston, Laredo, Lufkin, Pharr, and San Antonio. These Districts were selected because their PMIS, and treatment information was very well documented.

Pavement data was extracted from the Pavement Management Information System (PMIS), Construction Information System (DCIS), and the Decision Support System (DSS) legacy databases for years 1993 through 2012. Signed highway ID and reference markers were

used to identify sections to retrieve ride, distress, and condition scores from PMIS. In addition, independent pavement distresses quantity, traffic data (ADT, ESALs), pavement family type, climatic zone (county number), subgrade zone and the fiscal year of the condition assessment for the 0.5 mile sections were retrieved. Historical information including letting schedule, layman's description, and type of work were obtained from DCIS. DSS was used to verify construction dates and work descriptions. The major setback of using TxDOT databases came from linking the databases.

The missing link to reestablish the connection between PMIS, DCIS, and DSS was the location of the sections. PMIS uses state reference markers for 0.5 mile sections while DSS uses the Control-Section-Job (CSJ) and the Controlling-CSJ to identify construction projects for a certain length. To overcome these differences DCIS was used as the common link because it contains the CSJ as well as reference marker information. The following procedure shown in Figure 13 was developed to connect PMIS, DCIS and DSS.

First, the DSS and DCIS were merged using MS Access queries between the databases with the CSJ being the primary key to link the databases. The newly created table, DSS_DCIS, is then linked with PMIS by using a multi-key that includes the district, fiscal year, highway id, beginning reference marker, ending reference marker and reference marker displacements. All PMIS 0.5 mile sections within the construction project's length were retrieved. Only roadbeds L, R and K were considered. X and A are frontage roads and were excluded in the study. It is important to mention that the DSS project's layman description was used to exclude construction projects performed on the frontage roads. The resulting table, DSS_DCIS_PMIS, is an expanded database which includes the Ride, Distress, and Condition Scores for 0.5 mile sections within a construction project length for all available years. Table 13 shows the total number of projects that were successfully connected. The total percentage of projects is mostly under 50% since most projects located in the DCIS database before 2004 do not have reference marker information.

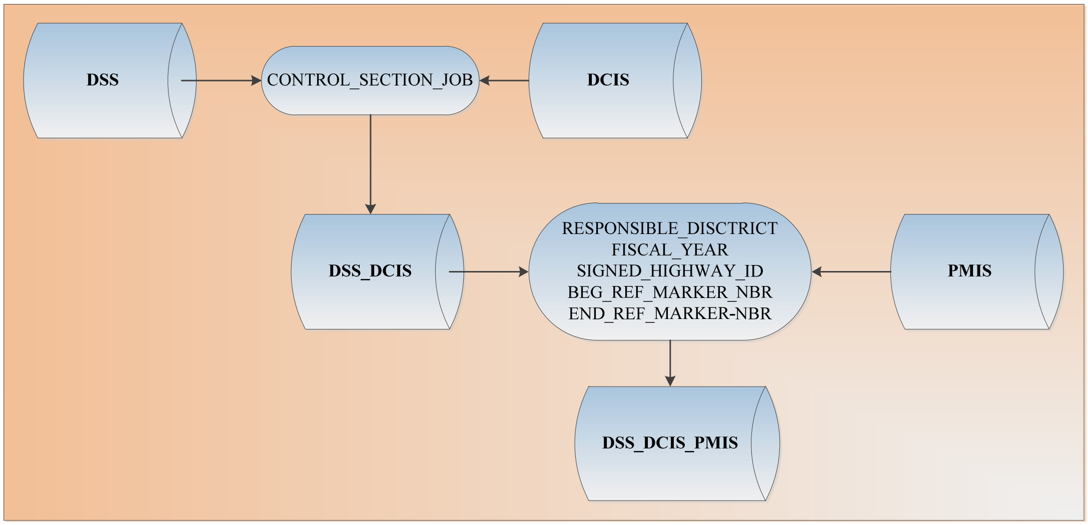

Figure 13: Schematics of the Procedure to Connect PMIS, DCIS, and DSS (Chang et al., 2013).

Table 13: Total Number of Linked Construction Projects (Chang et al., 2013).

District	DSS Projects	Merged Projects	Percentage (%)
Amarillo	1242	163	13
Atlanta	1280	496	40
Austin	782	241	32
Brownwood	922	450	49
Bryan	1733	245	14
Childress	800	128	17
Dallas	1190	215	26
EL Paso	446	144	38
Houston	915	340	54
Laredo	619	293	48
Lufkin	1294	546	42
Pharr	965	451	47
San Antonio	1729	1006	58

4.3 Summary and Concluding Remarks

The PMIS provides extensive pavement inventory information as well as detailed established condition indices. The condition indices are capable of monitoring the pavement deterioration of not only surface distresses but underlying pavement problems. The inventory also attempts to account for missing structural information through the subdivision of flexible pavement families. Although this surrogate index can provide satisfactory and affordable pavement monitoring, it is important to populate the database with reliable structural condition

measures and structure characteristic information. Their absence may impact the selection of different maintenance and rehabilitation treatments impacting the condition of the network and the allocation of funds. Another area that needs improvement is in the availability of maintenance and rehabilitation records. An alternative would be to populate the construction databases with reliable geographical location information such as reference markers. The PMIS had been designed with these factors in mind but the empty space shows that the availability of this information is not mandatory to the Districts. The merge of the construction legacy databases resulted into an expanded database with performance and M&R attributes. This expanded database provided information to quantify the short-term and long-term effectiveness because it set the year the treatment was applied making it possible to analyze the condition trends before and after the treatment.

Chapter 5: Establishing Treatment Levels

5.1 Existing Maintenance and Rehabilitation Treatment Level Categories

TxDOT districts are required to prepare a four-year pavement management plan describing the construction work by treatment level category to be performed in the road networks under their jurisdictions. PMIS) currently defines five treatment level categories: Needs Nothing (NN), Preventive Maintenance (PM), Light Rehabilitation (LRhb), Medium Rehabilitation (MRhb), and Heavy Rehabilitation or Reconstruction (HRhb). These treatment levels are meant to correct surface distresses and ride quality problems. PM, LRhb, MRhb, and HRhb treatments may lead to a certain amount of improvement in PMIS distress and ride scores. There are variations between the districts on the treatments to be considered as preventive maintenance. Some preventive maintenance treatments may be considered medium rehabilitation by other districts. This leads to difficulty in differentiating between construction alternatives; therefore, there is a need to identify which maintenance and rehabilitation treatments belong to each treatment category. Stampley et al. (1993) attempted to expand the previously recommended construction projects within each treatment level based on the asphalt pavement type. The recommended treatments in the report can be seen in table 14.

Table 14: Initial Treatment Levels Recommendations (Stampley et al., 1993).

Treatment Type	Thick ACP (Type 4)	Intermediate ACP (Type 5)	Thin AC (Type 6)	Composite (Type 7)	Concrete overlaid (Type 8)	Flexible overlaid (Type 9)	Thin-surfaced flexible base (Type 10)
PM	Crack seal, Surface seal	Crack seal, Surface seal	Crack seal, Surface seal	Crack seal, Surface seal	Crack seal, Surface seal	Crack seal, Surface seal	Surface seal, no patching
LR	Thin asphalt overlay	Thin asphalt overlay	Thin asphalt overlay	Thin asphalt overlay	Thin asphalt overlay	Thin asphalt overlay	Surface seal, Light/medium patching
MR	Thick asphalt overlay	Thick asphalt overlay	Mill and asphalt overlay	Mill and asphalt overlay	Mill and asphalt overlay	Thick asphalt overlay	Surface seal, Heavy patching
HR	Remove asphalt surface, Replace and rework base	Remove asphalt surface, Replace and rework base	Reconstruct	Remove asphalt surface, Replace and rework base	Remove asphalt surface, Replace and rework base	Remove asphalt surface, Replace and rework base	Rework base & surface seal

Murphy and Zhang (2009) attempted to consolidate the different construction projects by treatment levels but there were many treatment alternatives that were not included. One important piece of information available was that the paper provided the reasoning behind the categorization. Those treatments were used as the starting point when creating the surveys. Table 15-19 describe the treatments categorized by their treatment level.

Table 15: Routine Maintenance Treatments used by TxDOT Districts (Murphy and Zhang, 2009).

Treatment	Description
Fog Seal	Fog seal is used to rejuvenate the asphalt surface and seal cracks. Since the seal does not increase the structural index (SI), it does not qualify as a PM treatment and therefore does not improve the pavement Condition Score.
Crack Sealing	Crack sealing is assumed not to improve SI. It is also classified as 'cracks' based on the PMIS pavement rater's manual and therefore it is not considered to improve Distress or Ride Score.
Spot or Strip Seals	Spot or strip seals do not improve the Distress Score or SI although they may improve skid resistance and possibly seal cracks.
Edge Repair	Repairs are performed for safety purposes and prevention of further pavement damage due to tire loads at broken edge.
Partial or Full Depth Concrete Patching	These localized patches only improve the ride and eliminate a distress at a certain point. A distress may be removed, but the patch left in its place is still considered a 'distress' and therefore does not improve the Distress Score.
ACP Patching	These localized patches only improve the ride and eliminate a distress at a certain point. A distress may be removed, but the patch left in its place is still considered a 'distress' and therefore does not improve the Distress Score.
Localized base or edge repair and spot seal or spot overlay	These localized patches only improve the ride and eliminate a distress at a certain point. A distress may be removed, but the patch left in its place is still considered a 'distress' and therefore does not improve the Distress Score.

Table 16: Preventive Maintenance Treatments used by TxDOT Districts (Murphy and Zhang, 2009).

Treatment	Description
Microsurfacing	Microsurfacing may be combined with other work (e.g. full width underseal or emulsified asphalt seal) and still classified as Preventive Maintenance.
Seal Coat	The application of only seal coat is considered as preventive maintenance. If a seal coat is applied with other work (e.g. base repairs, level, up, patching), then it is considered as Light or Medium Rehabilitation.
Overlay or thin Overlay 2” thick or less	The application of an overlay with no other work (e.g. patching, base repair, under seal) is considered PM. This work does improve ride and friction, seals the pavement, but does not improve structural capacity.
Diamond Grind PCC Pavement	The short time improvement of ride and friction classifies this treatment as Preventive Maintenance.
Treatment	Description
Overlay greater than 2” but less than 3” thick	It was noted in the layman’s description that overlays between 2”and 3” were classified as LRhb.
Widened Pavement and application of full width seal coat	Widening lanes or adding width to the paved shoulder encourages traffic to travel along the center of the lane; therefore reducing rutting and edge failures. Full width seal coats restore surface friction and seals pavement.
Base Repair and Seal	Localized base repairs increase the potential for seal coats to perform according to the full design life. The ride is not necessarily improved by these repairs.
Mill, Seal and thin overlay	Distressed/damaged hot mix is not removed by milling, but it does provide a better surface to place and overlay. The ride is expected to improve more than a PM treatment when an overlay and seal are applied although structural capacity will not increase.

Table 17: Light Rehabilitation Treatments used by TxDOT Districts (Murphy and Zhang, 2009).

Treatment	Description
Overlay greater than 2” but less than 3” thick	It was noted in the layman’s description that overlays between 2”and 3” were classified as LRhb.
Widened Pavement and application of full width seal coat	Widening lanes or adding width to the paved shoulder encourages traffic to travel along the center of the lane; therefore reducing rutting and edge failures. Full width seal coats restore surface friction and seals pavement.
Base Repair and Seal	Localized base repairs increase the potential for seal coats to perform according to the full design life. The ride is not necessarily improved by these repairs.
Mill, Seal and thin overlay	Distressed/damaged hot mix is not removed by milling, but it does provide a better surface to place and overlay. The ride is expected to improve more than a PM treatment when an overlay and seal are applied although structural capacity will not increase.

Table 18: Medium Rehabilitation Treatments used by TxDOT Districts (Murphy and Zhang, 2009).

Treatment	Description
Mill and Inlay (Mill and Fill)	Milling removes deteriorating or stripped asphalt, distresses and pavement distortion (roughness); therefore, providing an improved surface and possibility of a higher ride. Mill and Inlay can be classified according to the amount and length of the project. If the budgeted amount is small for the length of the project, it is considered a spot Routine Maintenance work. If the amount budgeted is significant for the length of the project or the project is listed under the Construction PM work list, then it is categorized as Medium Rehabilitation.
Mill, stabilize base and seal	Milling removes distressed material. Stabilization of base increases structural capacity. Seal application increases friction and prevents moisture penetration.
Level up and overlay	Level up fills ruts, reshapes the roadway crown and restores cross slope and drainage.
Widen pavement, level up and overlay or seal coat	Widening of pavement encourages traffic to travel along the center line of the lane, therefore reducing edge failure. Level ups fill ruts, reshapes the roadway crown and restores cross slope and drainage. Applying a level up with an overlay or seal provide double protection to the pavement.
Overlay between 3" and 5"	An overlay of 3" seals the pavement, improves ride, addresses rutting and provides additional structural capacity.
Overlay defined as 'Thick' overlay	An overlay defined as 'thick' overlay with no other work description (e.g. milling, widening, bomag base or stabilize base) is considered Medium Rehabilitation.
Mill, patch, under seal and Inlay	Provide the potential for greater life and opportunity to improve ride.
Base repair, spot seal, edge repair and overlay	
Mill, cement stabilize base and overlay or seal	

Table 19: Light Rehabilitation Treatments used by TxDOT Districts (Murphy and Zhang, 2009).

Treatment	Description
Bomag, add base and seal	The application of these works provides the opportunity to restore good ride quality and remove distresses.
Reconstruction of the base and surface, milling and thick overlay	These activities restore pavement functional and structural condition to nearly original conditions.

5.2 Expert Knowledge Synthesis

The surveys were developed based on treatment levels found in the literature review (Chang et al., 2013). As stated, Murphy and Zhang (2009) was the starting point in the development of the surveys. In order to further understand the different treatment levels, the most important factors affecting their treatment selection process were identified as well as the

distresses treated by the each treatment independently. This analysis was done in an effort to find any common factors within the treatment levels which would allow easier categorizing. The step was crucial since all future calculations would be completely dependent on the established levels. The survey was sent to all TxDOT Districts. As was discussed in the previous chapter the first step in the hybrid methodology was the factorial design. The factorial design and the answers received are found in the "Improvement in Pavement Ride, Distress and Condition Based on Different Treatment Types" (2013). Once the responses were obtained statistical analysis were performed to draw preliminary treatment levels. Table 20 summarizes the responses on key factors for selecting maintenance and rehabilitation treatments for asphalt pavements (ACP). The first two columns show the treatments used for PM, LRhb, MRhb and HRhb by TxDOT. To identify the most common treatments used at the district level, the top 3rd quartile treatments are shaded in grey. The next columns reflect the three most important factors considered by TxDOT districts when deciding on that treatment. If the total weight given to a factor exceeds the median weight for that treatment category, the factor description appears bolded. The last columns show the most relevant distresses pondered when deciding for that treatment. Shaded distresses correspond to responses above the median number of total individual responses for a given treatment category. If any tie was encountered in the responses it was resolved by selecting the closest number to the median.

The preliminary treatment level guidelines were constantly updated in close talks with TXDOT engineers but an issue arose when the treatment descriptions were not enough to classify the projects found in the databases. To counter this obstacle another round of questionnaires was implemented, this time the questionnaires were tailored for every District. Sometimes the layman's description was not detailed enough or too detailed to arrive at a categorization conclusion. Table 21 shows the second questionnaire created, for the El Paso District, to arrest this problem. Refer to the first section of appendices B-N for the surveys and answers for each TxDOT District.

Table 20: TxDOT Key Factors and Distress when Selecting Maintenance and Rehabilitation Treatments for Asphalt Pavements.

Classification	Treatment Description	Most Important Factors			Most Important Distresses				
Preventive Maintenance	Chip Seal	**Time to Last Treatment**	**Safety**	Structural Condition	Raveling	Longitudinal Cracking	Transverse Cracking	Flushing	Longitudinal Cracking
	Crack Sealing	Structural Condition	**Time to Last Treatment**	**Environmental Factors**	Longitudinal Cracking	Transverse Cracking	Block Cracking	Alligator Cracking	Failures
	Fog Seal	**Time to Last Treatment**	Traffic Composition	Structural Condition	Raveling	Longitudinal Cracking	Transverse Cracking	Flushing	Block Cracking
	Microsurfacing	**Safety**	**Traffic Composition**	**Time to Last Treatment**	Flushing	Rutting Shallow	Raveling	Longitudinal Cracking	Transverse Cracking
	Thin Overlay 2" thick or less	**Ride**	**Safety**	**Structural Condition**	Rutting Shallow	Flushing	Raveling	Longitudinal Cracking	Transverse Cracking
	Ultrathin Friction Course	**Safety**	**Traffic Composition**	Ride	Flushing	Raveling	Rutting Shallow	Transverse Cracking	Longitudinal Cracking
	Cape Seal	Structural Condition	Time to Last Treatment	Safety	Flushing	Raveling	Rutting Shallow	Longitudinal Cracking	Transverse Cracking
	Slurry Seal	Safety	Time to Last Treatment	Traffic Composition	Rutting Shallow	Raveling	Transverse Cracking	Longitudinal Cracking	Block Cracking
	Cold in-place recycling	Ride	Traffic Composition	Safety	Transverse Cracking	Longitudinal Cracking	Block Cracking	Rutting Shallow	Raveling
Light Rehabilitation	Base Repair and Seal	**Structural Condition**	**Safety**	Traffic Composition	Failures	Alligator Cracking	Rutting Deep	Patching	Rutting Shallow
	Overlay greater than 2" thickness but less than 3" thick	**Ride**	**Structural Condition**	**Safety**	Rutting Shallow	Rutting Deep	Flushing	Raveling	Patching
	Hot in-place recycling	Traffic Composition	Ride	Structural Condition	Rutting Shallow	Raveling	Block Cracking	Rutting Deep	Flushing
Medium Rehabilitation	Overlay between 3" and 5"	**Structural Condition**	**Ride**	Safety	Rutting Deep	Rutting Shallow	Longitudinal Cracking	Transverse Cracking	Raveling
	Bomag, add base and seal	**Structural Condition**	**Safety**	**Ride**	Failures	Rutting Deep	Alligator Cracking	Patching	Rutting Shallow
	Base repair, spot seal, edge repair and overlay	**Structural Condition**	**Safety**	**Ride**	Failures	Rutting Deep	Rutting Shallow	Alligator Cracking	Patching
	Mill stabilize base and seal	**Structural Condition**	**Safety**	**Traffic Composition**	Rutting Deep	Failures	Alligator Cracking	Patching	Rutting Shallow
Heavy Rehabilitation	Full depth reclamation (Pulverization and resurfacing)	**Structural Condition**	**Ride**	**Traffic Composition**	Failures	Alligator Cracking	Rutting Deep	Patching	Rutting Shallow
	Mill, cement stabilize base and overlay	**Structural Condition**	**Ride**	**Traffic Composition**	Failures	Rutting Deep	Alligator Cracking	Patching	Rutting Shallow
	Thick' Overlay, greater than 5"	**Structural Condition**	**Ride**	Traffic Composition	Rutting Deep	Rutting Shallow	Alligator Cracking	Patching	Longitudinal Cracking

Table 21: Example of Projects Identified by PMIS Treatment Types.

CSJ	Controlling CSJ	County	High Way	Beg Ref Marker	End Ref Marker	DCIS Type Of Work	DCIS Layman Description	DSS Work Start Date	PM	LRhb	MRhb	HRhb
000105015	000105015	72	FM 259	10	12	2008 SEAL COAT PROGRAM	2008 SEAL COAT PROGRAM	2008				
232601020	232601020	72	FM 2529	310	312	2009 REHABILITATION PROGRAM	OVERLAY, MILL AND INLAY	2009				
000102049	000102049	72	SH 20	326	326	FY 06 SUPPLEMENTAL REHA BILITATION	REPAIR AND OVERLAY	2008				
000103033	000103033	72	SH 20	328	330	INTERSECTION IMPROVEMENTS AND REHAB	INTERSECTION IMPROVEMENTS AND REHA BILITATION	2003				
000210034	002011041	116	IH 10	130	134	MICRO MILL AND SEAL COAT	MICRO MILL AND SEAL COAT	2004				

5.3 Final Recommendations

After a number of interviews, a consensus was reach among District experts in the treatment level categorization. The treatment levels were defined and the methodology to categorize the treatments was explained. The final treatment levels concluded in this extensive iterative process, as well as their frequency of use are presented in table 22. The treatment levels were defined in Chang et al. (2013) as follow:

- **Preventive Maintenance** is used to reduce the rate of deterioration and retard failures of pavements still in good condition, extending its service life. This functional life of the pavement is extended by protecting the pavement structure from water infiltration and repairing any minor surface distresses at an early stage of development. While minor surface defects are temporarily corrected, combining the treatment with activities such as patching may result in a short term ride improvement. Structural capacity is not increased and low severity non-load related distresses are corrected.
- **Light Rehabilitation** is mainly composed of non-structural improvements to address surface distresses mainly related to aging and environmental effects. In addition, it restores functional characteristics and protects structural integrity. Structural capacity will not significantly improve but ride quality improvement is expected.
- **Medium Rehabilitation** is a structural improvement that will extend the service life of an existing pavement and increase its load-carrying capacity. This is usually

accomplished by increasing the pavement thickness to carry increased vehicular loading or volume. Treatments under this category also restore functional characteristics improving the ride quality considerably.

- **Heavy Rehabilitation** is the partial or complete removal and replacement of the existing pavement structure to restore functional and structural conditions to at least the original conditions. Good ride quality is restored and all distresses are removed. Treatments under this category are performed on pavement sections with extensive structural distresses.

Table 22: Established M&R Activities per PMIS Treatment Levels (Chang et al., 2013).

Treatment Level	TxDOT's Description	Frequency of Use by TxDOT		
		Frequent	Rare	Expanding
Preventive Maintenance	Cape Seal		X	
	Fog Seal	X		
	Microsurfacing		X	
	Seal Coat	X		
	Thin Overlay (2 in. thick or less)	X		
	Ultra-Thin Friction Course	X		
Light Rehabilitation	Base Repair and Seal	X		
	Cold In-Place Recycling		X	
	Hot In-Place Recycling		X	
	Mill and Inlay; or Mill, Seal and Thin Overlay	X		
	Overlay Greater than 2" Thick but Less than 3"		X	
Medium Rehabilitation	Base Repair, Spot Seal, Edge Repair and Overlay	X		
	Level Up and Overlay	X		
	Mill and Overlay	X		
	Mill, Stabilize Base, and Seal		X	
	Overlay Between 3" and 5"		X	
Heavy Rehabilitation	Full Depth Reclamation (Pulverization and Resurfacing)	X		
	Mill, Cement Stabilize Base, and Overlay	X		
	Reconstruction	X		
	Thick Overlay Greater than 5"		X	

5.4 Summary of Chapter Conclusions

Establishing treatment levels at the network-level is of outmost importance because Districts managers are required to develop 4-yr management plans which affect the way TxDOT

distributes funds across the different Districts to meet its pavement condition goals. Furthermore, all of the evaluation tools found in the Pavement Management Information System require M&R activities to be categorized. Previously, there was no consensus amongst the different treatment levels state wide. Medium Rehabilitation treatments in one District might have been categorized as preventive maintenance in another District.

To establish the treatment levels, engineering knowledge was retrieved through expert surveys and statistical analysis. At the end, consensus was achieved across the District experts. The hybrid methodology was successfully implemented to conclude in the best treatment categorization.

Chapter 6: Evaluating Short-Term Effectiveness for Flexible Pavements

6.1 Introduction

Ride and distress score improvements are used to project current and future predicted pavement network condition based on District pavement programs identified in their respective 4-year Pavement Management Plan. The PMIS short-effectiveness measure in use is the condition improvement jump (CIJ). These score improvements due to treatments were first established over 20 years ago. During this time, there have been a number of new treatment types, improvements to construction practices and new specifications that have resulted in changes to the ride and distress score improvement for the different treatment type. Therefore, there was a need to update the improvements for all the maintenance and rehabilitations treatments.

The short-term effectiveness calculation was not straight forward due to inconsistencies in the construction dates and condition assessment of the ride and distress scores. Consequently, the hybrid methodology was implemented to arrive at the CIJ that best describes the true short-term effectiveness due to M&R activities. The method involved a comprehensive statistical analysis of historical performance and construction data and compared with field survey investigations. Descriptive statistics, hypothesis testing and engineering judgment were implemented to finally recommend PMIS score increase and reset values for flexible pavements.

6.2 Methodology

Several approaches were considered with the important factors being the construction date, the project CSJ, and the PMIS 0.5 mile sections within the project. These different approaches were used to define what distress, ride and condition score values were representative of the score increases due to treatments. The data were filtered to have performance information 3 years before and 3 years after the treatment's starting dates. Moreover, the PMIS sections were grouped by roadbed ID (L, R, and K) to keep consistency when comparing the score increment.

6.2.1 Analysis by CSJ

The PMIS pavement scores were initially statistically summarized for all 0.5 mile section within a CSJ to have single representative values before treatment and after the treatment. The control-section-job (CSJ) is a nine-digit number with four digits representing the control, two digits the section and three digits the job number. The control defines the section of highway geographically, the section describes a shorter length of the control and the job is the unique number assigned to the limits of the control-section. The values used to represent the ride, distress and condition scores before treatment were taken as the minimum of all 0.5 mile sections and they were compared with values taken as the average score of all 0.5 mile sections after treatment. Preliminarily, the average of score increases before construction and after construction were compared but upon close examination of the PMIS score increases, it was found that most score increases were negative or no improvement was achieved. Therefore, this approach was rapidly discontinued. Figures 14 to 16 demonstrate the minimum-before treatment and average-after treatment approach for a Seal Coat project with 50 sections spanned over 7 years. The construction starting date was 06/01/2004 and was indicated by the vertical red line. The sections which fall on the red line were included when calculating the minimum and also when calculating the average. The condition improvement was sometimes captured the year before construction, the same year of construction or the year after construction. Furthermore, the year the condition improvement jump was captured was different depending on the condition measured used which can be ride, distress and condition scores. If the increase in performance was captured before or after the construction year, or in the same year as seen in Figure 14; the selected minimum value to describe the before construction condition did not change. On the other hand, the selected condition value after construction (the average) was independent of the year the improvement was observed. The difference of the two lines is the “jump” in score.

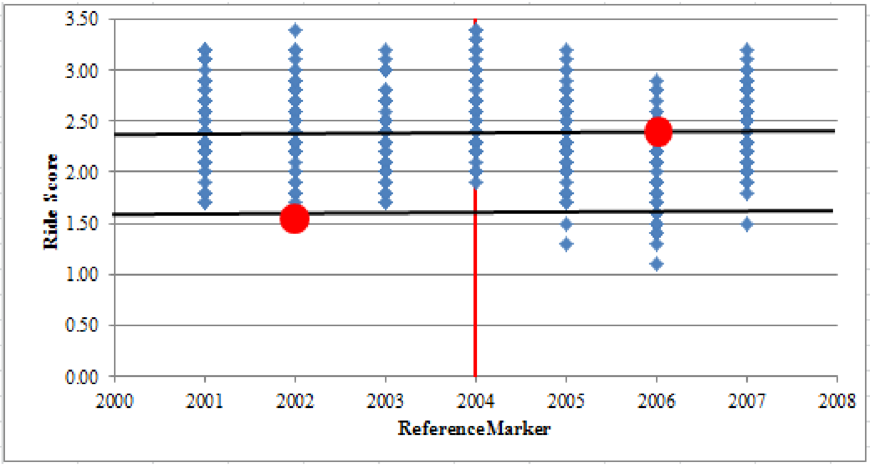

Figure 14: Change of Ride Score within CSJ.

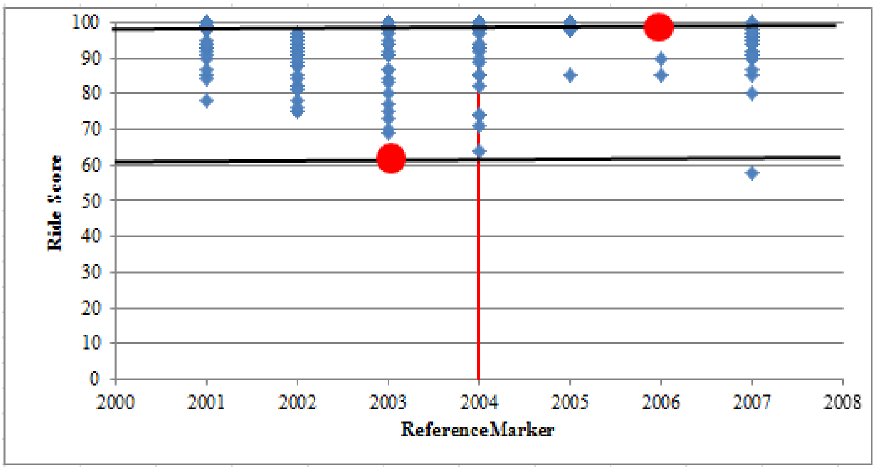

Figure 15: Change of Ride Score within CSJ.

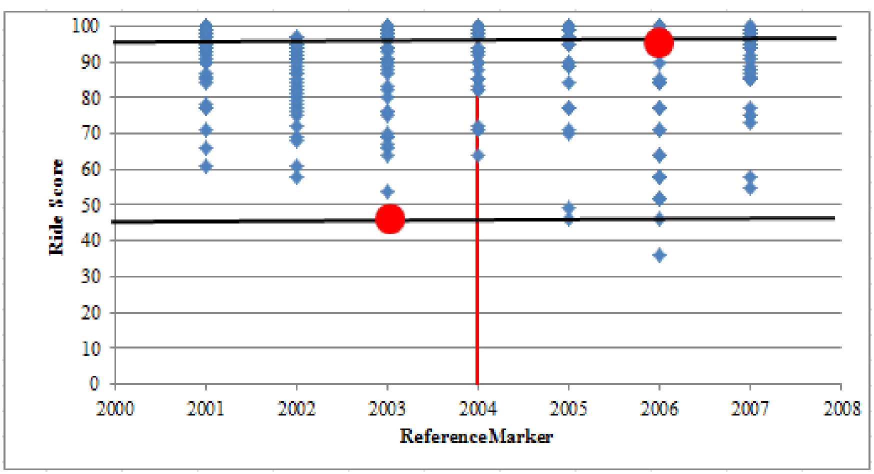

Figure 16: Change of Ride Score within CSJ.

6.2.2 Analysis by 0.5 Mile PMIS Sections

Similarly, PMIS performance scores were statistically summarized for all 0.5 mile PMIS sections within each CSJ but instead of having a single value representing the whole project, all sections within the project were compared across the years. To further refine the capture of the performance jump it was also important to base the improvement on the individual section not just the year. The 0.5 mile sections' location within the CSJ project was identified by reference markers and their respective PMIS scores were compared for these sections. Only if the sections had the same reference marker positioning could they be compared with each other. The following example is using the same Seal Coat project previously discussed. Figure 17 shows the ride score of the 0.5 mile sections in different years grouped by their reference marker which is their geographical location. According to figure 17, the improvement in each section was captured mostly between 2003 and 2004 for the ride score. In the case of the distress score (figure 18), the performance improvement was observed between 2002 and 2004 for the same project. The condition improvement (figure 19) follows the same trend as the distress score.

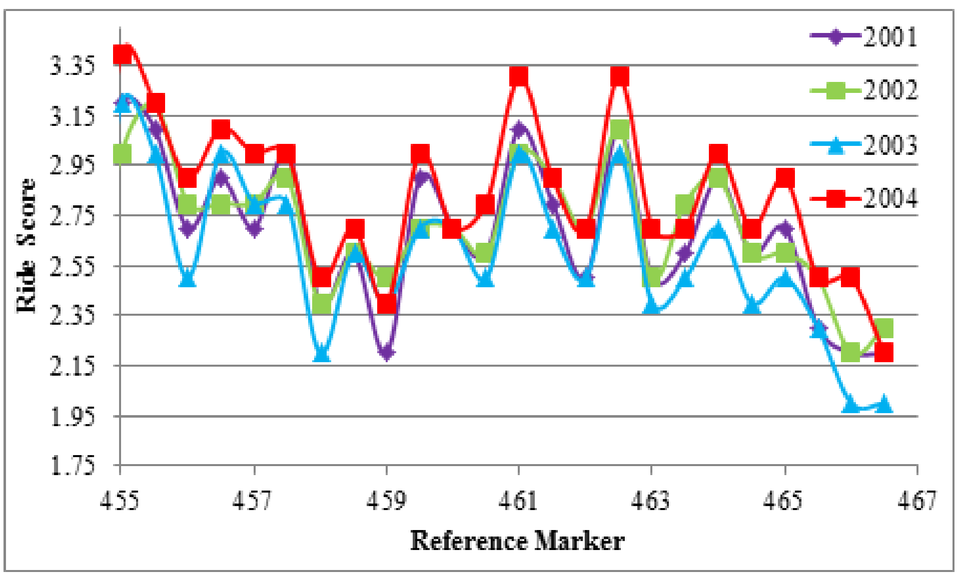

Figure 17: Change of Ride Score within CSJ.

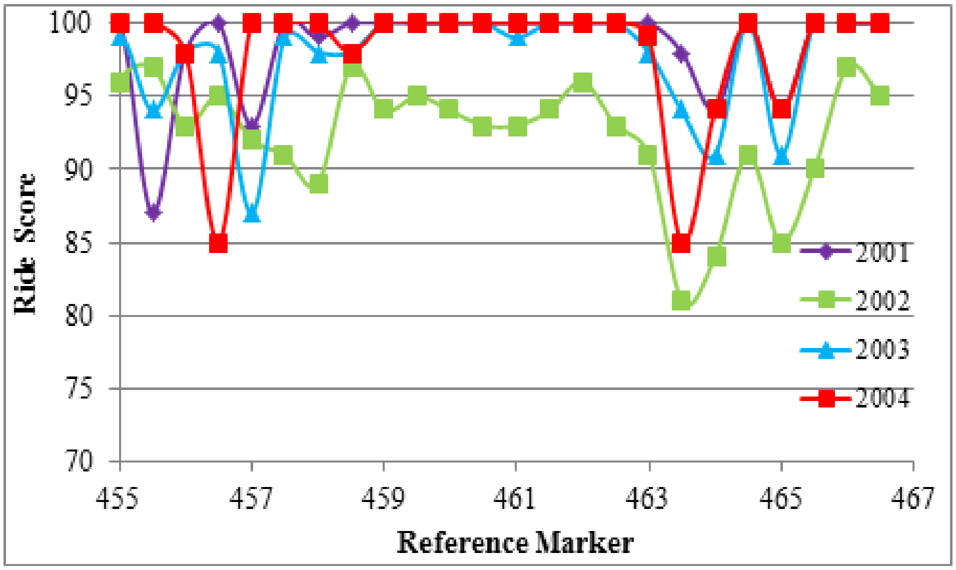

Figure 18: Change of Distress Score within CSJ.

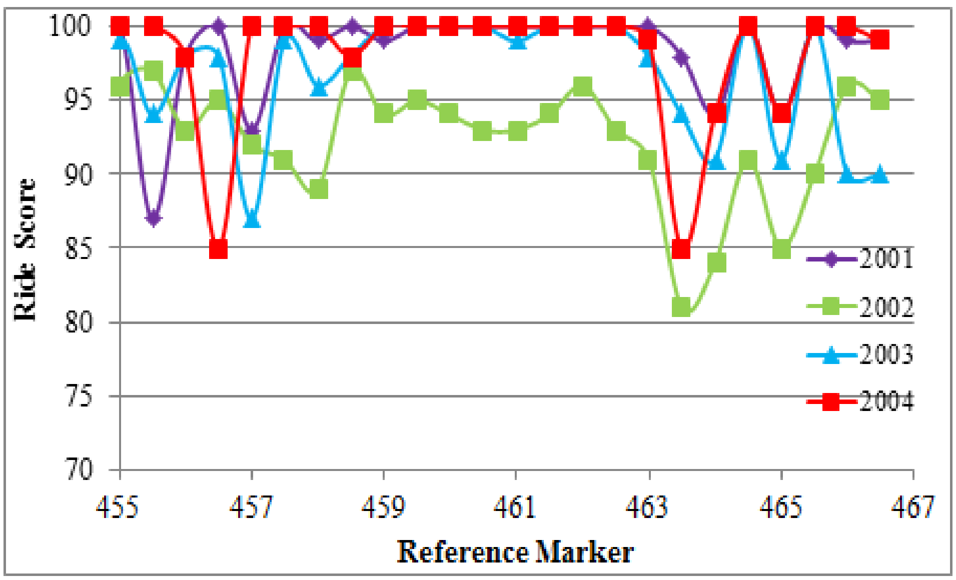

Figure 19: Change of Condition Score within CSJ.

Due to these observations, it was decided that to estimate the PMIS score increase due to treatment, the minimum score value on or before the construction year and the maximum score value on or after the construction year were selected for each 0.5 mile section within a CSJ. The minimum score before the reported construction year was selected because it was assumed that the sections were at their worst conditions right before the treatment. In figures 20-22 the

minimum trend for the ride, distress and condition scores were shown in black. The minimum values were also helpful in obtaining the worst scores for that 0.5 mile section even if that same lane was not rated in different years. Comparatively, the maximum score after the reported construction years should be achieved right after construction since pavement deteriorates over time and only M&R activities may raise the condition. Figures 20 through 22 show the maximum scores selected within the CSJ in red. Furthermore, the sections that have the same fiscal and construction year will only affect either the minimum or maximum depending only on the year the improvement was captured and not on the construction year.

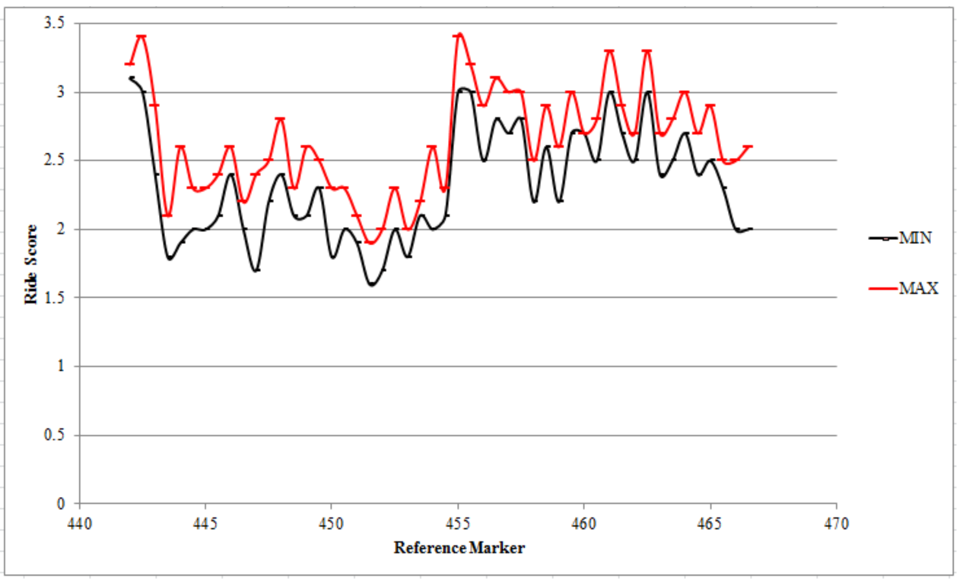

Figure 20: Ride Score before and after Treatment by 0.5 Mile Section.

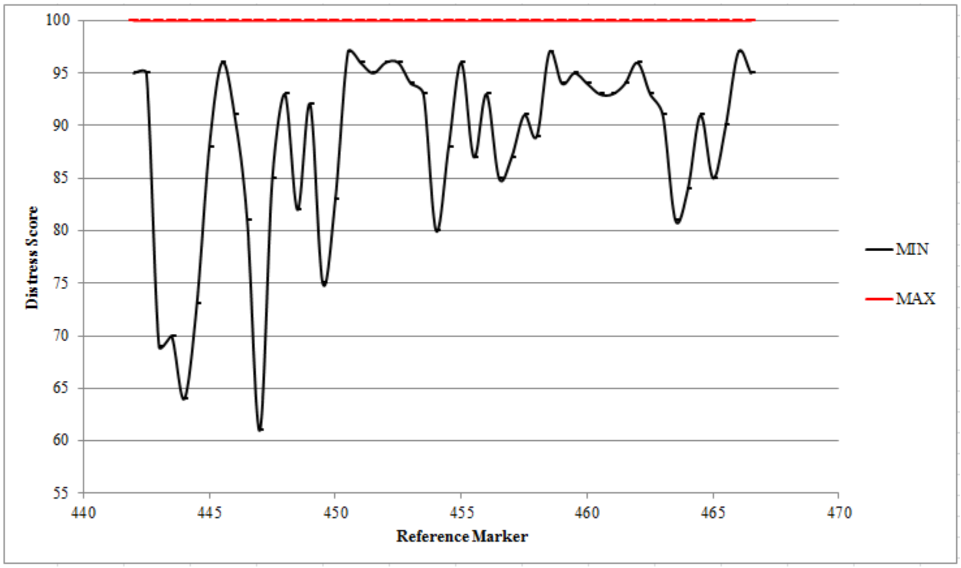

Figure 21: Distress Score before and after Treatment by 0.5 Mile Section.

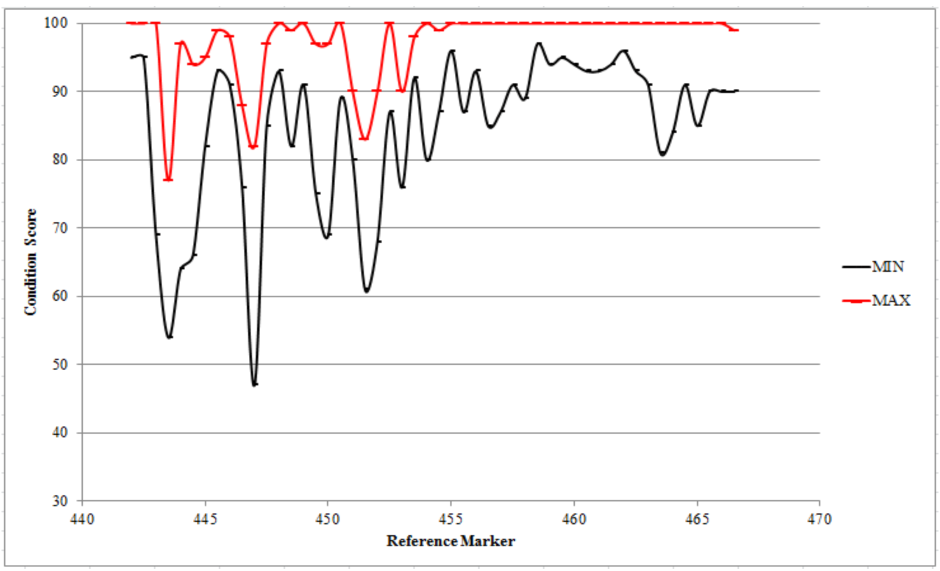

Figure 22: Condition Score before and after Treatment by 0.5 Mile Section.

Table 23 was created to further investigate the assumptions made on the year the performance improvement is captured. The fiscal year of the selected maximum value after treatment for all 0.5 mile sections for a seal coat treatment is shown in this table. Most of the maximum values selected for the ride, distress and condition scores are from the same year of construction or a year after, which are consistent with our assumption that the maximum values selected happened

right after the treatment. Some of the values selected that do not fall within the assumed timeline are a result of missing data or the condition assessment process. The condition assessment for the ride score with the inertial profiler and the distress score through visual surveys are done at different dates.

Table 23: Number of 0.5 Mile Sections per Fiscal Year Chosen to Represent the Maximum Score after Treatment.

Fiscal Year	**Number of 0.5 mile sections**		
	Ride	**Distress**	**Condition**
2004	40	26	33
2005	-	14	12
2006	2	10	2
2007	8	-	3

6.3 Pavement Performance Statistical Analysis

Initially, a comprehensive statistical analysis to compare the minimum scores before the treatment and the average score after the treatment by the CSJ was conducted. The analyses included descriptive statistics of the El Paso and Austin Districts, such as cumulative histograms by treatment category. It was concluded from that preliminary analysis that single score values by the CSJ were not representative of the scores of all sections within the CSJ. Therefore, the approach selected for further analysis was to obtain the minimum scores before the treatment and maximum values after the treatment for every 0.5 mile section within the CSJ. It was also important to study the scores after the treatment instead of the increase in performance scores. The procedure tested the recommended score reset in TxDOT Research Project 1993, "Pavement Management Information System Concepts, Equations and Analysis Models".

6.3.1 Statistical Analysis by Treatment level

Descriptive statistics on ride, distress and condition score increases and scores after the construction per treatment level were calculated for selected Districts. As an example, Table 24 shows the descriptive statistics performed on the ride score increase obtained from the thirteen

districts using the 0.5 mile section analysis for asphalt pavements. Chang et al. (2013) contains the overall detailed tables, including score increases and resets segregated by district.

Table 24: Descriptive Statistics for Ride Score Increase by Treatment Category, 13 Districts.

Treatment Level	Number of 0.5 (mi.) Sections	Ride Score Increase						
		Minimum	1st Quartile	Median	3rd Quartile	Maximum	Mean	STDV
PM	19691	0.1	0.2	0.4	0.6	3.6	0.5	0.4
LRhb	5135	0.1	0.4	0.8	1.2	4.4	0.9	0.5
MRhb	1295	0.1	0.6	0.9	1.2	3.4	1.0	0.5
HRhb	743	0.1	0.7	1.3	1.8	3.7	1.3	0.7

Histograms and cumulative distribution plots were created to reveal trends for the ride, distress and condition score increases for each treatment category or type of treatment applied. Histograms are important when trying to visualize the distribution of the data. As an example, Figures 23 shows the histogram for the PMIS ride score increment due to preventive maintenance of asphalt pavements for the thirteen districts. The score increases did not exhibit normal distributions, which indicated that the mean value may not be the most representative parameter of the score improvement. Histograms can be viewed in Chang et al. (2013).

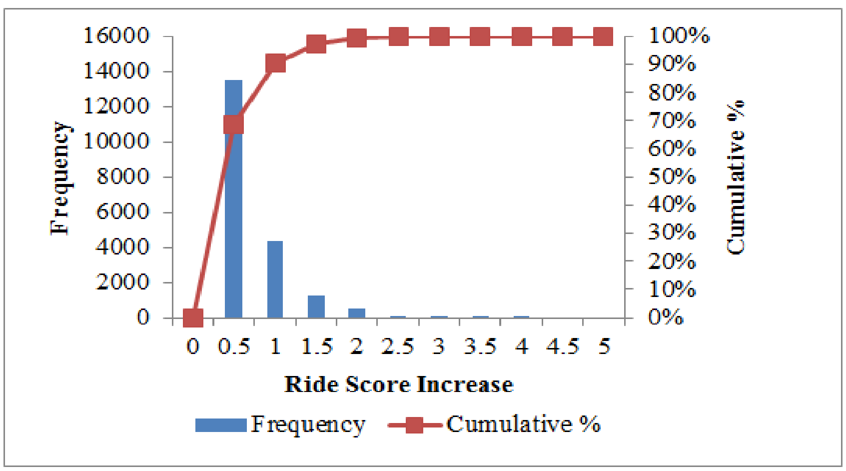

Figure 23: Histogram for Ride Score Increase due to Preventive Maintenance, 13 Districts.

Figures 24 through 26 shows summary plots prepared to compare PMIS score increases for Preventive Maintenance (PM), Light Rehabilitation (LRhb), Medium Rehabilitation (MRhb), and Heavy Rehabilitation (HRhb). The HRhb treatments resulted in greater increase than the other treatments. The MRhb and LRhb treatments showed similar trends due to complications in differentiating between the two from the layman's descriptions provided by different districts. In some districts, certain treatments were categorized as light rehabilitation while other districts may have labeled them as medium rehabilitation. The previously established treatment levels through the hybrid methodology, will help in preventing this shortcoming in future research.

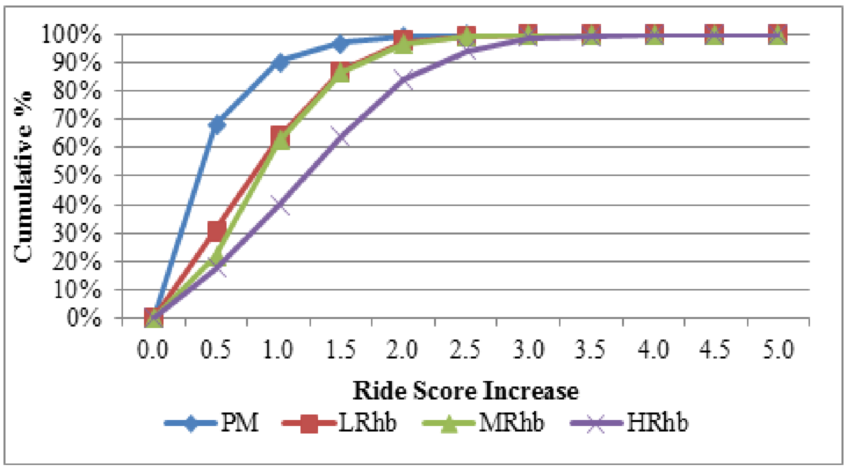

Figure 24: Summary Plot for Ride Score Increase by Treatment Category, 13 Districts.

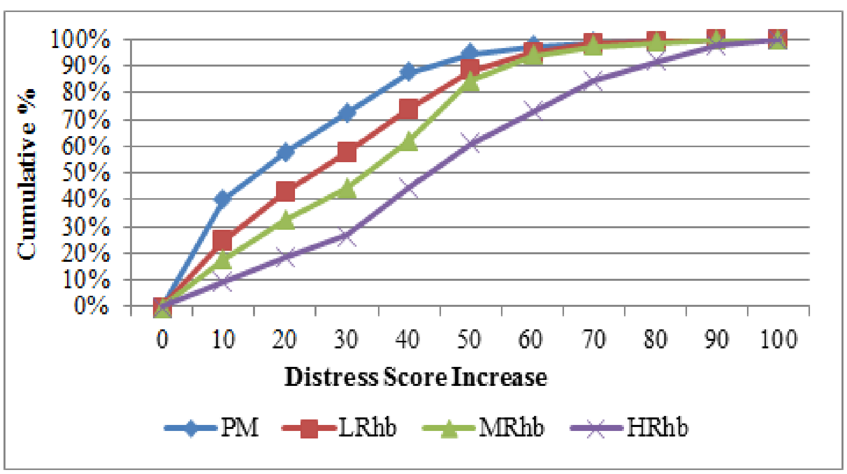

Figure 25: Summary Plot for Distress Score Increase by Treatment Category, 13 Districts.

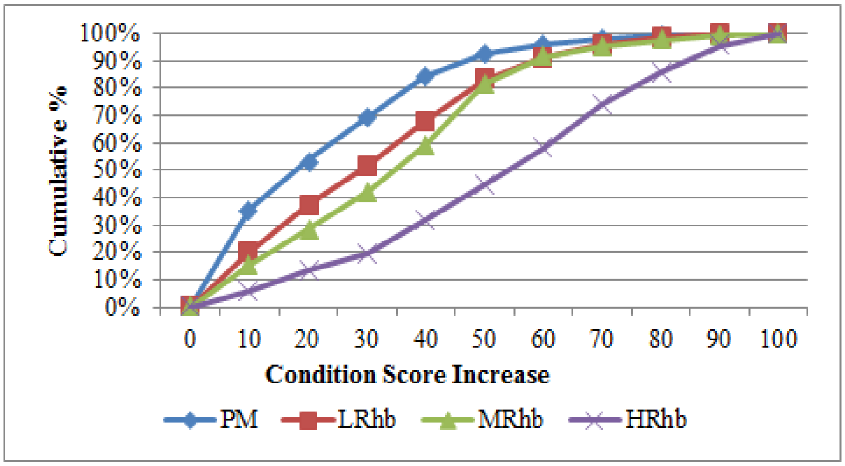

Figure 26: Summary Plot for Condition Score Increase by Treatment Category, 13 Districts.

Scatter plots of the PMIS scores before treatment and their increases after treatment were developed for each treatment level. These plots were helpful in determining the impact of the score before, on the score increase due to treatment. Figure 27 demonstrate the ride score increase due to preventive maintenance in all the 13 Districts. The red line is representative of the maximum values for the increase in score after treatment. Scatter plots were also completed for the score before treatment and the score after treatment or score reset, and can be viewed in Chang et al. (2013).

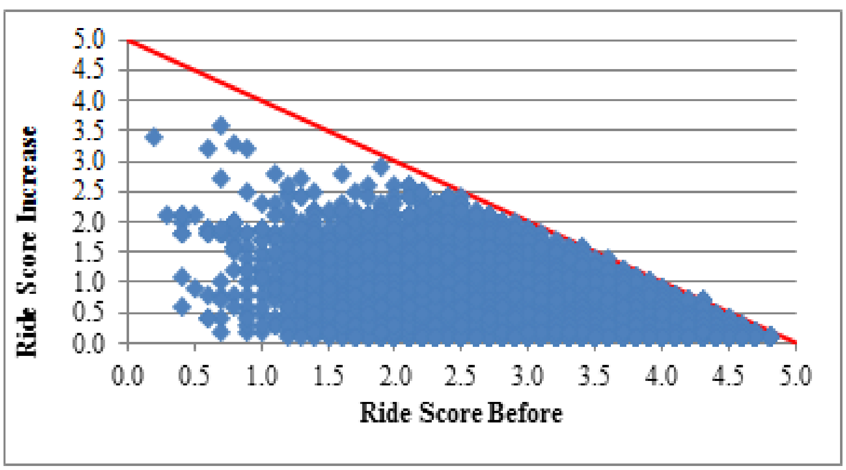

Figure 27: Ride Score Increase vs. Ride Score before due to Preventive Maintenance, 13 Districts.

The previous plots did not clearly reflect the impact of the score before construction on the ride score increase or score reset. Therefore, the following bubble plots were created. The bubble plots allow for the number of sections to be represented in the scatter plot. The size of the bubble represents the number of sections with the same score before and score increase. The way the bubble pattern slants also reflects the sensitivity of the score increase on the score before and it shows whether there is a finite increase or more of a reset. The more horizontal plots show less sensitivity, meaning the increase in ride score will be the same regardless of the score before. This horizontal plot also shows that there is a finite score increase. The more diagonal patterns describe a higher sensitivity of the score before on the score increase. In addition, the diagonal pattern reflects that there is more of a score reset. PM and LRhb showed more of a horizontal pattern, meaning the there is a finite score increase. In the case of MRhb and HRhb, the patter reflected a diagonal patter, meaning the ride should be recommended as a reset and not an increase. Furthermore, this means that the score before did not play a major role in the score after the treatment. Figure 28 to 31 shows the bubble plots created for all treatment levels and their respective ride score.

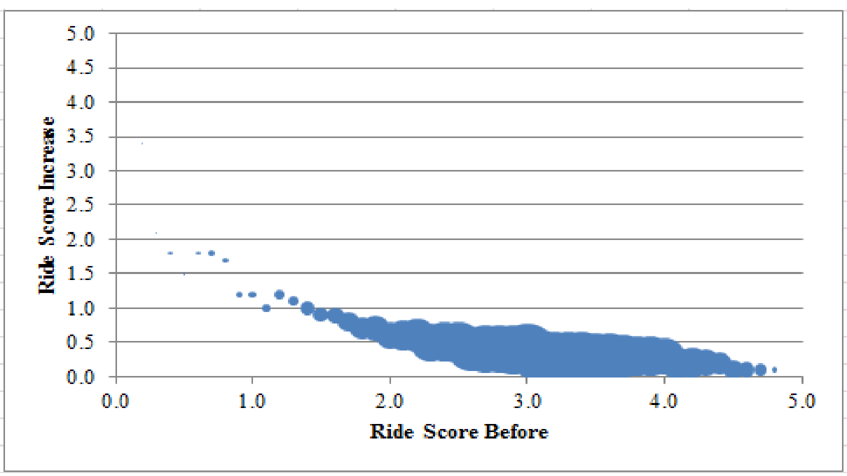

Figure 28: Bubble Plot of Ride Score Increase vs. Ride Score before due to Preventive Maintenance, 13 Districts.

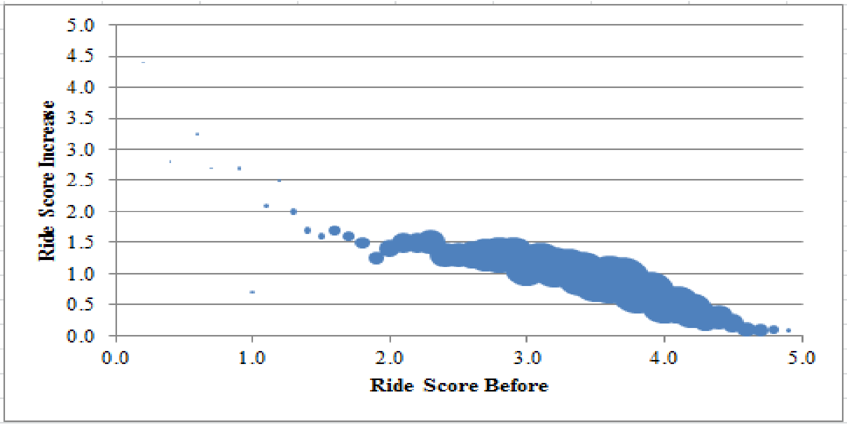

Figure 29: Bubble Plot of Ride Score Increase vs. Ride Score before due to Light Rehabilitation, 13 Districts.

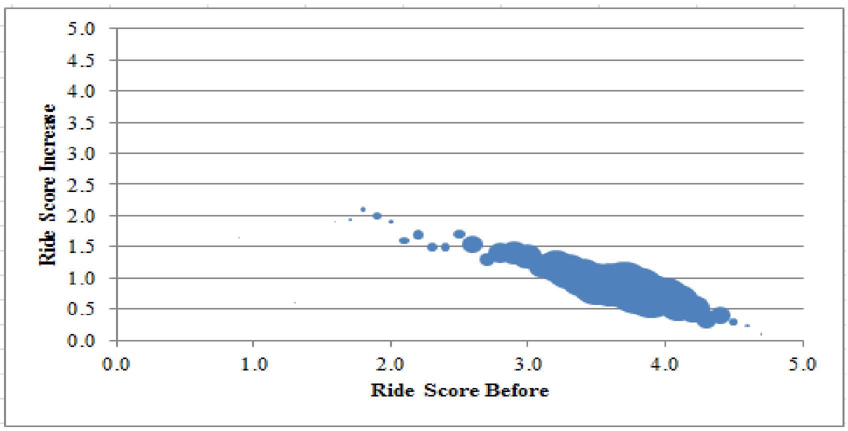

Figure 30: Bubble Plot of Ride Score Increase vs. Ride Score before due to Medium Rehabilitation, 13 Districts.

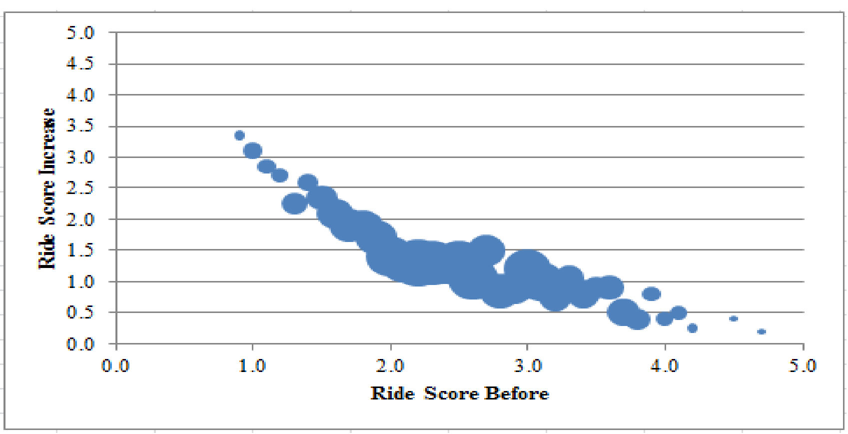

Figure 31: Bubble Plot of Ride Score Increase vs. Ride Score before due to Heavy Rehabilitation, 13 Districts.

6.3.2 Statistical Analysis by Independent Treatment

After examination of the statistical analysis results for each treatment level, further analysis was conducted clustering pavement performance data by specific treatments: overlays and seal coats. The layman's description was not detailed enough to segregate all CSJs by their treatment description or in this case by different overlay thickness. This procedure was used to evaluate and compare with the score increases and resets observed in PM and LRhb, since seal coats and most overlays were in the lower severity treatment levels. The descriptive statistics for the seal coats and overlays in all the 13 Districts for ride score increase are shown in table 25. As expected, the descriptives for seal coating agree with the preventive maintenance performance improvement. Overlays on the other hand, agree with the performance observations due to LRhb or MRhb treatments. The detailed analyses including plots and tables are located in "Statistical Analysis by Treatment Description" for asphalt concrete pavements (2013).

Table 25: Descriptive Statistics on Ride Score Increase due to Seal Coats and Overlays, 13 Districts.

Treatment	Number of 0.5 (mi.) Sections	Ride Score Increase						
		Minimum	1st Quartile	Median	3rd Quartile	Maximum	Mean	STDV
Seal Coats	17637	0.1	0.2	0.4	0.6	3.5	0.5	0.4
Overlays	1929	0.1	0.5	0.9	1.3	4.4	0.9	0.6

Histograms and frequency plots were developed for seal coats and overlays individually. Just like it was observed in the treatment level histograms, the score increases did not follow a normal distribution for seal coats or overlays. These plots also demonstrate how closely related the seal coat frequencies are to the frequencies observed in the PM. The most frequent ride score increase was 0.5. An example of the ride score increase obtained for the 13 District seal coats is shown in figure 32.

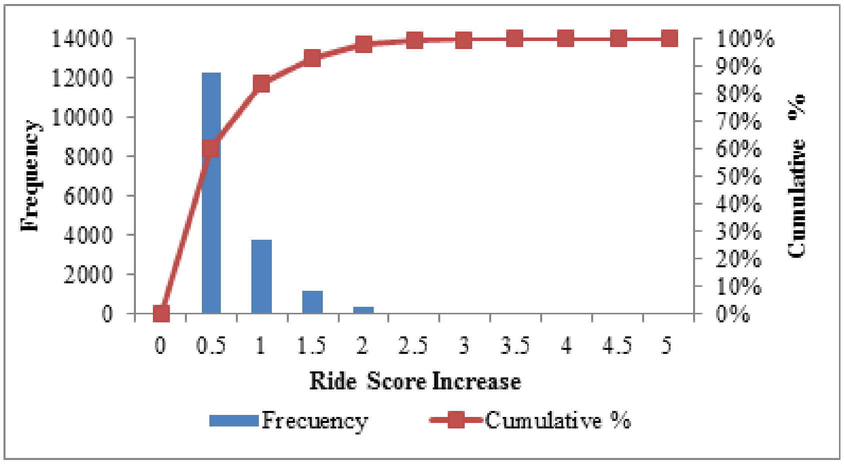

Figure 32: Histogram for Ride Score Increase due to Seal Coats, 13 Districts.

Scatter plots were created to analyze the influence of the PMIS score before treatment in the score increase. Figure 33 demonstrates the plots for the seal coats in all the 13 districts. The ride score had a close resemblance to the PM plots. Detailed analysis for each district is included in Chang et al. (2013).

Figure 33: Histogram for Condition Score Increase due to Seal Coats, 13 Districts.

6.3.3 Summary of PMIS Score Improvement Results

Table 26 summarizes the statistical parameters for the ride score increase due to treatment for all 13 Districts. The trend of the increase showed that HRhb had the greatest increase followed by MRhb, LRhb and PM. Light and medium rehabilitation showed very

similar performance. The median ride score increase between the two levels had a difference of 0.1. The increase of HRhb was low due to reconstruction projects that were constructed based on planning or other activities and not on pavement condition. The analysis also showed that when constructing PM and LRhb, the ride score increase had some dependence on the ride score before. The analysis by seal coat which is PM reinforced the ride increase of the preventive maintenance. The overlays on the other hand, which can be all four treatment levels, behaved as either light or medium rehabilitation.

Table 26: Summary of Ride Score Increase.

Treatment Level	Number of 0.5 (mi.) Sections	Ride Score Increase						
		Minimum	**1st Quartile**	**Median**	**3rd Quartile**	**Maximum**	**Mean**	**STDV**
PM	19691	0.1	0.2	0.4	0.6	3.6	0.5	0.4
LRhb	5135	0.1	0.4	0.8	1.2	4.4	0.9	0.5
MRhb	1295	0.1	0.6	0.9	1.2	3.4	1.0	0.5
HRhb	743	0.1	0.7	1.3	1.8	3.7	1.3	0.7

Table 27 summarizes the statistical parameters for the ride score reset or score after treatment for all 13 Districts. As it was observed in the ride increase, the performance of LRhb and MRhb was very similar. The HRhb score resets were comparable to the PM resets; this was because most HRhb projects were completed on FM roads. Since FM roads have lower speed limit and traffic volumes, the riding comfort does not hold such high standards as interstates and highways. In addition, the analysis showed that MRhb and HRhb ride score reset was not dependent on condition before. Again the seal coats behaved like PM, while overlays behaved as light or medium rehabilitation.

Table 27: Summary of Ride Score after Treatment.

Treatment Level	Number of 0.5 (mi.) Sections	Ride Score After						
		Minimum	1st Quartile	Median	3rd Quartile	Maximum	Mean	STDV
PM	19691	0.9	3.1	3.6	4.1	5.0	3.6	0.7
LRhb	5135	1.6	4.0	4.4	4.7	5.0	4.2	0.5
MRhb	1295	1.6	4.2	4.5	4.7	5.0	4.4	0.5
HRhb	743	1.7	3.4	3.8	4.3	4.9	3.8	0.6

Table 28 summarizes the statistical parameters for the distress score increase due to treatment level for all districts. The distress score increase showed that the trend is HRhb > MRhb > LRhb > PM. Preventive maintenance is the only treatment level that showed minor sensitivity to the distress condition before. The seal coat analysis showed this same sensitivity.

Table 28: Summary of Distress Score Increase.

Treatment Level	Number of 0.5 (mi.) Sections	Distress Score Increase						
		Minimum	1st Quartile	Median	3rd Quartile	Maximum	Mean	STDV
PM	19691	1	5	15	32	97	20	17
LRhb	5135	1	10	25	41	93	27	19
MRhb	1295	1	15	34	46	94	32	19
HRhb	743	1	29	44	62	97	45	23

Table 28 summarizes the statistical parameters for the distress score after treatment for all districts. The medians indicated that the distress score after treatment was not affected by the treatment level and resets to 100 in all cases. The plots created also reinforced this observation. When analyzing by treatment type, the score also was reset to 100.

Table 29: Summary of Distress Score after Treatment.

Treatment Level	Number of 0.5 (mi.) Sections	Distress Score After						
		Minimum	1st Quartile	Median	3rd Quartile	Maximum	Mean	STDV
PM	19691	18	100	100	100	100	99	5
LRhb	5135	14	100	100	100	100	99	6
MRhb	1295	27	100	100	100	100	99	6
HRhb	743	16	100	100	100	100	98	8

Table 30 summarizes the statistical parameters for the condition score increase due to treatment for all 13 Districts. The condition score increase was highly dependent on the distress score; therefore, we also observed that that the trend is HRhb > MRhb > LRhb > PM. The PM score increase was the only level that showed a slight sensitivity to the condition score before the treatment.

Table 30: Summary of Condition Score Increase.

Treatment Level	Number of 0.5 (mi.) Sections	Condition Score Increase						
		Minimum	1st Quartile	Median	3rd Quartile	Maximum	Mean	STDV
PM	19691	1	6	18	34	99	22	19
LRhb	5135	1	13	29	45	99	31	21
MRhb	1295	1	18	36	47	99	34	20
HRhb	743	1	36	55	71	98	53	24

Table 31 summarizes the statistical parameters for the condition score after treatment. It can be concluded that just like the distress score after treatment, the medians pointed to a condition score reset to 100 independently of the treatment applied. The seal coat and overlay analysis pointed to the same fact which is that the condition score was reset to 100.

Table 31: Summary of Condition Score after Treatment.

Treatment Level	Number of 0.5 (mi.) Sections	Condition Score After						
		Minimum	1st Quartile	Median	3rd Quartile	Maximum	Mean	STDV
PM	19691	10	100	100	100	100	98	8
LRhb	5135	8	100	100	100	100	98	7
MRhb	1295	8	100	100	100	100	99	8
HRhb	743	16	100	100	100	100	97	10

6.3.4 Preliminary Conclusions Conclusion of the Statistical Analysis

1. The analysis of individual PMIS scores for 0.5 mile sections within a CSJ was the approach that best captured the increase in scores due to treatment. The analysis by 0.5 mile clustered by treatment level and treatment applied was conducted considering not only the increase in score but also the score reset or score after treatment.

2. From the statistical analysis it was concluded that the score increase in ride, distress and condition did not follow a normal distribution. Medians were more representative of the datasets rather than means, therefore medians were to be used in comparisons and recommendations.
3. A summary of the results by treatment category for the score increase and reset value after treatment is shown in table 32. When these values were compared to the current PMIS recommendations, it was observed that the current PMIS ride score increase assumptions for PM and LRhb were higher when comparing to the median values obtained from the statistical analysis of historical datasets. Ride score reset values after median Rehabilitation and heavy rehabilitation were also higher.

The distress score was reset to 100 for all treatment levels. Currently, PMIS resets the distress score to 100 for LRhb, MRhb, and HRhb and to 95 for PM.

Table 32: Summary of PMIS Score Analysis due to Treatment Level.

Treatment Level	Ride Score			Distress Score			Condition Score	
	Current PMIS Recommendation	Historical Data		Current PMIS Recommendation	Historical Data		Historical Data	
		Increase	Reset		Increase	Reset	Increase	Reset
PM	Increase by 0.5	0.4	3.6	Reset to 95	15	100	18	100
LRhb	Increase by 1.5	0.8	4.4	Reset to 100	25	100	29	100
MRhb	Reset to 4.8	0.9	4.5	Reset to 100	34	100	36	100
HRhb	Reset to 4.8	1.3	3.8	Reset to 100	44	100	55	100

Table 33 shows the summary of PMIS score analysis for seal coats and overlays. The seal coat which is a preventive maintenance treatment, behaved very similarly to the historical performance of PM. On the other hand, the overlays, which can be any treatment level based on thickness, performed similar to light rehabilitation. This was because most overlays are of a thin nature and such overlays were categorized as LRhb. It was also observed that in both cases the distress and condition score was reset to 100 after treatment.

Table 33: Summary of PMIS Score Analysis due to Treatment.

Treatment	Ride Score		Distress Score		Condition Score	
	Increase	Reset	Increase	Reset	Increase	Reset
Seal Coat	0.4	3.5	16	100	18	100
Overlay	0.9	4.4	23	100	28	100

6.4 Impact on Score Increase Due to Climate and Subgrade Zone, Traffic, and Pavement Type

The potential impact of climatic regions, traffic volumes and pavement types on the ride, distress and condition score increase was analyzed. The objective was to determine if the preliminary recommendations for PMIS score increase and reset values would be affected by any of these factors. The results were later integrated with expert knowledge and the field experiment through the use of the hybrid methodology previously discussed. Pavement sections were first grouped by treatment level and then by the factor of interest. For this reason, it was first needed to determine the most important factors.

6.4.1 Pavement Characteristics Defined

The relevant factors selected were based on discussions with the research team and were incorporated from Gharaibeh et al. (2012) and they include:

- Climate and Subgrade Zones, described with table 34 and figure 35.

Table 34: Description of Texas Climatic Regions and Subgrade Characteristics.

Zone	Climate and Subgrade Characteristics for Zones
1	Wet-cold climate and poor, very poor, or mixed subgrade
2	Wet-warm climate and poor, very poor, or mixed subgrade
3	Dry-cold climate and good, very good, or mixed subgrade
4	Dry-warm climate and good, very good, or mixed subgrade

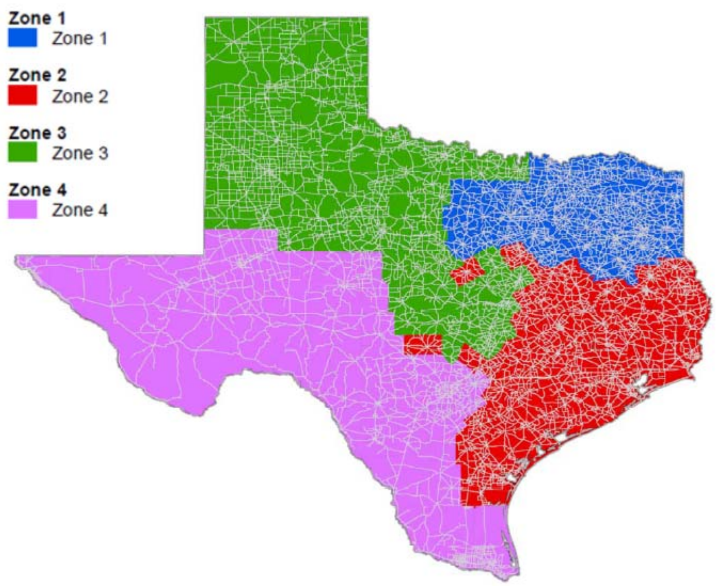

Figure 34: Illustration of Climate and Subgrade Zones throughout the State of Texas.

- Pavement Families which were split into 3 broader families A, B and C. Family A is composed of thick ACP (type 4), intermediate ACP (type 5) and overlaid ACP (type 9). Family B is composed of composite pavements (type 7) and concrete pavement overlaid with ACP (type 8). Family C includes thin ACP (type 6) and thin-surfaced ACP (type 10).
- Traffic Levels based on 20-year projected cumulative Equivalent Single Axle Load (ESAL) and annual daily traffic (ADT). The three traffic levels are defined as High, Medium and Low. Table 35 defines the levels in terms of 20-year ESALs.

Table 35: Traffic levels Based on Cumulative ESALSs.

Traffic Level	Cumulative ESALs
Low	< 1.0 million
Medium	1.0 million - <10 million
High	≥ 10 million

Traffic level definitions based on ADT are shown in table 36. These definitions are based on the research conducted for TxDOT in Gharaibeh et al. (2012). This research also proposed four ADT levels: below 100; between 100 and 1,000; between 1,000 and 5,000;

and 5,000 or greater. For this project the four traffic levels were simplified by combining the first two levels into one class.

Table 36: Traffic levels Based on ADT per Lane.

Traffic Level	ADT
Low	< 1,000
Medium	1,000 – 5,000
High	> 5,000

6.4.2 Analyses of Impact on Score Increase due to Pavement Characteristics

The analysis of PMIS score increase by climatic zone, pavement type, and traffic level included descriptive statistics summarized in box-whisker plots, Analysis of Variance (ANOVA), post-hoc statistical testing and non-parametric Mann-Whitney hypothesis testing.

Descriptive statistics summarized in box-whisker plots help understand the trend of the score increase to observe the influence of the factor under study. Box-whisker plots, like shown in figure 35, were generated to compare the score increase results by treatment level and the corresponding factor (Chang et al. 2013).

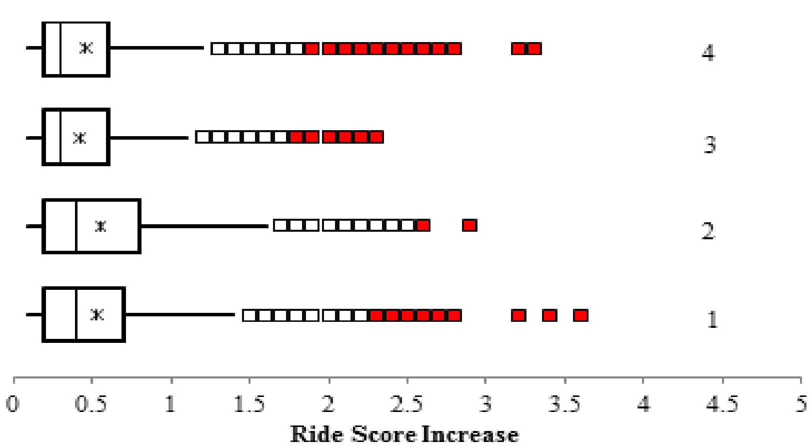

Figure 35: Example of a Box-Whisker Plot for PM Ride Score Increase by Climatic Region.

Figure 36 shows how to interpret the data shown in the whiskers plots. The whisker stretches as far as the difference between the 1st and 3rd quartile, also called the interquartile range (IQR).

Mild outliers are between 1.5*IQR and 3.00*IQR, and extreme outliers are greater than 3.00*IQR.

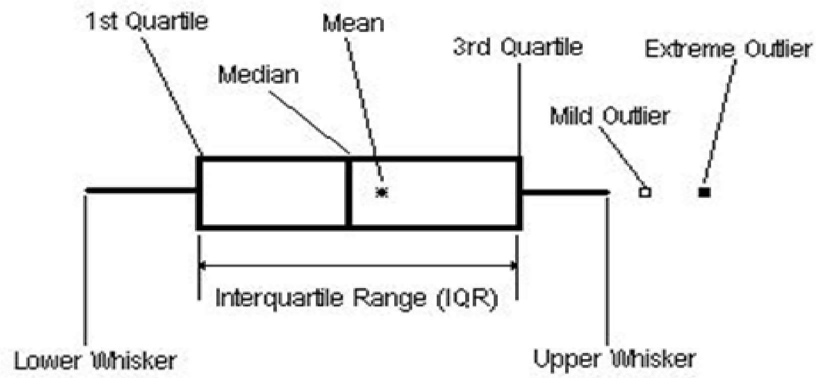

Figure 36: Box-Whisker Plot Data Format.

ANOVA and Mann-Whitney non-parametric tests were used to compare the differences between score increases within their respective treatment level. Both tests were used since the data does not follow a normal distribution, although when there are a large number of sections, it could have been assumed that the distributions are normal. Post hoc multiple comparisons were also conducted because in the ANOVA all variables were tested at once and further information on the one-to-one relationship was studied.

In the analysis of variance, the null hypothesis states that the means of several groups are equal. This null hypothesis is rejected when the p-value is below the 0.05 significance. To understand which score increases within the group are different on a one-to-one basis, Tukey's Honest Significant Difference (HSD) test was conducted. This test is a conservative post hoc multiple comparison, similar to the t-test, which analyzes if the means are different (Chang et al. 2013).

The Mann-Whitney test examines the null hypothesis that two populations have equal distributions. This test does not require the data to follow a normal distribution, but all observations must be independent. Similar to the ANOVA and Tukey's HSD, the Mann-Whitney test requires the p-value to be greater than 0.05 for the null hypothesis to be accepted.

6.4.3 Summary of the Impact Analysis on the Ride Score and Conclusions

When grouping climatic regions within each treatment level, it was observed that for PM medians and means are close to 0.5. For LRhb, climatic region 3 had the lowest ride score increase with a median score increase of 0.5 and a mean of 0.6. The statistical tests showed that there was no effect on the score increase due to the climatic region for HRhb and MRhb only. Overall there was no clear trend of an influence of climatic regions on the increase or reset of PMIS scores for the treatment categories although climatic region 3 showed the lowest ride score increase in all treatment levels except PM.

The grouped pavement families within PM showed no substantial difference in the ride score increase with a mean of 0.5 and a median of 0.4. For LRhb, pavement type B had a higher increase than the rest of the families with a mean of 1.1 and a median of 1.2. Pavement type B also shows the highest increase in MRhb. Pavement type A had the lowest increases for LRhb, MRhb and HRhb. However, in the overall comparison, there were no significant differences in the ride increase among them. The score reset investigated for MRhb and HRhb revealed that the trend observed for the mean was A > B > C but the ride scores were consistent with the observation of the 3rd quartile.

The effect of the ADT traffic levels was also analyzed. It was observed that PM grouped by ADT levels had a mean increase of 0.5 and a median around 0.4. The statistical tests revealed that ADT had no effect on the PM ride score increase. For LRhb ride score increase medians and means, are within 0.7 to 1.0. Overall the ride score increase trend pointed to high traffic roads having a smaller ride score increase. These results reflected TxDOT maintenance practice, in which high traffic level roads are repaired promptly. The ADT class had no effect on the HRhb ride score increase. In the score reset for MRhb a median of 4.5 was obtained.

Observations were made on the impact of ESAL traffic levels on the ride score increase. The performance was very similar to the results obtained for the ADT traffic levels. The ESAL traffic level had no effect for PM Ride score increase with a mean of 0.5. The mean of ride increase was centered on 0.90 for LRhb. MRhb and HRhb showed that the traffic had no effect

on the score increase but high traffic roads had the smallest ride score increase. Just like in ADT, the MRhb median ride reset of 4.5 was recommended.

The ride score increase and reset conclusions due to climatic regions, pavement families and traffic levels were:

- All relevant factors had no effect on PM ride score increase. Most increases showed values close to 0.5.
- There was no trend observed to differentiate the ride score increases and reset values due to the climatic regions.
- Light rehabilitation showed ride increases closer to 1.0 when analyzing all factors except the climatic regions. These values reflected that the recommended increase was low, or that a range of score increase would be more accurate.
- Higher traffic roads displayed a smaller increment than low traffic roads. However, the overall difference in ride score increase observed within the traffic levels is not significant.
- The ride score reset by pavement families for MRhb and HRhb showed a higher value for pavement type A then B and finally C (A > B > C). The differences among them were not major.
- The recommended ride score reset of 4.5 for MRhb was confirmed in the analysis by grouped factors. This value was also used for HRhb even though lower values were observed.
- The factors had no major effect on the score reset for MRhb and HRhb.

6.4.4 Summary of the Impact Analysis on Distress Score and Conclusions

The statistical tests revealed that the distress score increases were not dependent on climatic zones, traffic, or pavement type for MRhb and HRhb. However, PM and LRhb showed some sensitivity to the climatic regions and pavement families but not to traffic levels. For LRhb and PM the high traffic class, climatic region 1 and pavement type B showed the least distress

increases. However, all distress score medians were reset to 100 after treatment. For this reason, any effect on the distress score increases in PM and LRhb were not included. The distress score conclusion due to climatic regions, pavement families and traffic levels was that the medians distress score resets are equal to 100 after treatment. The lowest mean value encountered was 96.

6.4.5 Summary of the Impact Analysis on Condition Score and Conclusions

The observation of the condition score increase due to the relevant factors was very similar to the distress score increase observations. The statistical tests revealed that the condition score increase for HRhb and MRhb; and to some extent for LRhb were not sensitive to the factors. Only the climatic regions seemed to have an impact on the LRhb condition improvement. For PM, climatic region 1, pavement family B and high traffic ADT level had the lowest condition score increments as was also seen for the distress score. However, when analyzing the condition score reset, all median condition score resets were equal to 100 and the lowest mean was 96. This means that the factors had no effect on the condition score reset. The condition score conclusions due to climatic regions, pavement families and traffic levels were:

- The 75% quartiles of all condition score resets were equal to 100.
- Since all condition scores reset to 100, including PM, it was recommended to change the condition reset value from 95 to 100.

6.5 Field Experiment to Validate PMIS Score Improvements due to Treatment

Field surveys were conducted to register PMIS scores before and after treatment in order to validate the PMIS score increase values obtained from the historical data and expert knowledge. The approach was to use 4-Year plans from the Districts to identify treatments to be performed during the development of this research study. Sections were selected to represent the different climatic zones, treatment level, pavement surface types, and traffic categories in terms of AADT, and 20-Yr Cumulative ESALs.

In coordination with the TxDOT Project Monitoring Committee (PMC), the researchers obtained pavement management plans with maintenance and rehabilitation and developed a list

of projects grouped by pavement treatment levels. Given the information in pavement management plans, researchers ranked Districts in terms of the number of projects by pavement treatment level to identify candidate Districts for the field inspections. From the responses to the survey, the following Districts were found to have five or more years of maintenance and rehabilitation records: Atlanta, Beaumont, Bryan, Childress, Dallas, El Paso, Lufkin, Laredo, Paris, Pharr, San Antonio, Waco, and Wichita Falls. The Austin District was also considered for additional information.

6.5.1 Methodology

The work pavement maintenance and rehabilitation plans were solicited and received, and sections were finally selected in the Atlanta, Brownwood, Childress, Dallas, El Paso, Lufkin, Paris, Pharr, and San Antonio Districts. The original work plan called for 100 sections, but in order to increase the distribution and ensure better coverage, 387 individual test sections were identified. Most of these sections were 0.5 miles long and begun or ended at a Reference Marker (RM). On these sections, when a location was chosen, a test section was established in a lane and a replicate section was established in the same location, but in the opposite direction. That is, if a section was established on US0271, from RM0274+0.0 to RM0274+0.5 in the K1 direction, another section was established on US0271, from RM0274+0.5 to RM0274+0.0 in the K6 direction. No distinction was made between the "test" section and the "replicate" section.

After the sections were identified in the field, pictures were taken and the test section was inspected using the TxDOT Pavement Management Information System (PMIS) methodology. Sections were inspected in 2012 and 2013 to establish the condition before and after the treatment. In addition to the PMIS inspection, requests were made to TxDOT District staff to collect profile data on the sections. Figures 37 and 38 illustrate a before and after picture.

Figure 37: FM 3418, RM 272, K1, Pre-Construction.

Figure 38: FM 3418, RM 272, K1, Post-Construction.

After the second round of inspections, there were still some sections where the treatment had not been placed. Of the 387 sections identified in 2011 when the project started, 131 were not constructed at the time of the last inspection, leaving us with 256 test sections. The pavement section list is within Chang et al. (2013), including PMIS scores before and after the treatments were applied.

6.5.2 Distribution of Pavement Sections

It was of importance to select the sections which could account for the different treatment levels and pavement characteristics (previously identified) in order to validate the historical results and expert intervention. This goal was restricted because TxDOT projects are planned 4 years ahead and as mentioned not all planned projects are actually constructed. The experiment matrix attempted to provide a balance of projects among the different treatment levels but many more highways receive Preventive Maintenance (PM), than Light Rehabilitation (LR), Medium Rehabilitation (MR), or Heavy Rehabilitation (HR). Figure 39 demonstrates the distribution accomplished among the different levels.

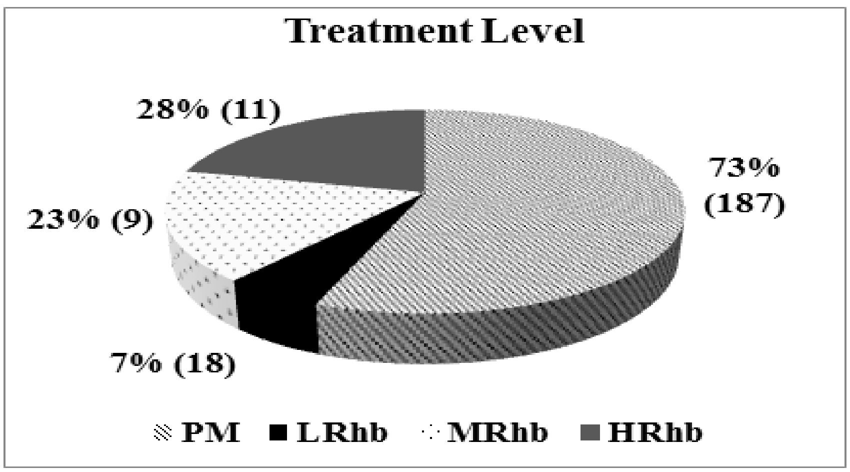

Figure 39: Distribution of Test Sections by Treatment Level.

In the case of pavement types, figure 40 shows the distribution accomplished. The distribution among the families shows a large difference because for example, pavement family C, which is the category with the thin pavements, are mostly less traveled roads. Hence, these roads don't require as much maintenance, much less rehabilitation.

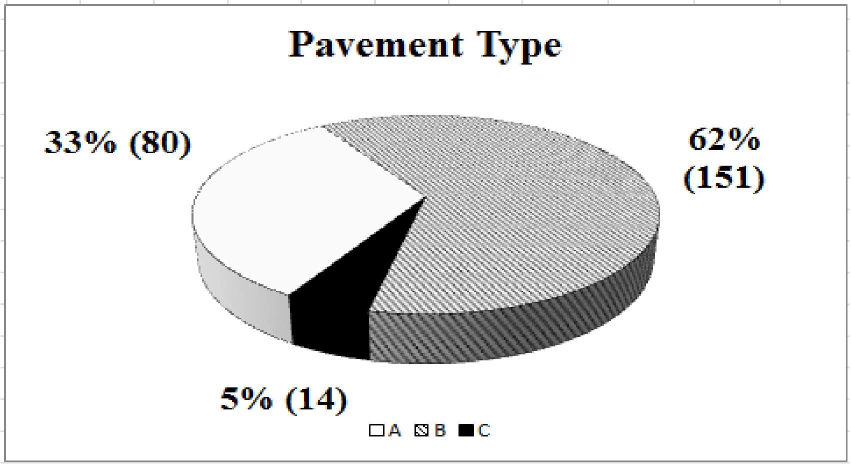

Figure 40: Distribution of Test Sections by Asphalt Pavement Families

The same applies for the distribution of pavement sections by traffic levels. Higher traffic sections require continuous M&R activities because they deteriorate at a much fast rate. Furthermore, these sections are required to be in acceptable condition because it becomes a matter of safety. Figure 41 and 42 demonstrate the distribution accomplished for 20-year ESALs and ADT respectively.

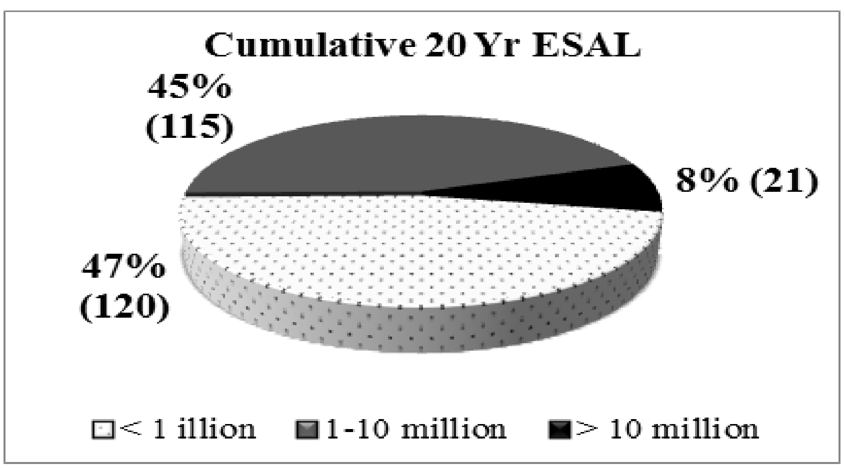

Figure 41: Distribution of Test Sections by Cumulative 20-Yr ESAL.

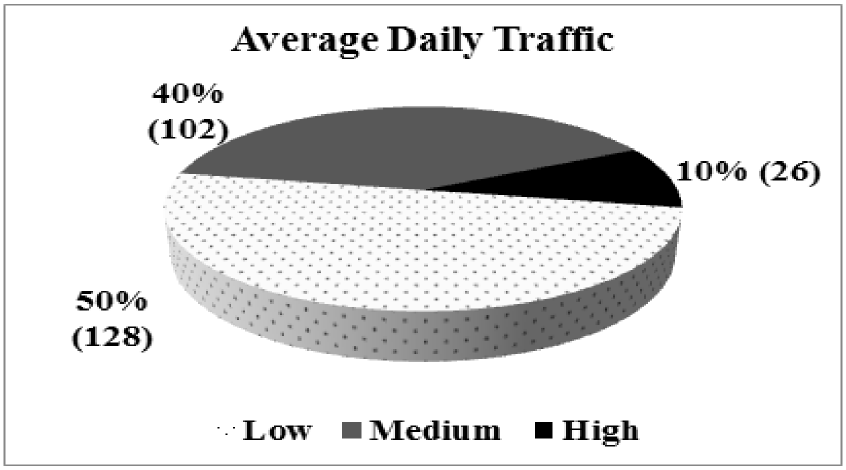

Figure 42: Distribution of Test Sections by Average Daily Traffic per Lane.

To distribute the sections rated among the different climatic and subgrade zones, districts were selected using table 37 and figure 34. The final distribution among climatic regions is shown in figure 43.

Table 37: Counties in Climate and Subgrade Zones.

Zone	Counties
Zone 1	1, 19, 32, 34, 37, 43, 57, 60, 61, 71, 73, 75, 81, 92, 93, 103, 108, 112, 113, 117,120, 127, 130, 139, 155, 172, 175, 182, 183, 184, 190, 194, 199, 201, 213, 220, 225, 230, 234, 249, 250
Zone 2	3, 4, 8, 11, 13, 20, 26, 28, 29, 36, 45, 62, 74, 76, 80, 82, 85, 87, 89, 90, 94, 98, 101, 102, 106, 110, 114, 121, 122, 124, 126, 129, 137, 143, 144, 145, 146, 147, 149, 154, 158, 166, 170, 174, 176, 178, 181, 187, 196, 198, 202, 203, 204, 205, 210, 228, 229, 235, 236, 237, 239, 241
Zone 3	5, 6, 14, 18, 23, 25, 38, 39, 40, 42, 47, 50, 54, 56, 58, 59, 63, 65, 68, 79, 84, 86, 91, 96, 97, 99, 100, 104, 105, 107, 111, 115, 128, 135, 141, 153, 157, 171, 173, 177, 180, 185, 197, 206, 209, 215, 219, 243, 244, 246, 252
Zone 4	2, 7, 10, 15, 22, 24, 31, 41, 46, 48, 52, 53, 55, 64, 66, 67, 69, 70, 72, 83, 88, 95, 109, 116, 119, 123, 125, 131, 133, 134, 136, 142, 151, 156, 159, 162, 163, 164, 165, 186, 189, 192, 193, 195, 200, 207, 214, 216, 218, 222, 226, 231, 232, 233, 238, 240, 245, 247, 248, 253, 254

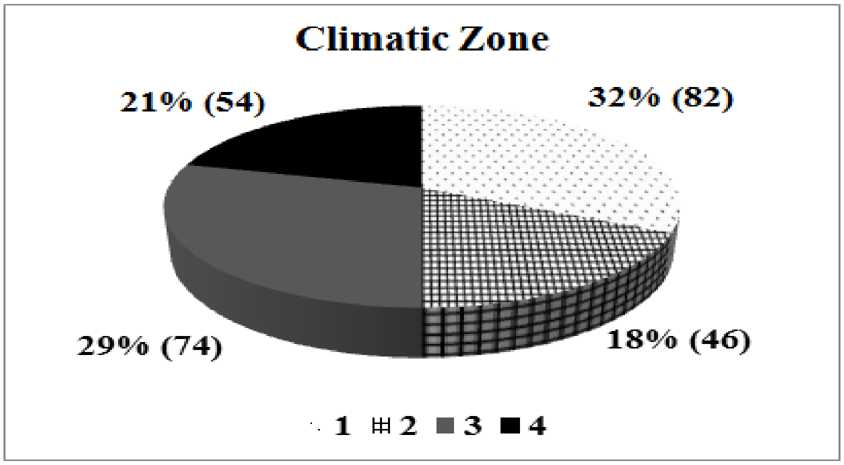

Figure 43: Distribution of Test Sections by Cumulative 20-Yr ESAL.

6.5.3 Summary of the Field Experiment Validation and Conclusions

The main objective for the field experiment was to compare the results with the recommendations drawn from the historical PMIS data analysis and expert judgment. In addition, it served to provide the controlled feedback required for the Delphi technique to ensure expert consensus at the last stage of the short-term effectiveness recommendations. The same analyses described in 6.4.2 were utilized; in this case the field data was compared to the historical data. The descriptives, frequency tables and statistical testing of the field can be found in Chang et al. (2013). The main observations found from this field survey data analysis are as follows:

- Low traffic sections reflected a higher ride score increase than high traffic sections.
- No difference in distress and condition score reset between any treatment levels.
- The PM ride score increase for the field data was very close to the recommended values from PMIS historical data.
- The LRhb ride score increase for the field data had the same distribution as the ride increase in the historical data. The difference is that the median and mean were higher and closer to 1.7.
- The ride score reset for MRhb in the field data had a median of 4.3 which was closer to the previously recommended values.

The investigation of the effect of climate, traffic and pavement families on the score increases for ACP concluded that these factors only impacted the LRhb ride score increase with variation of +/- 0.5. Climatic region 3, pavement family A and high traffic ride score increases are expected to be at the lower end; while low traffic and pavement family B are expected to be at the recommended 1.2 value or higher.

6.6 Summary of Chapter Conclusions

The difficulty in the capture of the performance improvement jump led to the investigation of different approaches. The best approach feasible was to calculate the minimum before and maximum after the construction treatment was applied. The data was then extensively investigated through statistical analysis, histograms and summary plots to quantify the CIJ per treatment level. These preliminary results were continuously adjusted with expert input to derive final recommendations. Furthermore, the impact of pavement characteristics such as climatic region, pavement families and current condition, was deeply investigated. The only treatment which showed sensitivity to these factors was the LRhb ride score increase. The distress score increase was reset among all treatment levels. To validate the results an extensive field experiment complemented the study. In the end, the field investigation, historical data and engineering judgment provided reliable results for the recommendation of CIJ for every treatment level. The final recommendations for the ride, distress and condition improvements due to the treatments are shown in table 38.

Table 38: Final Recommendations of PMIS Scores Due to Treatment for Flexible Pavements.

Treatment Level	Ride Score	Distress Score	Condition Score
PM	Increase by 0.5	Reset to 100	Reset to 100
LRhb	Increase by 1.2	Reset to 100	Reset to 100
MRhb	Reset to 4.5	Reset to 100	Reset to 100
HRhb	Reset to 4.5	Reset to 100	Reset to 100

Chapter 7: A Simplified Performance Model for Flexible Pavements

7.1 Introduction

The evaluation of the long-term effectiveness requires the development of deterioration models. There are several factors that introduce limitations into the modeling process. To develop deterioration models that reflect the real deterioration experienced in the field, it is required to generate reliable methodologies. The hybrid methodology was introduced to incorporate engineering knowledge into the models, but an important piece was using historical data as the starting point. Once the models have been created, long-term effectiveness measures can be derived.

In the state of Texas, site-specific, non-linear sigmoidal models have been the basic building block of the Pavement Management Information System's evaluation tools that include the treatment selection process, project prioritization and funding allocation. The drawbacks of the current design process are the complexity of the sigmoidal regression coefficients, the absence of key pavement information in the inventory database (M&R activities), the different distress independent deterioration models and the sheer size of the inventory information. In this chapter, the steps taken to provide the engineering expert with a starting performance model baseline derived from historical data will be described.

7.2 Background

As stated in chapter 2 section 3, TxDOT currently uses equation 1 to deteriorate pavement distresses independently. The models then forecast distress quantities over the age of the pavement that include shallow rutting, deep rutting, patching, failures, block cracking, alligator cracking, longitudinal and transverse cracking. Theses forecasted distresses are then used as trigger values in the PMIS hierarchical decision tree. The decision tree recommends any of the 4 treatment levels PM, LRhb, MRhb and HRhb. Severe distresses like deep rutting and alligator cracking trigger the heavier treatments, medium and heavy rehabilitation The distress quantities are then turned into a utility value based on equation 2. From all the distress utilities

equation 6 is used to arrive at the distress score. A similar procedure is used in the case of the ride score but instead of independent distress value quantities, the ride score is modeled over time based on the ride quality lost. The ride quality lost is dependent on the speed and traffic of the pavement section.

7.3 Flexible Pavement Performance Model

The current performance model incorporated by the Texas Department of Transportation can be problematic due to the large amounts of regression coefficients and the extra steps taken to convert the distresses or ride quality lost to utilities. For this reason, it was decided to simplify the process and implement equation 8. The equation models the distress or ride score based solely on age and it is based on the sigmoidal equation used by the agency.

$$DS\ or\ RS = X_{max} - \alpha e^{-\left(\frac{\rho}{Age}\right)^{\beta}} \qquad \text{Equation 8}$$

DS or RS = Distress Score or Ride Score.

X_{max} = Maximum value possible, 5 for *RS* and 100 for *DS*.

e = base of the natural logarithm.

α = alpha, horizontal asymptote factor, controls maximum amount of *DS* or *RS* that can be lost.

β = beta, slope factor that controls how steeply *DS* or *RS* is lost in the middle of the curve.

ρ = rho, prolongation factor that controls how steeply *DS* or *RS* is lost in the middle of the curve.

Age= age of pavement in years.

The different regression coefficients have different effects on the shape of the curve. Figure 44 describes in detail how the coefficients impact the curve. The maximum amount of DS or RS lost from the starting age to the end is controlled by alpha. It should be noted that in the case of DS the value cannot exceed 100 and for RS it cannot exceed 5. The beta coefficient controls the

deterioration rate. When the value of beta is increased the curve turns more vertical. Oppositely when the coefficient is lowered, the curve slopes more gently or more horizontally. In the case of rho, the coefficient controls the elongation of the curve. This is useful when modeling the deterioration of a new pavement under low traffic for example. The new pavement stays at a perfect condition because there are no traffic loadings affecting the condition. When the value of rho is raised, the pavement condition stays at the top for longer time. If the value of rho is lowered, the pavement starts deteriorating sooner.

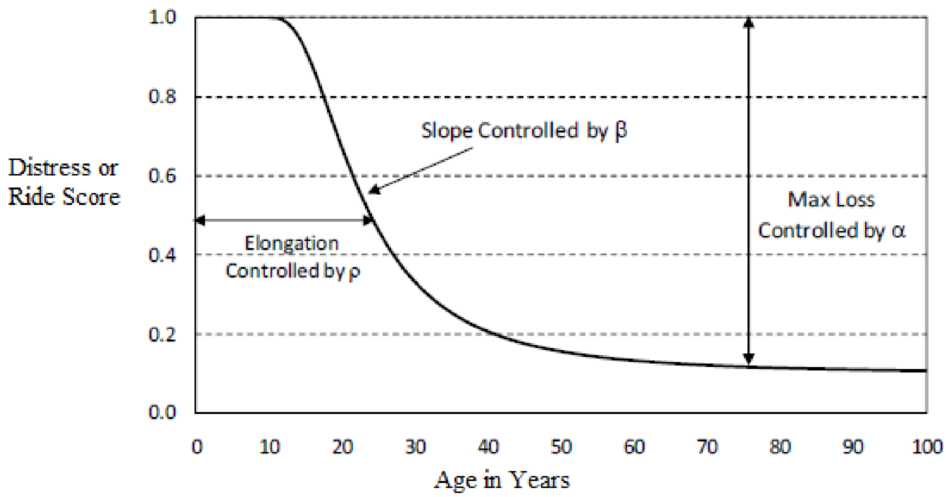

Figure 44: Effect of Regression Coefficients on the Performance Curves (Gharaibeh et al., 2012).

7.4 Methodology

7.4.1 Data Synthesis

The first step in the process was to expand the data retrieved in chapter 4.2 to include 10 years before construction and 10 years after construction. This step introduced many difficulties in the manipulation of the data. The first was the very large database created which did not allow any common computer software to be used such as MS Excel, MS Access and IBM's statistical software SPSS. To counter this complication a MATLAB Graphical User Interface (GUI) program was created. The GUI allows a rapid and interactive filtering of the large data and an iterative regression process.

7.4.2 "Windows" Method for Aggregating Data

The pavement deterioration is affected by different factors including traffic loading, climate and pavement structure. TxDOT accounts for these wide ranging characteristics by aggregating pavement sections with similar site-specific factors, but with different ages. This process is referred as the "windows" method. The resulting empirical method results in more reliable performance models which represent the deterioration observed in the field. This method also allows recalibrating the performance models to tailor the curves for the District. The different grouping factors used were the previously described climate and subgrade characteristic zones, traffic levels, treatment levels, and pavement families.

7.4.3 Assumptions

As explained in chapter 4.2 less than 50% of M&R projects were able to be linked to the performance data in PMIS. This means that in the 10 year span of performance data there will be projects which were not identified and were needed to be filtered out. Take figure 45 as an example. The figure demonstrates the ride score deterioration before placing a light rehabilitation treatment. Year 8 would be the condition right before the treatment and year 0 the condition 9 years before the treatment. In the long-term deterioration it can be observed, through the condition improvement jumps between years 1-2 and 4-5, that there have been previous M&R activities. To simplify this step, it was assumed that the year the latest score increase was recorded, in this case year 5, was the starting year in the regression. Obviously, this assumption is may not be correct and it will introduce bias when deciding the starting point of the regression model. Due to this addition of inaccuracy the hybrid methodology was introduced and previously described which implements expert knowledge.

Another important assumption taken during the regression process was the value of the ride score or distress score at the starting year in the regressions using equation 8 (X_{max}). The assumptions differed depending on which regression curve was analyzed. For the pre-construction curve, the average of the sections at the starting year was selected. In figure 45, the

starting year is 5 and the average, which is the red square, is 2.75. The 2.75 is the X_{max} used in the regression. Once the regression was performed, the curve was then vertically shifted to have a starting value of 5.0 for RS or 100 for DS. In the case of the post-construction curve, the X_{max} is dependent on the performance improvement jump. The X_{max} for DS is always 100 due to the distress score always resetting to 100. The ride score on the other hand, always resets to 4.5 when modeling the MRhb and HRhb performance curves. For the PM and LRhb post-treatment curves, the X_{max} is dynamic, because the value before the treatment is increase by 0.5 and 1.2 respectively. The highest RS achievable for these last treatments was limited at 4.5. The implementation of engineer experience will aid in the establishment of reliable deteriorations curves, if the assumptions do not result in representative models.

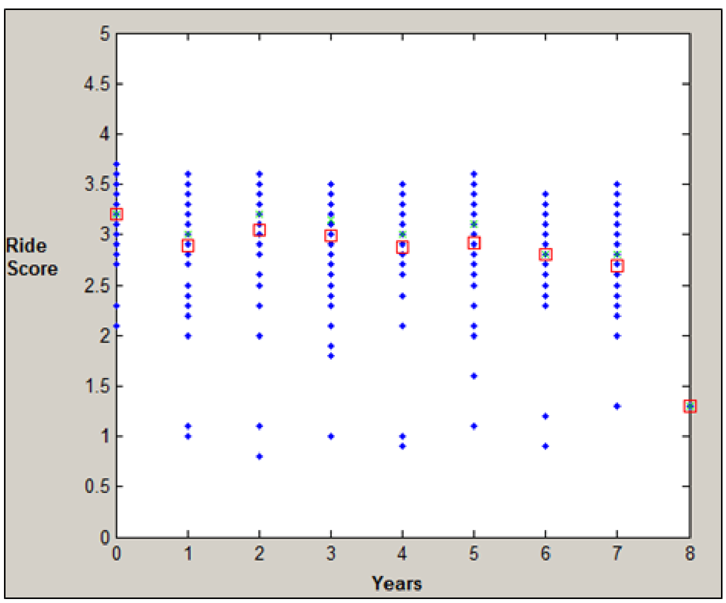

Figure 45: Long-Term Deterioration before the Placing of Light Rehabilitation.

Most PMS create a "do-nothing" curve as the universal pre-treatment model. This is because pavement management systems perform trade off analysis. Trade off analysis is the procedure to prioritize the different identified treatment projects plans due to the budget limitations. The tradeoff analysis is important when it is assumed a new pavement needs to be

treated based on the present or forecasted condition. If the pavement is in very good condition, it is not effective and economical to perform rehabilitation. Therefore, this process determines which treatment will be the best option. The state of Texas uses the heavy rehabilitation deterioration curves coefficients as the "do-nothing" curves but the treatment is selected based on the PMIS hierarchical decision trees. In this analysis, it is of interest to achieve the long-term effectiveness and optimal timing based on the different pre- and post-construction deterioration rates. Therefore, it was not assumed that the treatment is performed on a newly constructed pavement but rather on a pavement that has received several maintenance and rehabilitation treatments. This pre-treatment curve is dependent on the treatment selected including the condition and deterioration rate. This assumption means that the deterioration rate and condition before a PM is of higher quality than the same indices of HRhb. Consequently, the goal of this analysis was to find the treatment optimal time, which can aid in the long-term planning and the prioritization amongst the previously selected projects when there are budget constraints. This assumption was given great importance by capturing the expert's opinion using the hybrid methodology.

7.4.4 Non-linear Regression Analysis

The MATLAB's nonlinear curve-fitting algorithm "lsqcurvefit" was selected to perform the non-linear regression analysis due to its ability to set upper and lower constraints to the regression coefficient values. The mathematical equation the algorithm uses is stated in equation 9. The equation is in essence an optimization problem that minimizes the sum of the squared difference between the observed data and the predicted data. The left side of the equation is related to the minimization of the squared norm. A norm is a function that assigns only positive lengths to each vector.

$$\underset{x}{Min}\|F(x, xdata) - ydata\|_2^2 = \underset{x}{min} \sum_i (F(x, xdata_i) - ydata_i)^2 \qquad \text{Equation 9}$$

$F(x, data_i)$ = observed data.

$ydata_i$ = predicted data.

The constrains are a major factor in the regression, because for the pre-treatment curve the treatment with the highest deterioration rate must follow the trend HRhb>MRhb>LRhb>PM. On the contrary, the post-treatment curve must have the highest deterioration for PM and finally HRhb. In addition, the traffic level also sets deterioration rate constrains. The higher the traffic level, the higher the deterioration rate. This last constrain was not achievable for the pre-treatment ride score deterioration due to TxDOT's maintenance goals of keeping higher traffic roads at higher condition ratings because of safety concerns. This limitation was addressed in the hybrid methodology.

7.4.5 Validation of Curve Fitting

The root-mean-squared-error (RMSE) is frequently used to quantify how well the predicted values fit the model used (Miles and Sheylin, 2001). Equation 10 describes the RMSE. The smaller value indicates that the model fits the observed data sufficiently. The RMSE is the summation of the difference between the predicted and the observed value which is then squared and divided by the number of observations. Finally, the squared root of the value is taken.

$$RMSE = \sqrt{\frac{\sum_{k=1}^{n}(Pred_i - Obs_i)^2}{n}} \qquad \text{Equation 10}$$

$Pred_i$ = Predicted value.

Obs_i = Observed value.

The MATLAB algorithm facilitates this calculation because it returns the squared 2-norm of the residual, which is the summation of the squared difference between the predicted and observed values.

7.5 Overview of Graphical User Interface for Regression Calculations

Figure 46 demonstrates the GUI created in MATLAB for filtering, plotting and the regression calculations. The drop down menus located at the top of the GUI filter the data according to the important categorization factors selected. Only the pre- or post-treatment data

can be analyzed at once. Pressing the “Plot” button will display the ride score and distress score values per year.

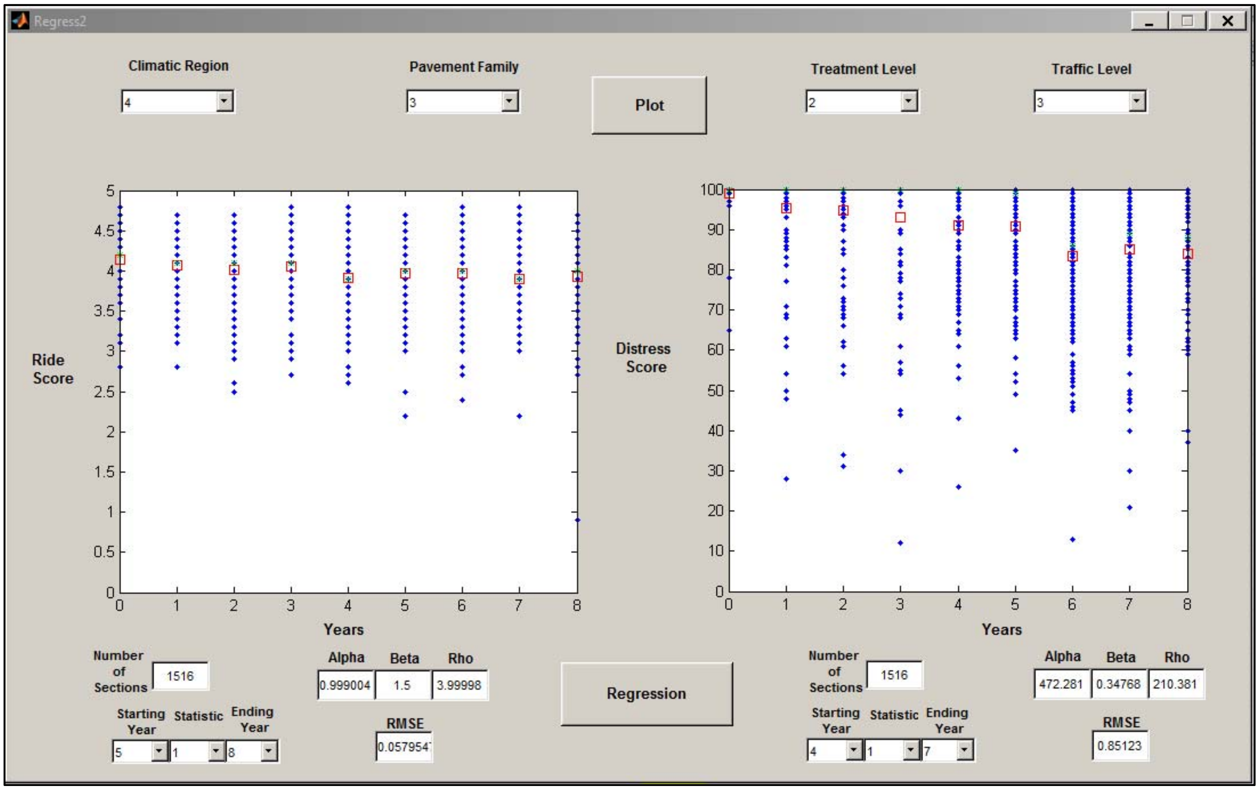

Figure 46: MATLAB Graphical User Interface when Plotting Data.

The averages per year are calculated and shown as red squares and the medians per year are also calculated which are shown as blue asterisks. At the bottom of the GUI, the number of sections is displayed. To derive the curve coefficients, the time interval where the regression is desired must be stated. This is done with the drop down menus in the starting year and ending year. Moreover, the regression is performed using the data points selected with the drop down menu, it can be the averages or medians. Allowing real time filtering of this time span tries to reduce the bias that past M&R activities introduce to the deterioration trends. Once the bounds are given, pressing the “Regression” button will result in plotting the regression curve, calculating the regression

coefficients and the RMSE for the ride and distress score curves. Figure 47 demonstrates the output once the regression button is pressed.

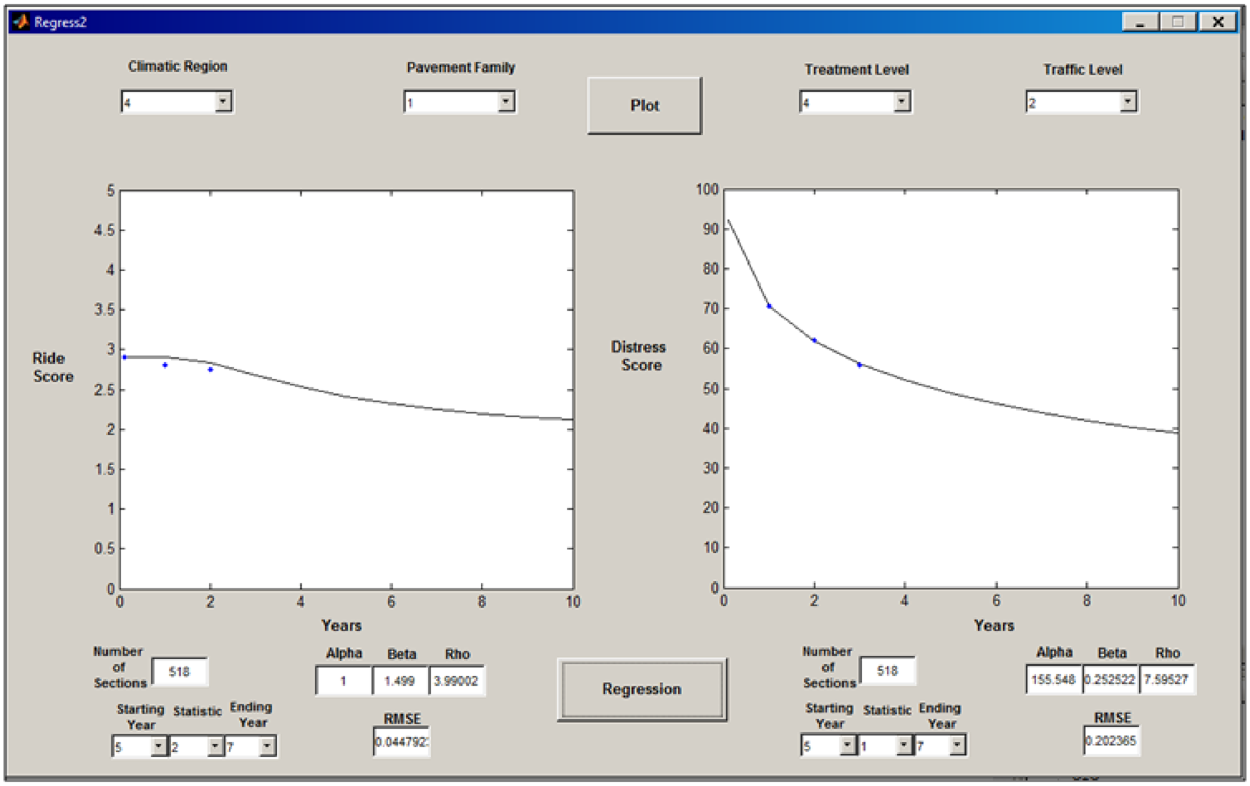

Figure 47: MATLAB Graphical User Interface when Performing Regression.

7.6 Simplified Performance Model Results

The creation of the deterioration curves is dependent on the quality and quantity of data. Data aggregation by the different pavement characteristics through the "windows" method did not yield enough pavement sections to create all deterioration curves that result from the different combinations. The models for Climatic and subgrade zone 4, pavement family A and all treatment and traffic levels were selected to illustrate the methodology. High traffic pavements are not allowed to deteriorate in great extent. Therefore, the high traffic models resulted in less accuracy when fitting the pavement deterioration curve. The deterioration rate constraints added to the model also had a negative impact on the curve fitting. Overall, the accuracy of the data dependent models was of secondary importance since the models would be used only as a

starting point for the factorial design prepared for engineering experts. The hybrid method would implement expert knowledge and revise the performance curves to fit actual pavement deterioration trends observed in the field.

7.6.1 Ride Score Simplified Deterioration Models

The pre-treatment deterioration curves for climatic region 4, pavement type B, heavy traffic and all treatment levels are presented in figure 48. The survey created in table 4 for section chapter 3used this heavy rehabilitation curve. The curves follow the expected deterioration rate among treatment levels. The gentle slope of PM is consistent with the recommendations of when to treat a pavement sections. These recommendations state that preventive maintenance treatments should be applied to the pavement before the condition falls below the adequate threshold. If the threshold is surpassed, the treatment will not be effective in deterring further deterioration. The HRhb curve is also consistent with the expected performance of pavement sections that require reconstruction. It would not be cost-effective to reconstruct pavement sections that are in good condition. All performance curves can be found in appendix A.

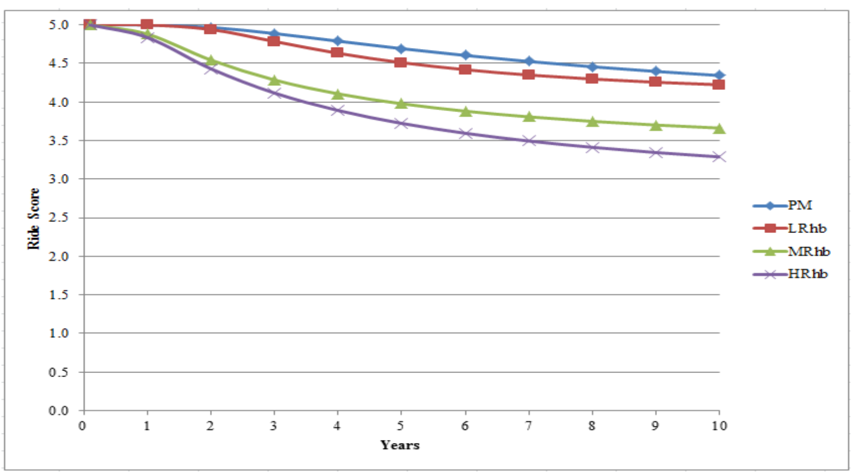

Figure 48: Ride Score Pre-Treatment Performance Curve for Heavy Traffic.

Figure 49 demonstrates the deterioration curves after the treatment is applied. The survey created in table 5 for section chapter 3 used this heavy rehabilitation curve. The resulting curves agree

with established concepts which state that the deterioration rate after treatments will have a positive change in deterioration. Furthermore, the more substantial treatments had the greatest change in deterioration. This can be viewed in the figure where the newly reconstructed performance deterioration rate more gently slopes as opposed to the PM curve.

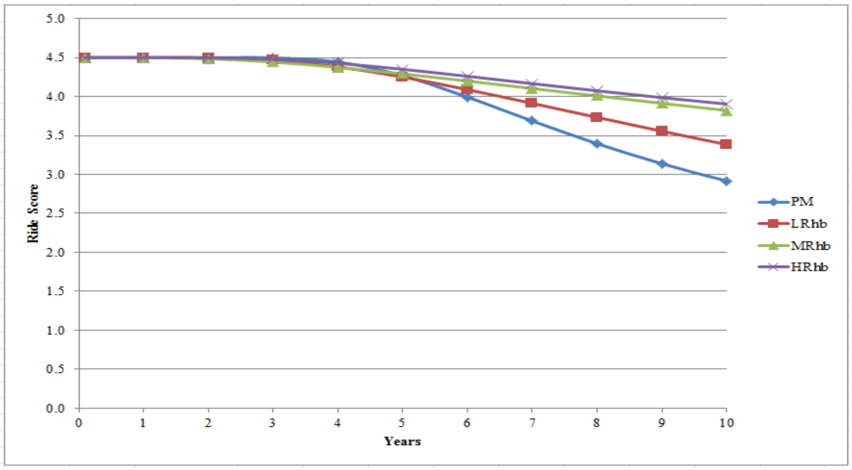

Figure 49: Ride Score Post-Treatment Performance Curve for Heavy Traffic.

The calculated regression coefficients and root-mean-square-errors for the figures are shown in table 39. As expected, the heavy rehabilitation curves have the greatest level of inaccuracy in the curve fitting, which is due to the small amount of sections found. The large variability in the post- treatment rho coefficients are due to the constraints imposed to follow the theoretical expected deterioration reflected in the literature review. However, in practice, expert judgment is implemented to limit this data misinterpretation.

Table 39: Ride Score Performance Curve Coefficients and RMSE.

Treatment Level	Traffic Level	Pre-Treatment				Post-Treatment			
		Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	Medium	1.40	7.58	1.00	0.003	3.00	8.00	2.00	0.125
LRhb	Medium	1.00	4.00	1.50	0.049	1.00	15.00	1.00	0.150
MRhb	Medium	1.75	2.69	1.00	0.012	5.00	28.09	0.67	0.053
HRhb	Medium	2.40	3.00	0.90	0.190	2.00	11.90	1.10	0.200

7.6.2 Distress Score Simplified Deterioration Models

The pre-treatment deterioration curves for climatic region 4, pavement type B, heavy traffic and all treatment levels are presented in figure 50. The survey created in table 4 for section chapter 3used this heavy rehabilitation curve. The curves follow the expected deterioration rate among treatment levels. The gentle slope of PM is consistent with the notion that preventive maintenance treatments should be applied to the pavement before the condition falls below the adequate threshold. The HRhb curve is also consistent with the expected performance of pavement sections that require reconstruction. All performance curves can be found in appendix A.

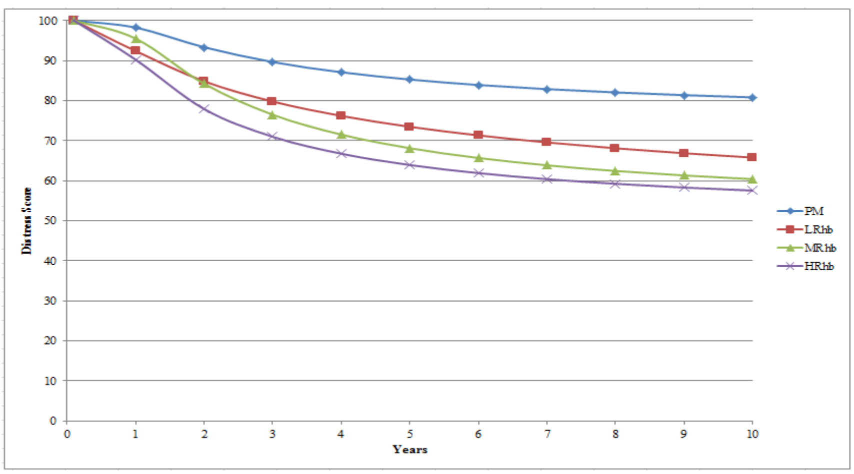

Figure 50: Distress Score Pre-Treatment Performance Curve for Heavy Traffic.

Figure 51 demonstrates the deterioration curves after the treatment is applied. The survey created in table 5 for section chapter 3 used this heavy rehabilitation curve. The resulting curves agree with the deterioration rate expected after treatment placement where the deterioration has a positive change. This can be viewed in the figure where the newly reconstructed performance curve not only has a more gentle slope than MRhb, LRhb and PM but, it stays at a higher distress score for longer.

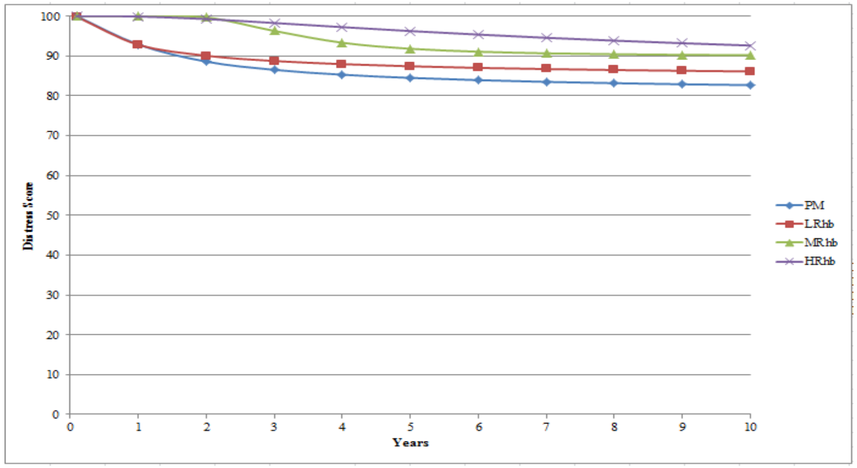

Figure 51: Distress Score Post-Treatment Performance Curve for Heavy Traffic.

The calculated regression coefficients and root-mean-square-errors for the figures are shown in table 40. The heavy rehabilitation curves have the greatest variability in the curve fitting except for the pre-MRhb treatment. The inconsistency in that curve can be seen in the figure 50, where the curve was forced to deteriorate at a higher rate than LRhb. This limitation was due to the similar observations found in the condition performance jump, where LRhb and MRhb have similar performance. The similarity was a limitation introduced in the treatment categorization of construction projects of the database. This signals the dependency and importance of establishing clear M&R projects in treatment levels. In addition, this signals the importance to factor in expert knowledge which addresses any irregularities observed in the models.

Table 40: Distress Score Performance Curve Coefficients and RMSE.

Treatment Level	Traffic Level	Pre-Treatment				Post-Treatment			
		Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	High	25.00	2.64	1.00	1.400	19.66	1.02	0.90	1.005
LRhb	High	55.00	3.00	0.62	1.990	16.00	0.75	0.75	1.390
MRhb	High	48.00	2.20	1.09	3.300	10.00	3.00	3.12	0.760
HRhb	High	50.00	1.63	1.00	2.570	20.00	10.00	0.75	1.740

7.7 Summary of Chapter Conclusions and Recommendations

Performance models for pre- and post-treatment are an important step in the quantification of long-term effectiveness. In the hybrid methodology the first step was to develop models on the historical data. The development of performance models is an intensive process that required simplification of the current models employed by the TxDOT. The new sigmoidal model implemented the sigmoidal equation used in the state but modified it by reducing the regression coefficients and the step process to derive utilities from the independent distresses. The "windows" method was followed to aggregate the pavement sections based on similar characteristics and prepare it for regression. The difficulties in the synthesis of the data led to the generation of many assumptions when deriving the regression coefficients and the inclusion of expert knowledge. One of the major assumptions taken was that that treatment is not performed on newly constructed pavement sections but rather on the pavement sections that have been treated with maintenance and rehabilitation projects. Making the pre-treatment deterioration rate and condition dependent on the current treatment applied.

Two major obstacles were identified in the calculation of the coefficients. These were the very large amount of data and the influence of past maintenance and rehabilitation activities on the deterioration rates. Addressing the obstacles required the creation of a graphical user interface. The GUI provided flexibility when setting the interval where the regression was to be calculated. It was important to set constrains on the deterioration rate based on traffic and treatment level. The constraints included that the highest deterioration rate must follow the trend HRhb>MRhb>LRhb>PM. Also, the higher traffic levels must have greater deterioration rates. The root-mean-squared-error was used to check how well the historical performance data fits the model. As an example, the regressions were focused on the following pavement characteristics: Climatic and subgrade zone 4, pavement family A, and all treatment and traffic levels.

Overall the theoretical process was adequate but it included many assumptions that may impact the reliability on the models. For this reason, the hybrid approach described in chapter 3 was used to generate the final pavement deterioration models.

Chapter 8: Evaluating Long-Term Effectiveness and Optimal Treatment Application

8.1 Introduction

The quantification of long-term effectiveness relies heavily on the short-term effectiveness and the performance models. Furthermore, the time the treatment is applied and the unit cost greatly influences this calculation. The long-term effectiveness is in essence the combination of all these pavement performance effects into a single index that will aid in the decision making process to maximize the allocation of funds through the optimization of different M&R projects. The importance of this index exhibits the need to develop a process to derive this index and to hinder the impact of the limitations in the quantification process. This is the objective presented in Chapter 3 which proposes a hybrid model to systematically implement engineering expert judgment and reliability in the process. The key attribute of the methodology is to first derive these values based on historical performance data. This chapter will explain the methodology used in their derivation.

The most common measures of the long-term performance improvement have been identified as the benefit and the extended service life. This quantification results in subrogate effectiveness values, that although important, may not provide the best decision-making support. Moreover, the measures are only performance dependent and do not take into consideration the limited funds of transportation agencies. For this reason, cost-effectiveness measures have been introduced which include the unit costs of treatments and improve the engineering decision basis. The decisions taken by engineers have far reaching effects not only in the present but in the long time horizon. Future planning requires further support of what is the best time to implement treatments. If the preventive maintenance is deployed too late, it may not be effective at preserving the pavement. If the pavement is reconstructed very early, the treatment may have not been cost adequate. Therefore, there is an optimal treatment timing which will result in the best treatment effectiveness for the least cost.

8.2 Long-Term Effectiveness Measures

The previously implemented methodologies in PMIS to quantify the benefit, the extended service life and cost-effectiveness will be followed.

8.2.1 Benefit

The calculation of benefit was performed following equation 11. The equation derives the area under the pre- and post-treatment curves by integrating equation 8 and their respective calculated regression coefficients. There are two benefits per treatment, depending on the condition index in use, meaning there is benefit for DS and RS. These are usually combined through a weighting process but in this study they were analyzed separately.

$$-\left[\int_{a1}^{a2} X_{max_1} - \alpha_1 e^{-\left(\frac{\rho 1}{a}\right)^{\beta 1}} dx\right] + \left[\int_{b1}^{b2} X_{max_2} - \alpha_2 e^{-\left(\frac{\rho 2}{b}\right)^{\beta 2}} dx\right] \qquad \text{Equation 11}$$

a = The boundary conditions for the pre-treatment curve from the year the treatment was applied to the first triggered boundary condition year.

b = The boundary conditions for the post-treatment curve from the year the treatment was applied to the first triggered boundary condition year.

$\alpha_1, \beta_1, \rho_1$ = Calculated pre-treatment regression coefficients described in equation 8.

$\alpha_2, \beta_2, \rho_2$ = Calculated post-treatment regression coefficients in equation 8.

X_{max1} = Maximum value possible for pre-treatment curve, 5 for *RS* and 100 for *DS.*

X_{max2} = Maximum value possible for post-treatment curve, dependent on CIJ.

As previously stated, the calculation of the benefit is highly dependent on the condition improvement jump calculations of chapter 3 and the time of treatment. Take for instance the X_{max2}. The X_{max2} is always 100 in the case of the distress condition index and 4.5 when dealing with the ride score of MRhb and HRhb. The X_{max2} for the ride score in preventive maintenance and light rehabilitation is the summation of the ride score value in the pre-treatment curve at the time of treatment, by 0.5 and 1.2 respectively. Therefore, the values are dynamic and dependent

on the time. Figure 52 explains in more detail how X_{max2} is calculated. The red dot is the condition value of the pre-treatment curve at the time of treatment, adding the CIJ gives the blue dot or the starting point of the post-treatment curve. If the treatment is applied at a later time, the starting point can be significantly smaller because it will always be the value of the red dot plus the CIJ. Refer to appendix B for the calculated benefit for all the deterioration curves.

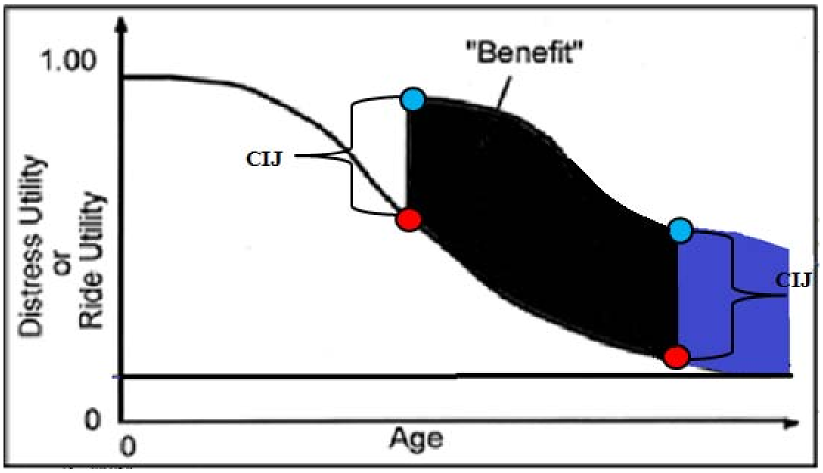

Figure 52: Effect of Condition Improvement Jump and Treatment Timing on Benefit (Modified from Stampley et al., 1993).

The benefit relies heavily on the accuracy of the CIJ and the deterioration models derived. Therefore, the calculated benefit will suffer from the same sources of variability. The hybrid methodology described in chapter 3 attempts to correct any of these discrepancies.

8.2.2 Extended Service Life

The extended service life is simply the year the boundary condition is triggered, minus the year the treatment was placed. This value is represented by subtracting between b_2 and b_2 from equation 11. The constraints implemented in the study are the same offered by the PMIS. They include boundaries set by the failure criteria of 60 for DS and 3.0 for RS the age the upper and lower curves cross and if the curves never cross each other the age is set at 20 years. There are two extended lives extensions, one fore DS and the other for RS. The smaller of the two is selected. Refer to appendix B for the calculated service lives.

The calculated service life for most curves resulted in 20 years. This is a reflection of the inaccuracy that is introduced to the process and the score reset nature, for this reason the factorial design in chapter 3, and most importantly table 7 was created. The table introduces the historical and literature based extended service live to provide the experts with an initial criterion they can modify.

8.2.3 Cost-effectiveness

The cost-effectiveness was computed with equations 3-5 and the previously derived benefit and extended service life. Cost-effectiveness was not calculated for the distress scores. Appendix B has the detailed results. Assumptions were taken in the calculation of the effectiveness. The assumptions are the following:

1. Inflation rate was taken as 0.65.
2. Discount rate was taken as 0.65.
3. The vehicle miles traveled was suggested as 1,000.
4. The Unit cost was adopted from Gharaibeh et al. (2012).

The unit cost is very important and has large variations across Districts in the state. Some of the most important factors are the materials available, the contractors available, construction treatments used, construction experience of the District and District budgets. The hybrid methodology of chapter 3 uses engineering knowledge to derive unit costs per treatment level at the network-level. This step maybe tailored and detailed for each District since it may not be feasible to create consensus across the varying Districts. Other important factors that will affect the construction costs include the pavement type, the traffic loading, the existing condition of the pavement and the environment. The treatment level guidelines developed in TxDOT project 0-6673, “TxDOT Guidelines to Assign PMIS Treatment Levels” (2013) can be implemented at the project level to assist pavement managers in treatment selection.

8.3 Optimal Treatment Time

The optimal time of treatment ties the short- and long-term effectiveness measures, as well as the unit costs. The optimal treatment time concept is described with figure 52. Figure 52 shows that if the treatment is applied at an earlier time there will be a greater area under the curve (black area) which is due to the treatment having the same CIJ and the same post-treatment curve regardless of the time of treatment application. If the treatment is applied at a later time (blue area) the benefit will be smaller. The goal is to find the year that the benefit is maximized while minimizing the cost. The optimal time can also be calculated based on the benefit without the treatment unit costs. This process is an iterative, time consuming, and computer intensive process with many changing factors. Therefore, a MATLAB graphical user interface (GUI) was created to make the calculations faster and investigate the optimal treatment time.

8.3.1 Overview of Graphical User Interface for Optimal Treatment Time

Figure 53 demonstrates the GUI created to aid in the calculations of the optimal time. The GUI is interactive, meaning the different regression coefficients for pre- and post-curves, the bounds of the integration, the condition index and the treatment level can be easily changed. Plotting capabilities were added to visualize the way the post-construction curve shifts horizontally to the year the treatment is applied and where the boundary condition is met. This is done when pressing the “Plot” button. In figure 57, the medium rehabilitation curve for climate region 4, heavy traffic level, pavement type A and the ride score index is presented. The area between the curves is calculated with equation 11 and pressing the “Calculate” button. Although the GUI doesn’t show the extended service life, this is simply the difference between the bounds and it is used in the calculation of the cost-effectiveness.

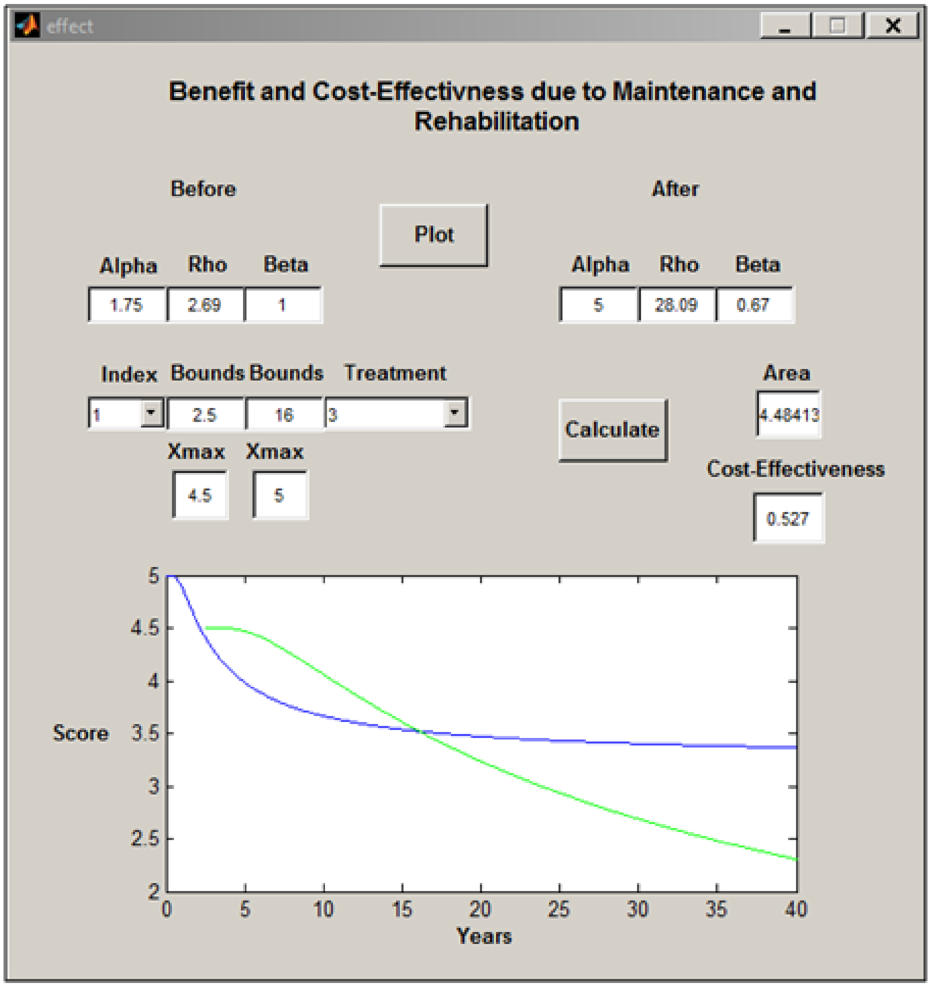

Figure 53: MATLAB Graphical User Interface for Benefit and Cost-effectiveness Calculations.

8.3.2 Optimal Treatment Time Results

The GUI's output from the previous example resulted in table 41. The table shows the calculated benefit, extended service life and cost-effectiveness. A major observation was that when applying the treatment very early in the life of the pavement, resulted in no benefit, no life extension and no cost-effectiveness. In table 41, the benefit, extended service life and cost-effectiveness began after year 2. The year of treatment where the benefit first began was larger for HRhb then MRhb, LRhb and finally PM. The optimal time in the case of figure 41 is the highlighted row at 6 years, which is the year the largest cost-effectiveness ratio was accomplished. Based on benefit, no optimal time was accomplished. This effect is due to the CIJ nature of the MRhb treatment level. The CIJ resets the ride score to 4.5 regardless of the ride

score before. The maximized benefit would be accomplished when the pavement sections deteriorates to its lowest possible condition. This statement is the largest shortcoming of the long-term effectiveness calculations and it is also observed for the ride score reset of HRhb and the distress score resets across the treatment levels. To overcome this issue, the hybrid methodology can be implemented to incorporate the engineering expert judgment.

Table 41: Optimal Time for Medium Rehabilitation Treatment in High Traffic Level.

Year of Treatment	Benefit	Extended Service Life	Cost-Effectiveness
0.0	0.0	0.0	0.00
0.5	0.0	0.0	0.00
1.5	0.0	0.0	0.00
2.0	0.0	0.0	0.00
2.5	4.5	13.5	0.53
3.0	4.9	13.7	0.57
3.5	5.3	13.8	0.60
4.0	5.6	13.9	0.64
4.5	5.9	14.0	0.66
5.0	6.1	14.1	0.69
5.5	6.4	14.2	0.71
6.0	6.6	14.2	0.73
10.0	6.6	20.0	0.44
11.0	6.8	20.0	0.45
12.0	7.0	20.0	0.46
13.0	7.3	20.0	0.48
14.0	7.5	20.0	0.50
15.0	8.7	20.0	0.57
20.0	8.4	20.0	0.55
30.0	9.1	20.0	0.60
40.0	9.8	20.0	0.65

8.4 Concluding Remarks and Recommendations

The quantification measures derived included the benefit and the extended service life. The measures are highly dependent on the condition improvement jump as well as the timing the treatment is applied. These measures tied together the short and long-term effectiveness measures. The measures alone are not sufficient to provide the pavement managers with background to prioritize among competing projects. For this reason, the cost is included in the

effectiveness measure the cost-effectiveness ratio. To provide future planning support it is necessary to derive the best treatment time.

The process to calculate the optimal treatment time is an iterative, time consuming, and computer intensive process with many changing factors. To aid in the derivation of this measure, a graphical user interface program was created. The program provided a bridge to simultaneously analyze combinations of the effectiveness, cost, and time. The results were satisfactory but there were some inconsistencies. The main inconsistency observed was that the benefit was not able to be maximized for the distress score in any of the treatment levels. This is because the score resets to the brand new condition of 100 for all treatments. This means the benefit is maximized the moment the pre-treatment curve is at its worst condition. Another discrepancy was that most of the calculated extended service lives were 20 years, which is the boundary condition for the calculation of benefit. This effect was due to the pre-treatment and post-treatment performance curves becoming parallel and never crossing or reaching the threshold condition of 3.0 and 60 for RS and DS. Another major observation of the optimal treatment time was that the benefit, extended service life and cost-effectiveness began at large years depending on the treatment applied.

Due to the discrepancies observed, it is recommended to incorporate the hybrid approach which introduces expert knowledge and overcomes the limitations set by the historical data. In the approach, the criterion and literature are combined with expert knowledge to create reliable optimal treatment times. The derived cost-effectiveness measures from the approach can also be used to prioritize different feasible maintenance and rehabilitation projects

Chapter 9: Final Summary, Conclusions and Recommendations

9.1 Summary of Research

The accuracy of the effectiveness modelling relies heavily on the quality and quantity of pavement data available. In addition there are many sources of variability which affect their reliability. These complications can negatively affect the decision-makers while selecting maintenance and rehabilitation treatments to preserve the network at an acceptable level. The decisions taken by engineers have far reaching effects not only in the present but in the long time horizon.

This thesis described in detail a hybrid modelling approach to systematically implement expert knowledge in the quantification of treatment effectiveness and determination of optimal treatment timing for flexible pavements. This process systematically merges statistical analyses of historical data, literature review findings, and engineering expert knowledge to create a robust and reliable decision support system

Chapter 3 describes in detail the hybrid approach to quantify the effectiveness of asphalt maintenance and rehabilitation treatments. The process included implementing expert engineering knowledge, using Delphi and rational factorial techniques, to statistically inferred effectiveness measures from historical condition information. There are four major areas in which the hybrid approach was adapted which include: to define the treatment levels, the short-term effectiveness, the creation of pre- and post-construction models for the calculation of long-term effectiveness, and the optimal treatment time.

Chapter 4 provides the pavement data extraction process to link the Pavement Management Information System (PMIS), Construction Information System (DCIS), and the Decision Support System (DSS) legacy databases. This step was necessary because currently the PMIS, which contains the pavement performance historical information, does not have M&R information.

Chapter 5 described the hybrid process to establish the maintenance and rehabilitation alternatives categorized in each treatment category at the network-level. The PMIS treatment

levels include preventive maintenance (PM), light rehabilitation (LRhb), medium rehabilitation (MRhb) and heavy rehabilitation (HRhb). The process included extensive surveys from District personnel and detailed literature findings.

Chapter 6 provided the quantification of short-term effectiveness or the condition improvement jump (CIJ) through extensive statistical analysis of historical data, and continuous adjustment from expert input. Furthermore, the impact of pavement characteristics such as climatic and subgrade zone, pavement families, traffic levels and current condition, was investigated. Finally, an extensive field experiment that monitored the pre-treatment and post-treatment condition throughout the state of Texas was completed to validate the final recommendations.

Chapter 7 included the creation of deterioration performance models for pre- and post-treatment curves through the use of the "windows" method. In addition, it described the calculation steps taken to derive the regression coefficients including the data synthesis, the non-linear regression analysis, the assumptions taken and the pavement deterioration model used. The process in this chapter points to the complications encountered in the creation of the performance curves, the limitations of the modeling process, the expected inaccuracies, and how the hybrid approach can be used to overcome these limitations.

Chapter 8 describes the process to derive the long-term effectiveness measures based on historical performance data. Since the measures are only performance dependent and do not take into consideration the limited funds of transportation agencies, cost-effectiveness measures were introduced and derived. The optimal treatment timing which will result in the best treatment effectiveness for the least cost was also calculated. These values were used in the hybrid approach to address the limitations of historical performance data with the addition of references from the literature and expert engineering judgment.

9.2 Research Contributions

The research performed in this thesis demonstrates a detailed approach in the quantification of maintenance and rehabilitation treatments of asphalt pavements. The approach combines the available short-term and long-term effectiveness measures such as the condition improvement jump, the benefit and the extended service life to derive the optimal treatment time to maximize effectiveness and minimize the cost. In addition, it shows a clear methodology in developing pavement deterioration models based on M&R. Furthermore, the research identified and explained the sources of inaccuracies in the quantification process and the modeling limitations due to the data quantity and quality. To address these sources of variability, the research presented the hybrid modelling approach. The hybrid modelling approach is the systematic implementation of engineering expert knowledge to address and overcome the limitations that are encountered when deriving effectiveness measures from historical data. Models which solely rely on historical data or engineering knowledge alone have great limitations in their implementation. This is because there are great sources of inaccuracies which lead the model to incorrectly represent the pavement performance behavior in the field, affecting the distribution of funds and the condition of the road network. The hybrid modelling approach accomplished a detail, clear and coherent process to merge the best attributes of statistical methods and expert knowledge. This resulted in a more robust, reliable and flexible effectiveness modelling process. This means that the approach can be applied to any transportation agency using any condition index to provide improved support for the decision maker when selecting M&R projects to maximize budget allocation while maintaining the network at a satisfactory level more effectively.

9.3 Concluding Remarks

During the development of the hybrid approach a number of assumptions were made based on expert knowledge summarized as follows:

1. The short-term effectiveness calculation was not straight forward since there were inconsistencies in the dates of the construction commencement and the condition assessment of the ride and distress scores. The visual surveys to calculate the distress scores and the profiler readings to derive the ride score are taken at different dates. For this reason, the condition improvement jump was observed the year before treatment, the same year of treatment or the year after. To address this observation it was assumed that the value before the treatment was the minimum in the three years before the construction year and the value after treatment was the maximum in the three years after the construction year. The values were selected for each 0.5 mile sections within a Construction-Section-Job.
2. The complexity of the sigmoidal regression coefficients used in the pavement deterioration model for TxDOT and the step process currently in use where independent distresses are modeled and turned into a single utility index, lead to the requirement of a new simplified model. The new simplified model combined the two sigmoidal curves and reduced the number of regression coefficients in order to have a deterioration curve where the distress and ride score depended only on the age of the pavement. The resulting performance curves were adequate for the long-term effectiveness calculations.
3. One of the major assumptions taken when creating the pre-treatment performance curves was that the treatment is not performed on a newly constructed pavement but rather on a pavement that had received several maintenance and rehabilitation treatments. This means that the condition and the deterioration slope before the treatment is dependent on the type of treatment. Therefore, the deterioration rate and condition before a preventive maintenance is of higher quality than the same indices for heavy rehabilitation. This assumption was made to reflect the observed pavement deterioration in the historical data.

4. Since only 50% of M&R activities were merged to the performance monitoring database PMIS, it was not possible to filter out previous treatments and observe the actual deterioration of the pavement. In the deterioration pavement analysis, condition improvement jumps were observed over time which represents the treatment applications. To address this limitation, a MATLAB GUI was used to filter out instances were performance improvement jumps were present before the regression analysis.
5. The pavement deterioration rate was assumed to have constraints based on traffic and treatment level. The constraints included that the highest deterioration rate must follow the trend HRhb>MRhb>LRhb>PM. Also, the higher traffic levels must have greater deterioration rates than medium and low traffic sections.
6. It was assumed that the condition improvement jump or deterioration rate was not impacted by the year at which the treatment was applied. For example, if a preventive maintenance treatment was applied at year 3 or at year 10, the condition improvement jump would be the same value. Furthermore, the deterioration rate will also have the same slope for year 3 and year 10. The only difference is that the value at which the post-treatment deterioration curve starts is higher for year 3 and lower for year 10.

As a result of the application of the hybrid approach, the following conclusions were found:

1. The largest limitations observed for the modelling of the M&R treatment effectiveness was the quality and quantity of pavement historical data. This is due to the sensitivity that the regression analysis has to outliers, small sample sizes and incorrect observations for the development of performance models.

2. The hybrid approach proposed in this thesis, systematically merges statistical analyses of historical data, literature findings, and engineering knowledge to create a robust and reliable decision support system. Furthermore, the approach is capable in accounting for factors that although not measured directly can affect the management of the network such as the pavement structure, and economic downturns.
3. There was a need to identify which maintenance and rehabilitation alternatives belong to each network treatment category because there was no overall consensus among TxDOT Districts managers of which construction activities belonged to a treatment level. This is important because the quantification of the effectiveness was dependent on how the historical performance data was categorized and analyzed. In addition, it is not wise to group preventive maintenance and heavy rehabilitation projects when trying to prioritize projects because of their different costs and scope of work.
4. The main observations of the CIJ were that the PM and LRhb ride score had a finite increase, whereas the MRhb and HRhb showed a ride score reset. The distress score and condition score showed a complete reset across all levels.
5. The separate analysis for independent treatments seal coat and overlay further reinforced the CIJ results observed for ride, distress and condition score calculated for PM, LRhb and MRhb.
6. The investigation of the effect of climate, traffic, and pavement families on the ride, distress and condition score increases for ACP concluded that these factors were not significant. Only, LRhb showed a slight variability of +/- 0.5 to these factors when analyzing the ride score CIJ.
7. Validating the regression fit was of outmost importance due to the many assumptions and constraints. The root-mean-squared-error (RMSE) resulted in a

reasonable measure due to its wide use when validating non-linear regression analysis.

8. The data synthesis process referred as the “windows” method, in which pavement sections with similar characteristics and wide ranging ages are aggregated, resulted in reliable data sets for the non-linear regression curve fitting. The reliability was further reinforced with the low calculated values of the RMSE. This means that the aggregations of historical data reflected the assumptions made where higher traffic sections deteriorate at a faster rate than low traffic sections.
9. The benefit relies heavily on the accuracy of the CIJ. It also relies in the deterioration models derived because the benefit is the area under the pre- and port-treatment curves. In addition, this measure highly impacts the calculation of the cost-effectiveness ratio. Therefore, to derive reliable calculations, the implementation of expert knowledge through the hybrid modelling approach was required.
10. The calculated extended service life for the distress deterioration curves, across all treatment levels and traffic levels resulted in 20 years. This was due to the CIJ for distress scores were all treatments reset to 100 regardless of the treatment. The limitation did not allow the derivation of an optimal treatment time to maximize the benefit and the cost-effectiveness ratio. The hybrid approach proposed will overcome this obstacle by using expert knowledge and literature recommendations on the extended service life.
11. The unit cost has large variations across Districts in the State of Texas. Some of the most important factors are the materials available, the contractors available, construction treatments used, construction experience of the District and District budgets. Therefore, it is necessary to ask for minimum, maximum, and average values since it may not feasible to have an overall consensus.

12. When deriving the optimal treatment time, it was observed that the year of treatment at which the benefit first began was larger for HRhb then MRhb, LRhb and finally PM. This observation is rational because it would not be efficient to reconstruct a road that is in good condition.

9.4 Recommendations

The following recommendations are derived from the results of the research:

1. To overcome the many difficulties and sources of variability in the quantification of effectiveness and the optimum treatment timing, a hybrid modelling approach to merge expert knowledge with statistical analysis of historical data must be used.
2. The difficulty in deriving the deterioration models and the many different combinations of the pavement characteristics will not allow for engineering opinion to be harnessed for all combinations of characteristics. Therefore, models derived from historical data must be used as a baseline.
3. An important factor to determine is regarding the use of the HRhb curve for the pre-construction curve or as the "do-nothing" curve.
4. It may not be feasible to ask the expert the score deterioration over a large span of time. This is due to the many different pavement characteristics that impact the pavement deterioration and the large size of the network. In addition, the engineering expert is usually working in a site-specific location where there may not be certain traffic levels, pavement families or climatic and subgrade zones. For this reason, the last year of deterioration is recommended at 5 years. Furthermore, it can be expected for the engineer to have experience in determining when the treatment hits the PMIS threshold values since they select treatments based on these assumptions. To support the engineer answer, the information derived from the historical data should be provided alongside.

5. Due to the lack of recommendations for the optimal timing of treatment applications, it is wise to add flexibility to the experts being surveyed. This flexibility can be added in the same way that literature has done which is to recommend optimal treatment times dependent on only the construction treatment itself and ignoring the effect the pavement's characteristics have on it. This research established that at the very least the pavement traffic will play an important role in the optimal treatment timing.
6. There are a wide range of factors that affect the cost, even inflation, or the discount rate. In this instance, the factors that affect the cost the most are the treatment itself, the climatic and subgrade zones, and the pavement family. When surveying engineering experts, the question should have a more general approach such as asking for the minimum, maximum, and average values.
7. It is important to populate the database with reliable structural condition measures and structure characteristic information. Maintenance and rehabilitation records must also be available. This is important because the structural condition illustrates in a more complete manner the condition of the whole pavement structure and not just the pavement surface. Furthermore, in TxDOT the distress score did not seem to be sensitive to any treatment level. Having the structural condition data and M&R information will increase data quality and will result in the creation of more reliable effectiveness quantification.

9.5 Future Research

The following future research comments are included:

1. To determine if the use of the HRhb curve or the "do-nothing" curve should be implemented as the pre-treatment performance curve when applying any treatment to the pavement. In this research, it was assumed that each treatment level had its own pre-treatment performance curve.

2. The hybrid approach for quantifying long-term effectiveness should be further investigated. This includes the pre-treatment and post-treatment performance curves, the benefit and the extended service life.
3. The hybrid approach for the optimal treatment time based on benefit and cos-effectiveness ratio needs further investigation. The hybrid approach presented in this thesis can be easily expanded to other condition indices.
4. The effect of different discount and inflation rates on the cost-effectiveness ratio is a subject of future research. These factors have a major impact on the project prioritization by state agency engineers but it is not widely understood.
5. The addition of long-term field performance monitoring such as the Long-Term Pavement Performance (LTTP) program will greatly benefit the hybrid method for the development of pavement deterioration curves and the understanding of the effects that pavement characteristics have on the deterioration. In addition, it will provide greater detail in the quantification of M&R treatment effectiveness.
6. The hybrid approach can be expanded to include project optimization over a multi-year time horizon.

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Appendix A: Developed Pavement Performance Curves

A.1 Ride Score Pre-Treatment Deterioration Curves

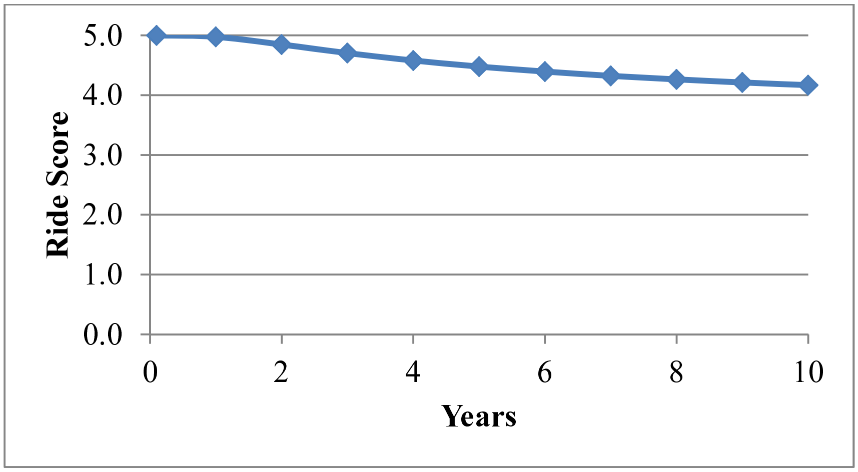


Figure A.1.1: Deterioration Curve for Preventive Maintenance, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

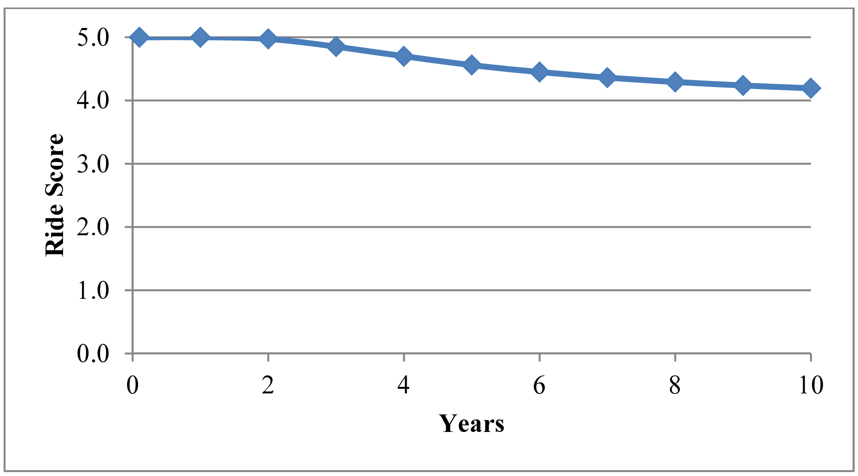
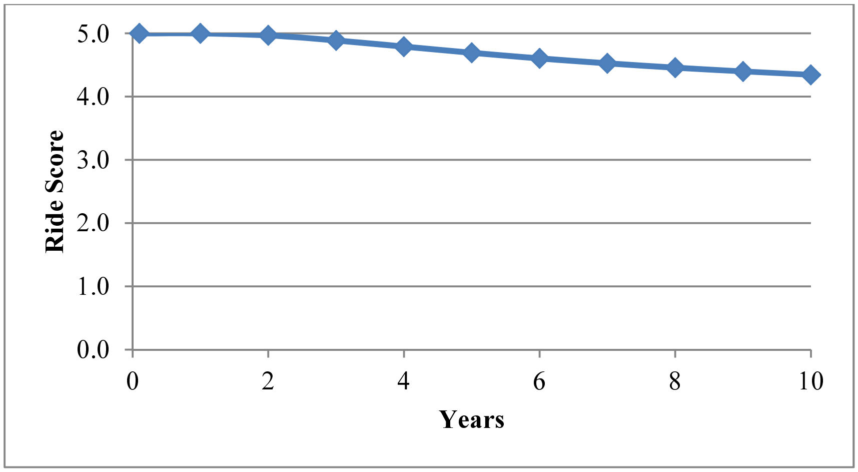


Figure A.1.2: Deterioration Curve for Preventive Maintenance, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.



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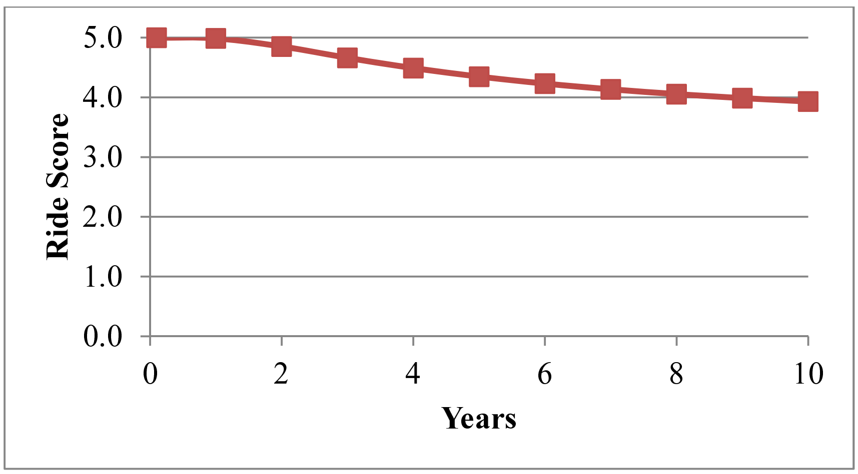


Figure A.1.4: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

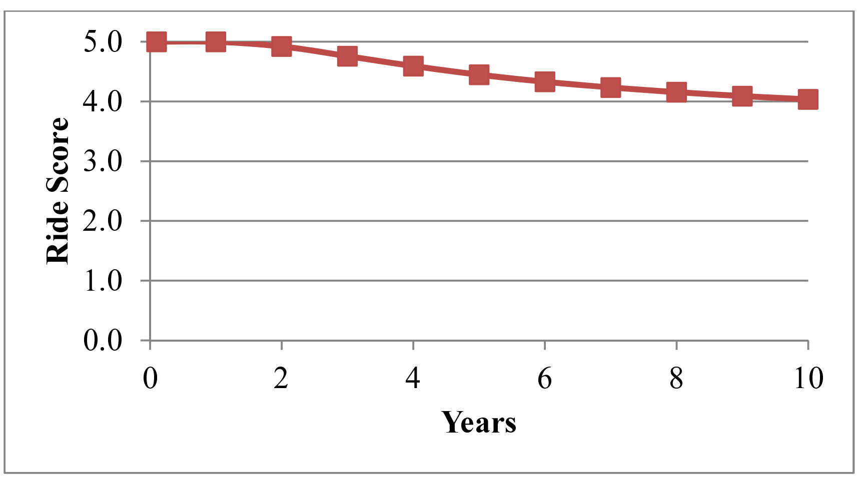


Figure A.1.5: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

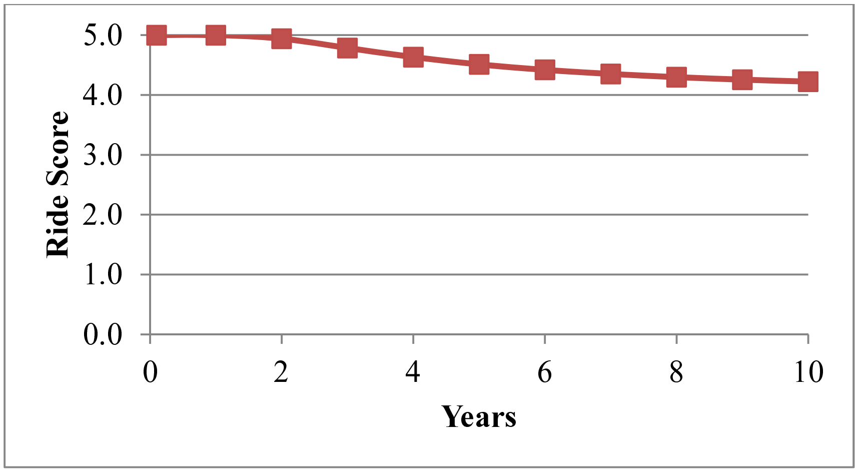


Figure A.1.6: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

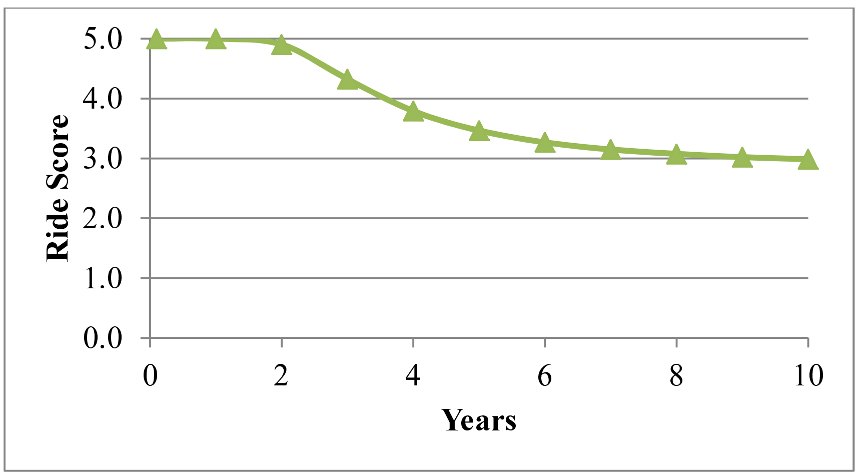


Figure A.1.7: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

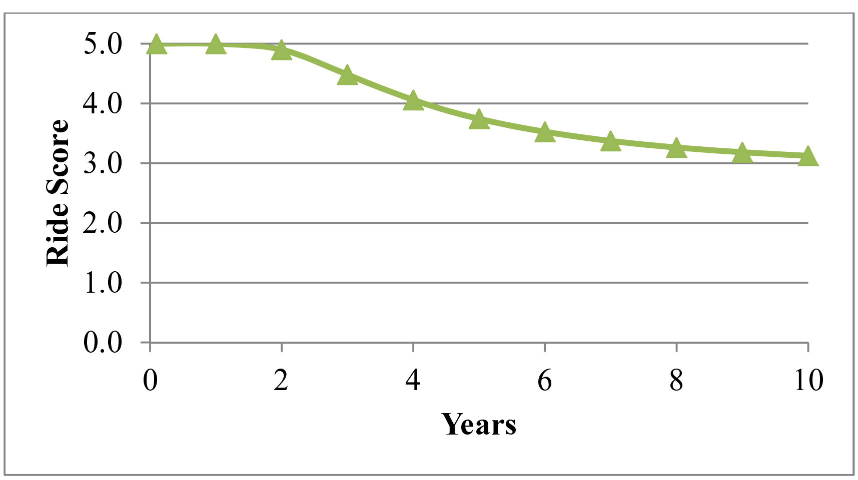


Figure A.1.8: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

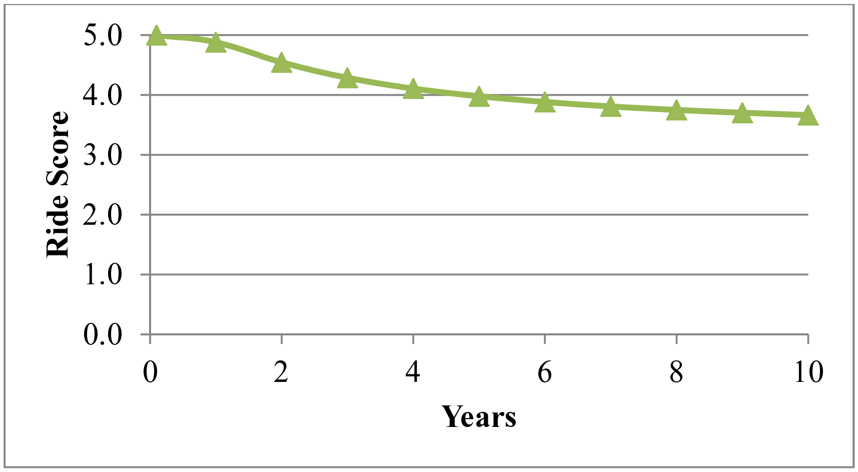


Figure A.1.9: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

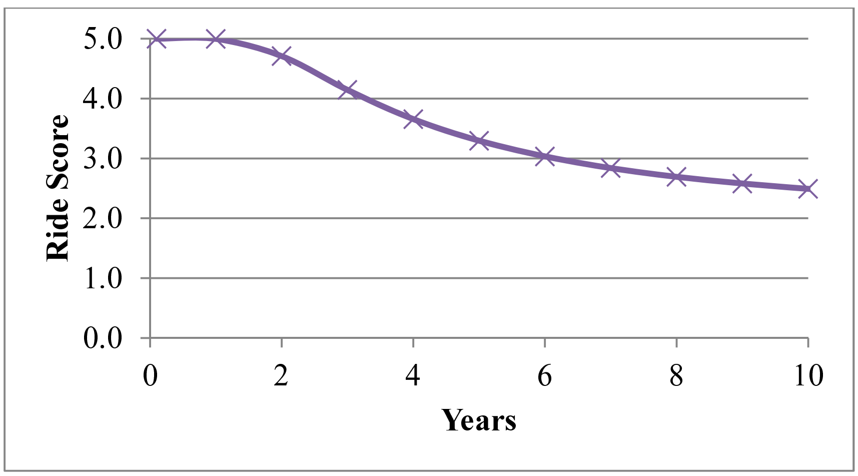


Figure A.1.10: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

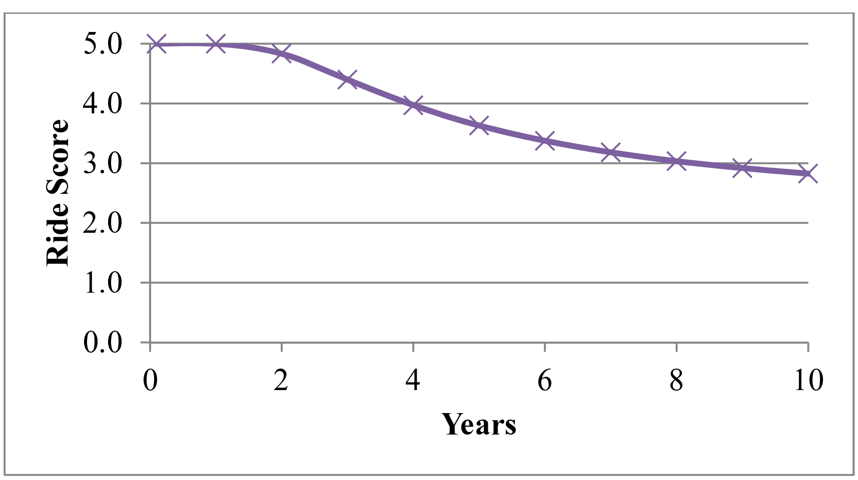


Figure A.1.11: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

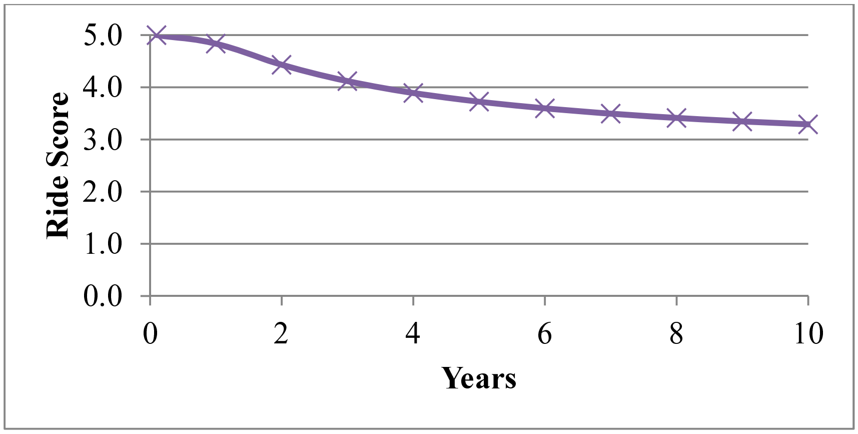
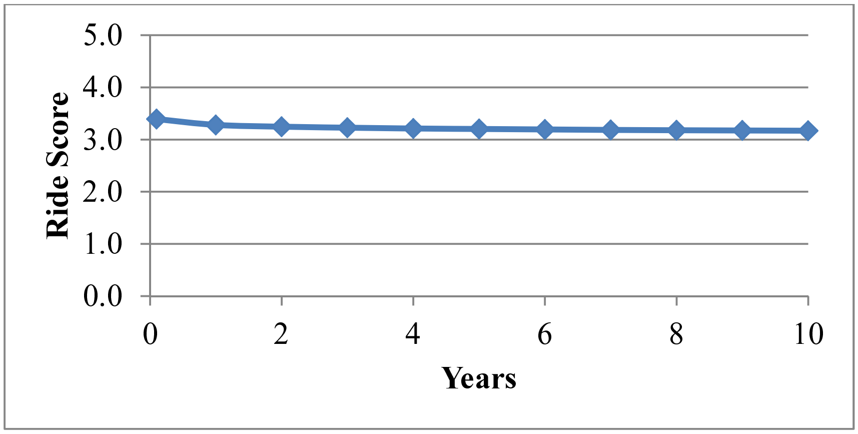


Figure A.1.12: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

A.2 Ride Score Post-Treatment Deterioration Curves



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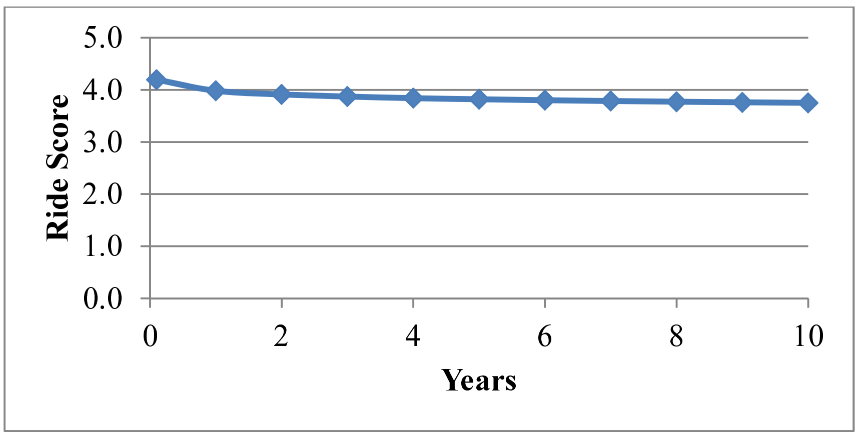
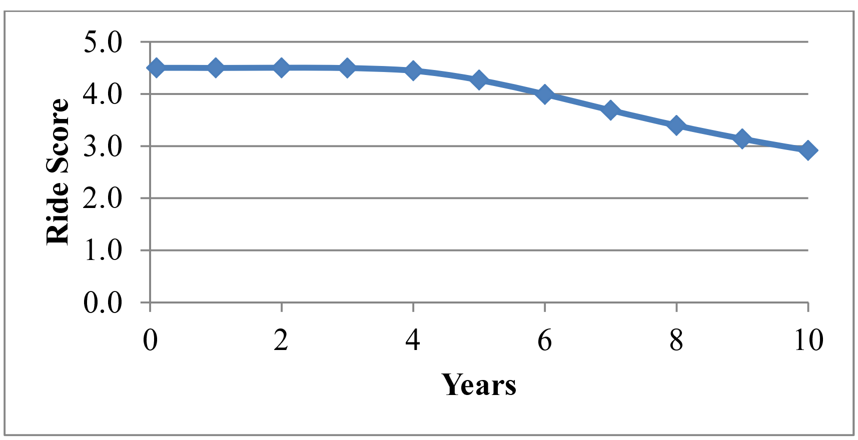


Figure A.2.2: Deterioration Curve for Preventive Maintenance, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.



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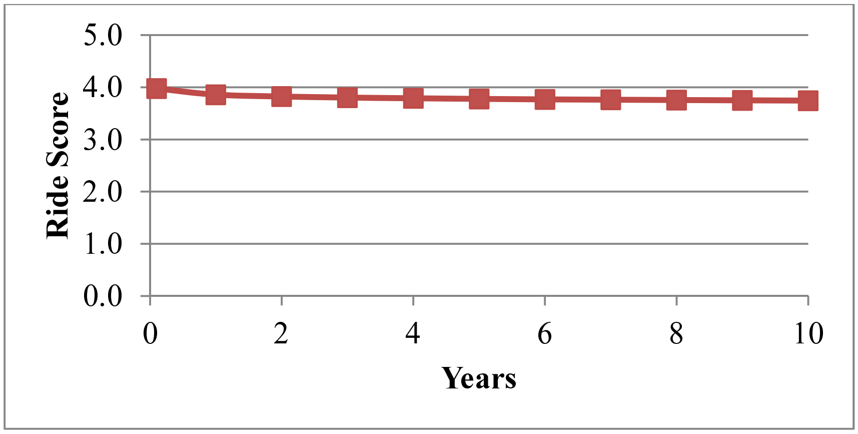


Figure A.2.4: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

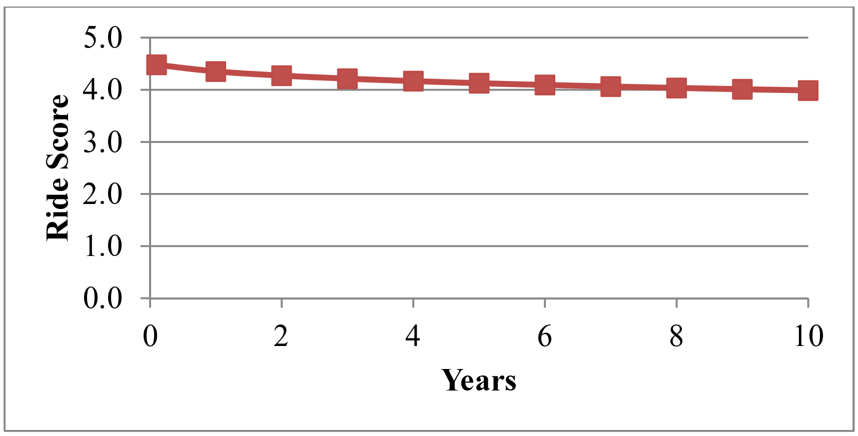
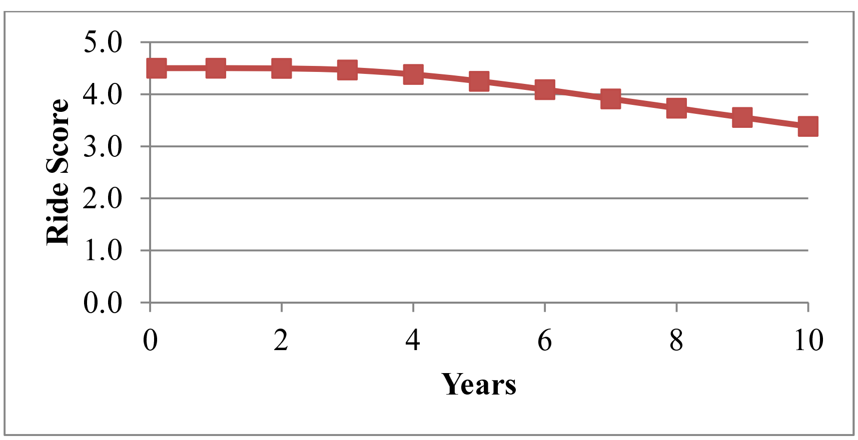


Figure A.2.5: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.



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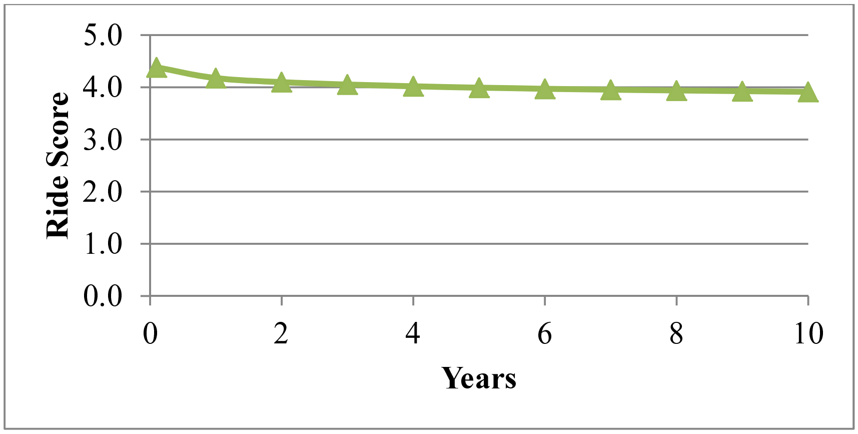
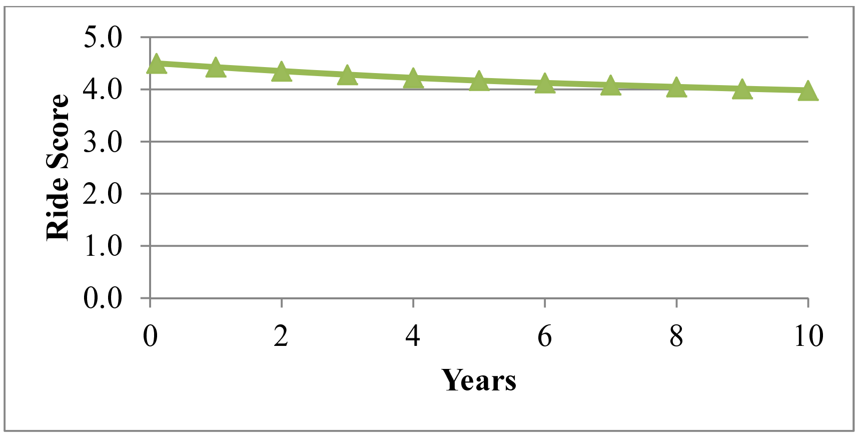


Figure A.2.7: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.



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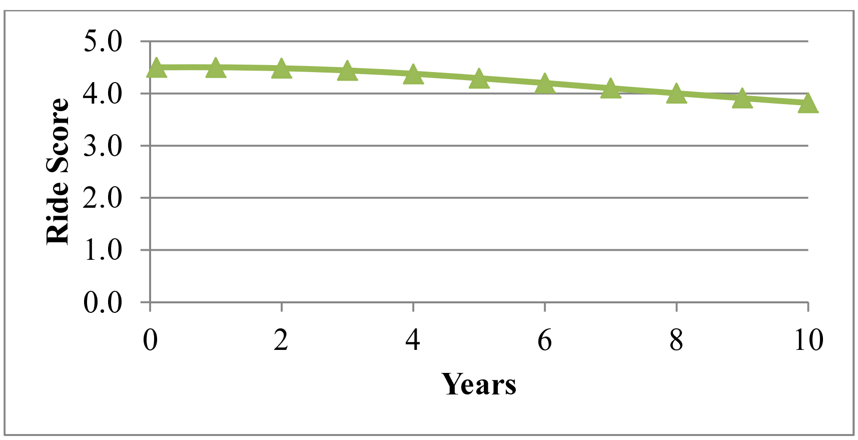

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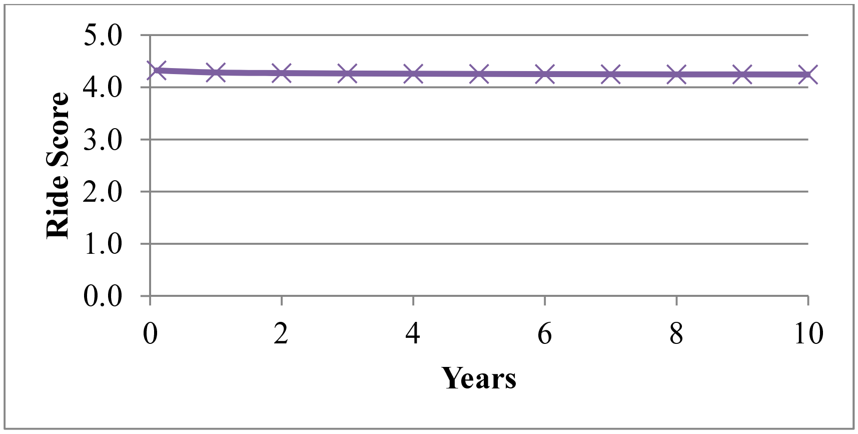

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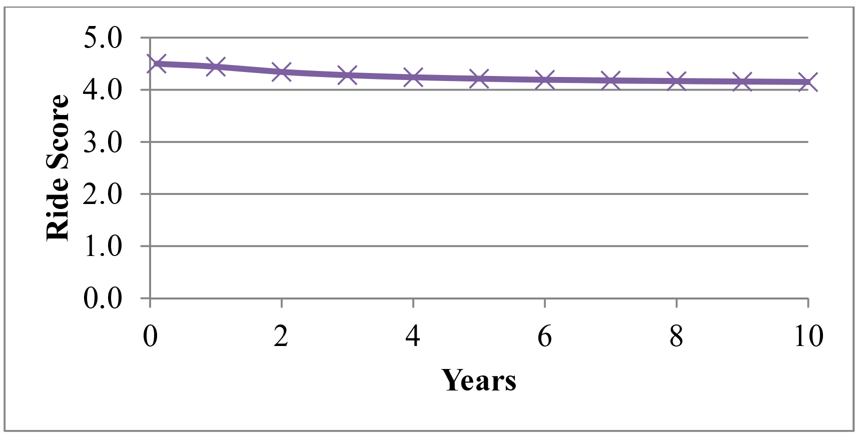


Figure A.2.11: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

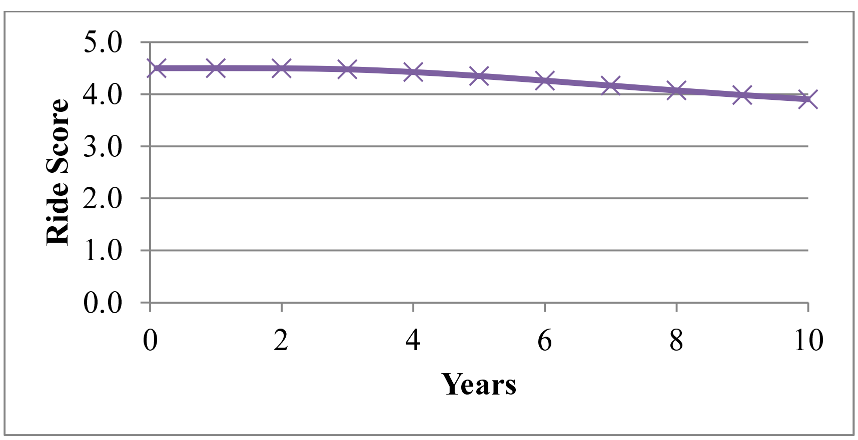
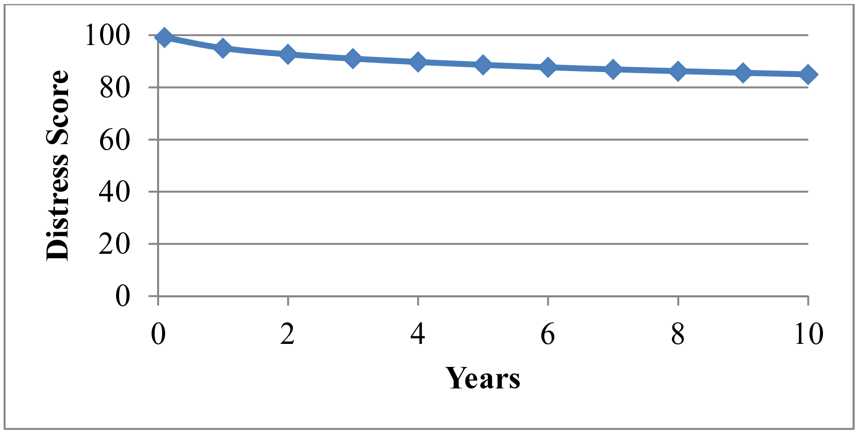


Figure A.2.12: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

A.3 Distress Score Pre-Treatment Deterioration Curves



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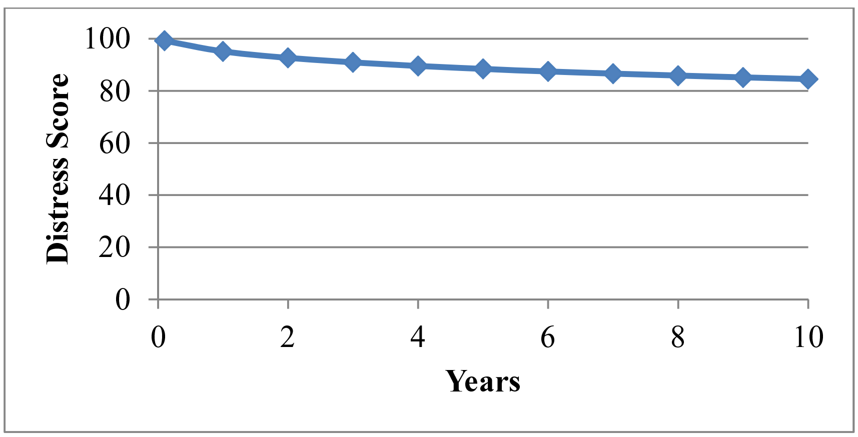

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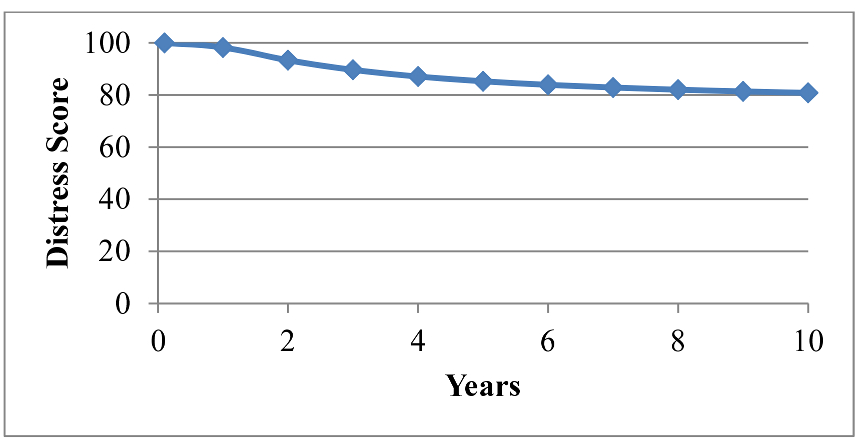

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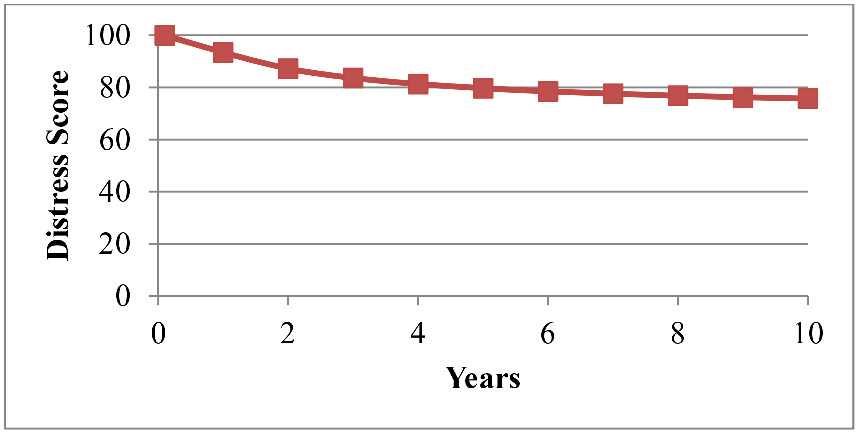

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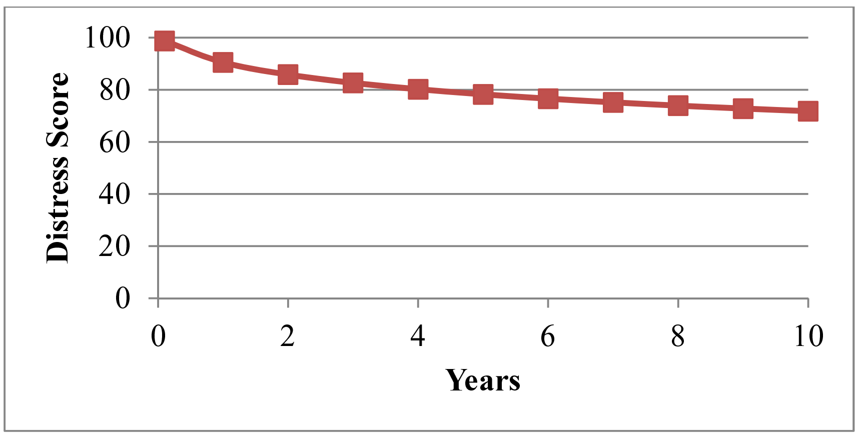

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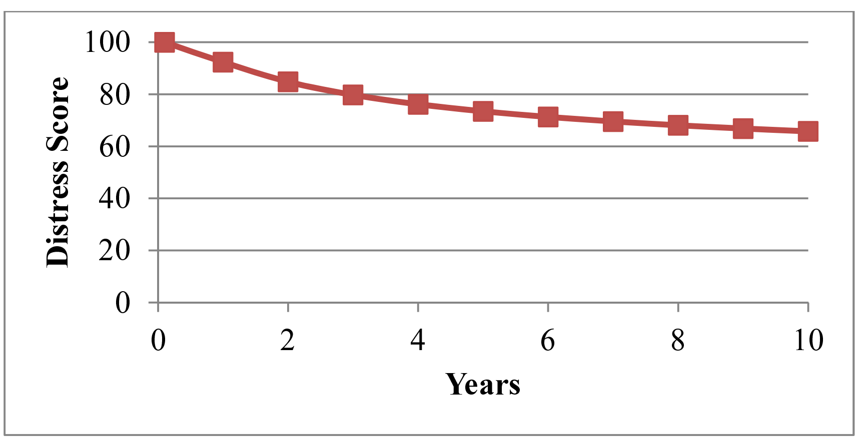

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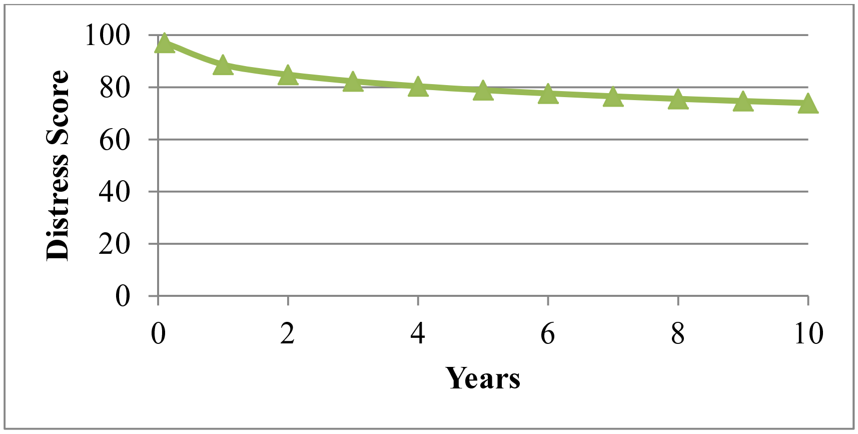

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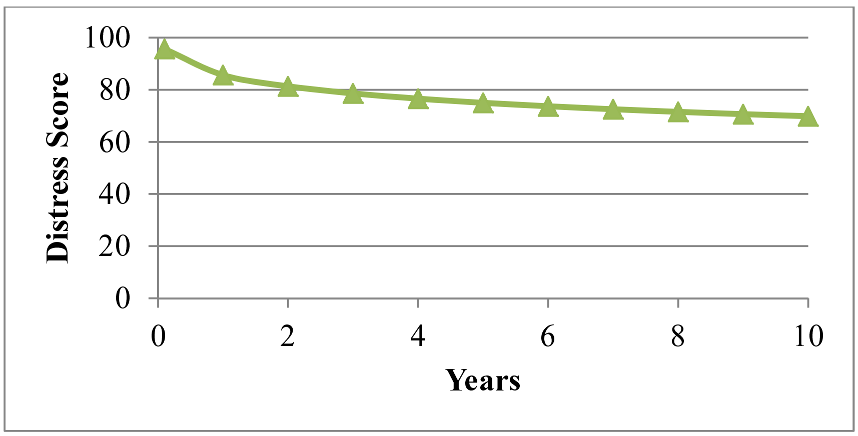

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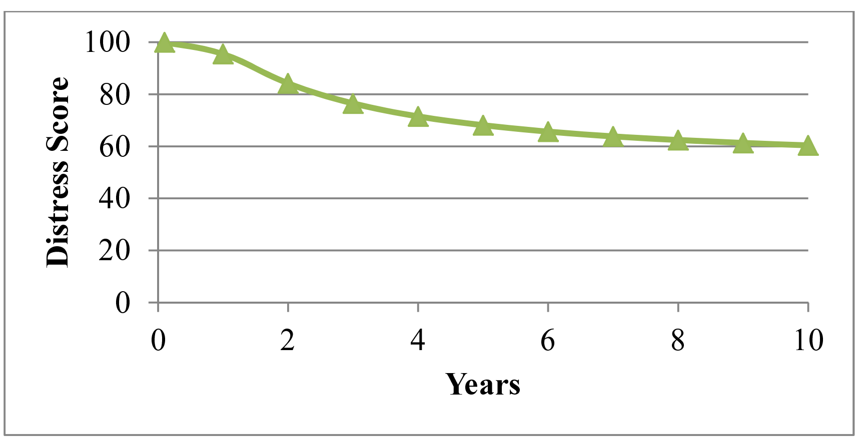


Figure A.3.9: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

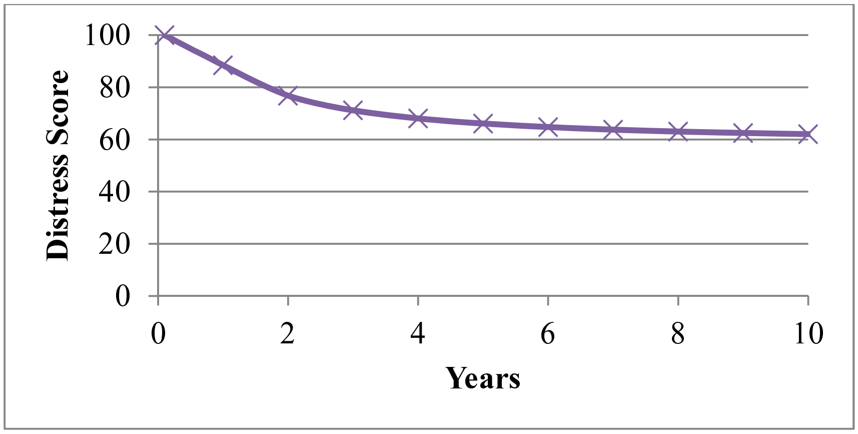


Figure A.3.10: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

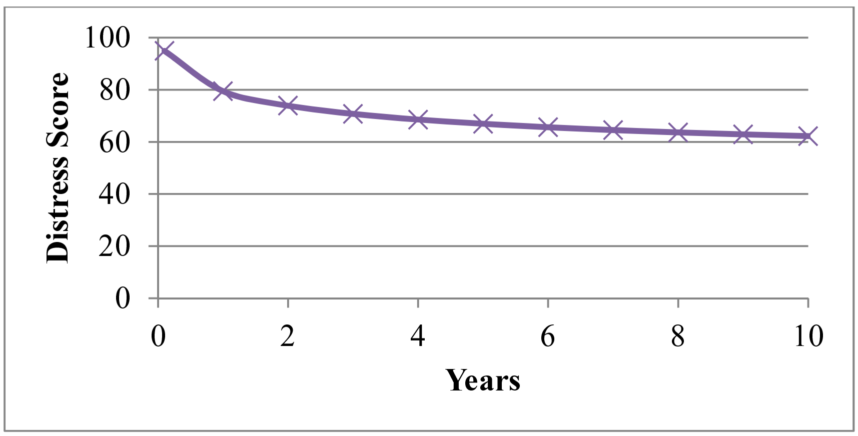


Figure A.3.11: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

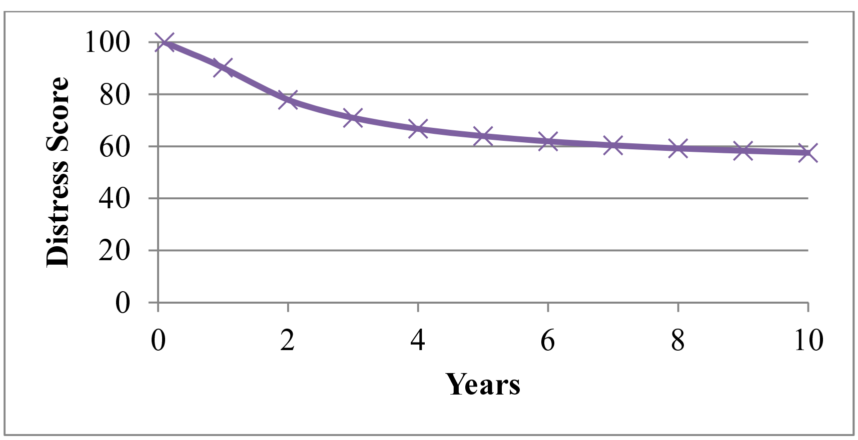
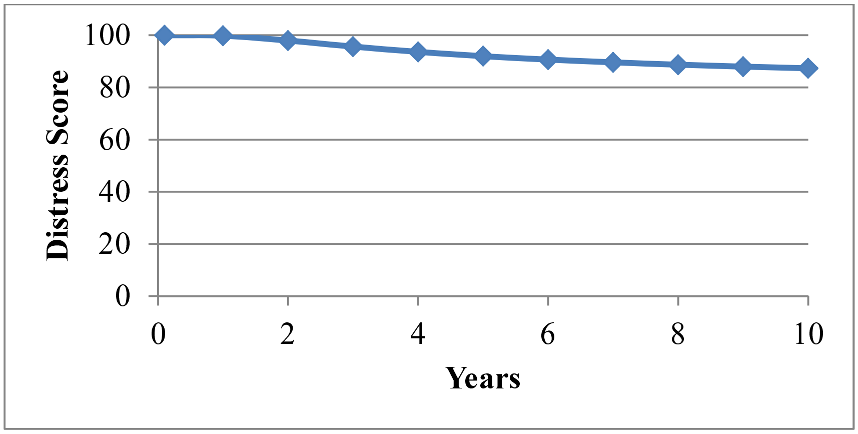


Figure A.3.12: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

A.4 Distress Score Post-Treatment Deterioration Curves



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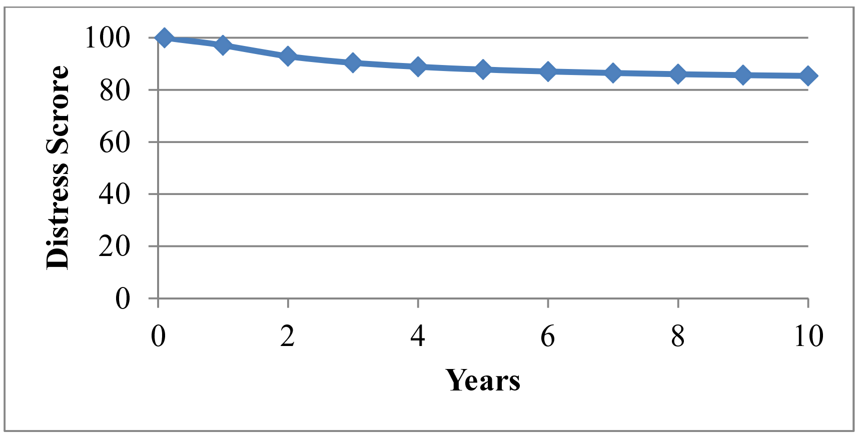

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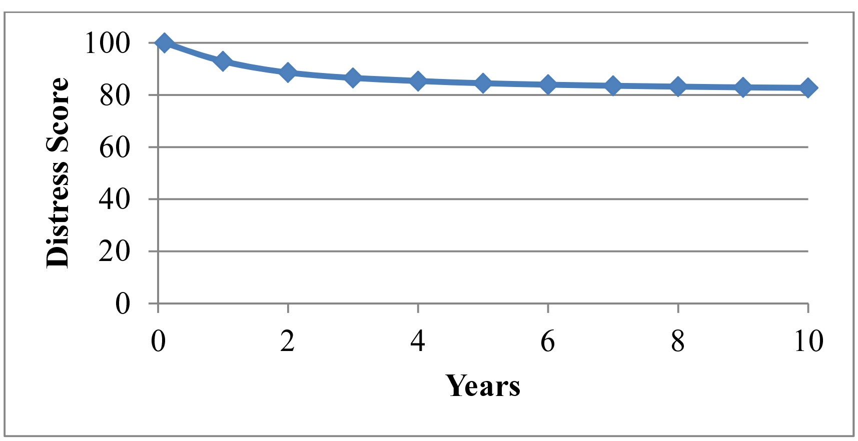

Figure A.4.3: Deterioration Curve for Preventive Maintenance, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

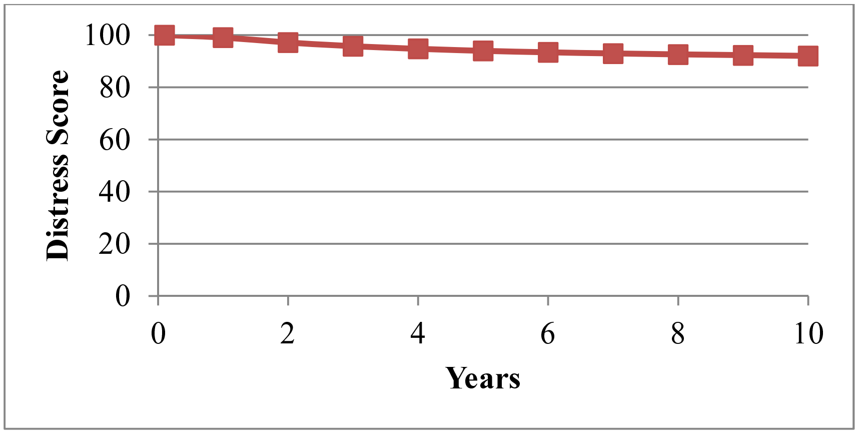

Figure A.4.4: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

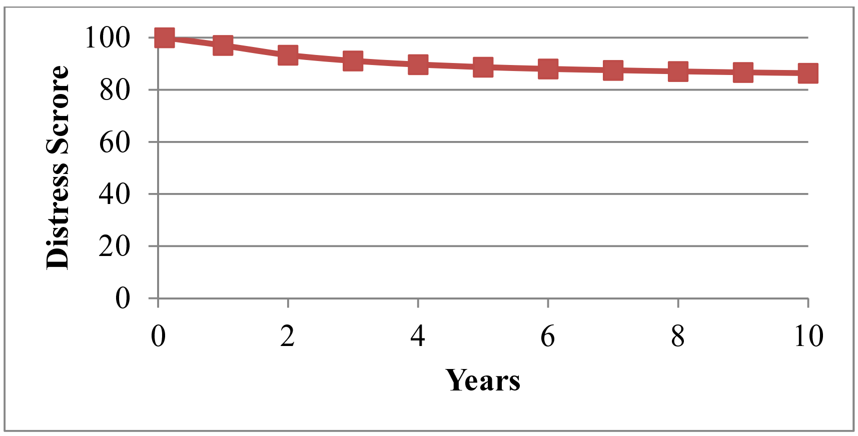

Figure A.4.5: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

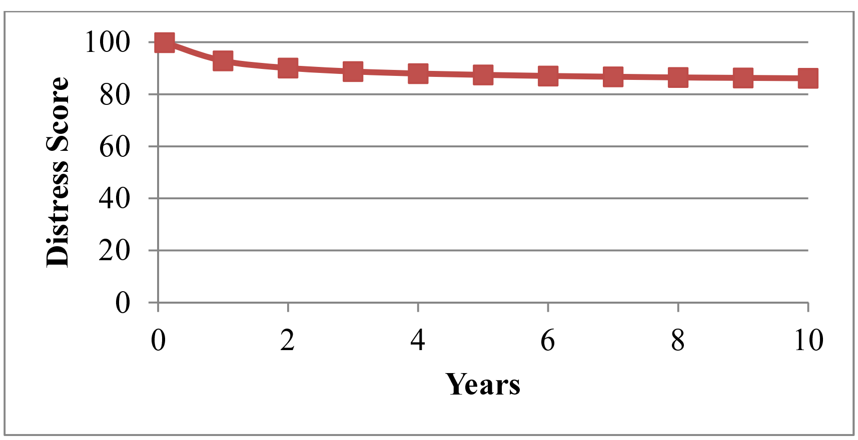

Figure A.4.6: Deterioration Curve for Light Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

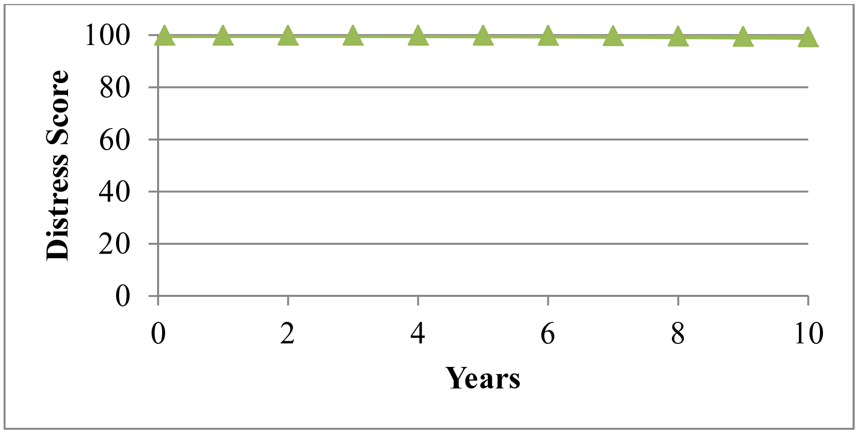

Figure A.4.7: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

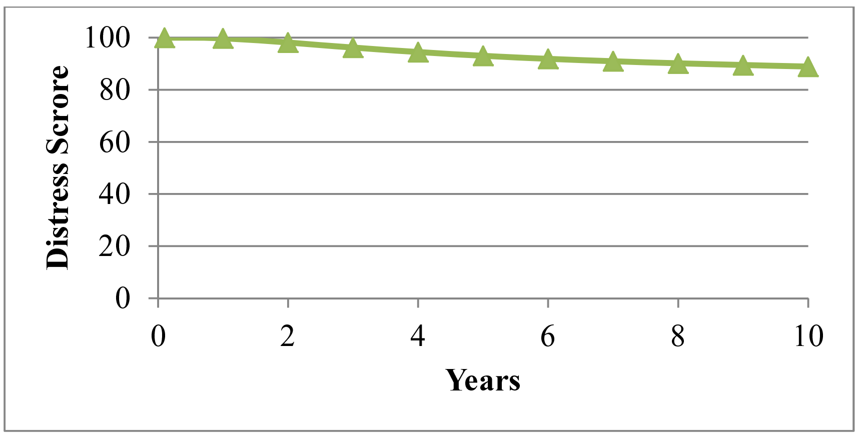

Figure A.4.8: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

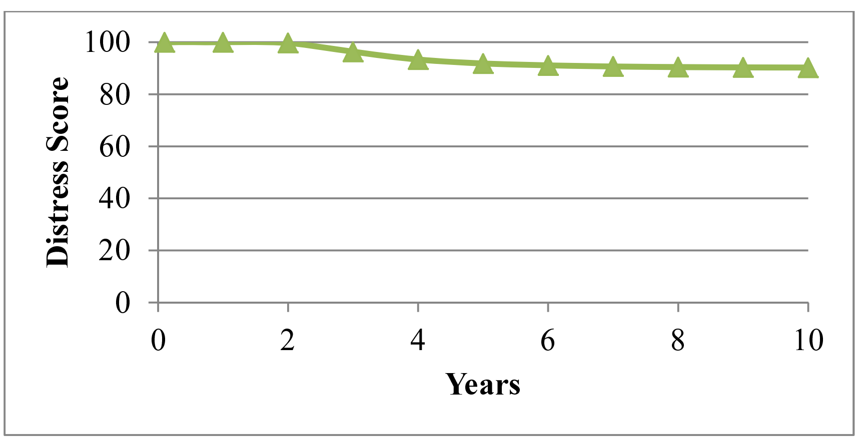

Figure A.4.9: Deterioration Curve for Medium Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

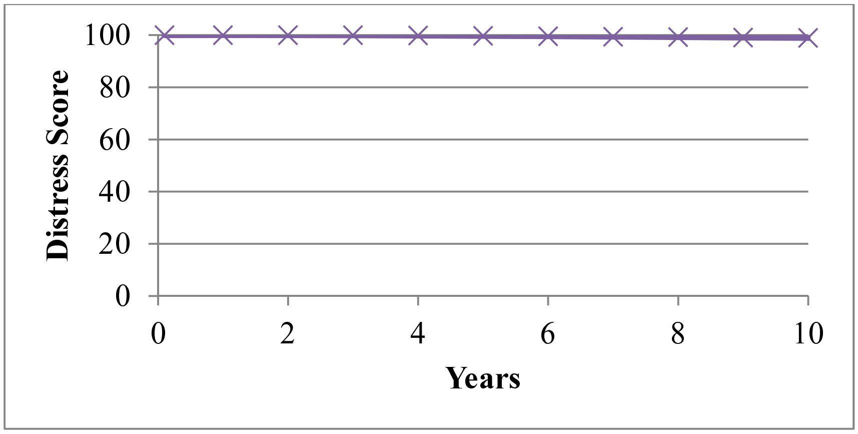

Figure A.4.10: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Low Traffic.

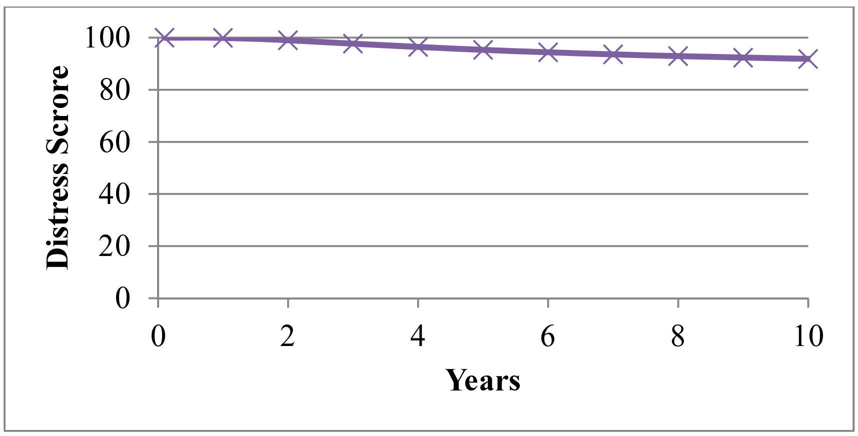

Figure A.4.11: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and Medium Traffic.

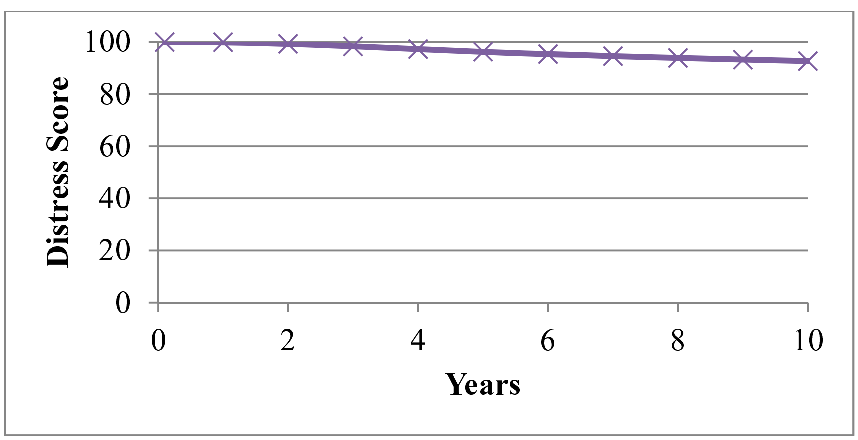

Figure A.4.12: Deterioration Curve for Heavy Rehabilitation, Climatic and Subgrade Zone 4, Pavement Family A and High Traffic.

A.5 Ride Score Deterioration Curve Coefficients and RMSE

Table A.5.1: Deterioration Curve Coefficients for Climatic and Subgrade Zone 4, Pavement family A and Low Traffic.

Treatment Level	Pre-Treatment				Post-Treatment			
	Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	1.50	5.33	0.84	0.019	1.33	1.00	0.10	0.020
LRhb	1.75	4.93	1.00	0.017	1.42	0.10	0.10	0.030
MRhb	2.14	3.18	2.44	0.025	1.38	5.00	0.23	0.033
HRhb	3.10	3.55	1.50	0.150	0.48	0.10	0.10	0.020

Table A.5.2: Deterioration Curve Coefficients for Climatic and Subgrade Zone 4, Pavement family A and Medium Traffic.

Treatment Level	Pre-Treatment				Post-Treatment			
	Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	1.12	4.79	1.51	0.005	1.33	2.25	0.21	0.001
LRhb	1.50	5.00	1.18	0.040	5.00	755.68	0.19	0.015
MRhb	2.18	3.64	1.88	0.012	3.50	80.00	0.31	0.069
HRhb	2.80	4.00	1.50	0.160	0.43	2.00	1.00	0.100

Table A.5.2: Deterioration Curve Coefficients for Climatic and Subgrade Zone 4, Pavement family A and Heavy Traffic.

Treatment Level	Pre-Treatment				Post-Treatment			
	Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	1.40	7.58	1.00	0.003	3.00	8.00	2.00	0.125
LRhb	1.00	4.00	1.50	0.049	1.00	15.00	1.00	0.150
MRhb	1.75	2.69	1.00	0.012	5.00	28.09	0.67	0.053
HRhb	2.40	3.00	0.90	0.190	2.00	11.90	1.10	0.200

A.6 Distress Score Deterioration Curve Coefficients and RMSE

Table A.6.1: Deterioration Curve Coefficients for Climatic and Subgrade Zone 4, Pavement family A and Low Traffic.

Treatment Level	Pre-Treatment				Post-Treatment			
	Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	100.00	242.94	0.20	0.290	20.00	4.56	1.00	0.830
LRhb	30.67	1.70	0.82	0.440	11.53	2.99	0.84	0.002
MRhb	100.00	41.00	0.21	0.780	10.00	26.36	1.03	0.001
HRhb	41.78	1.25	1.13	0.700	4.00	13.02	1.00	0.700

Table A.6.2: Deterioration Curve Coefficients for Climatic and Subgrade Zone 4, Pavement family A and Medium Traffic.

Treatment Level	Pre-Treatment				Post-Treatment			
	Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	100.00	193.83	0.21	0.460	17.50	1.80	1.00	1.250
LRhb	100.00	23.91	0.27	0.620	17.00	1.85	0.90	0.550
MRhb	99.30	23.11	0.21	0.180	19.32	5.13	0.90	0.320
HRhb	60.68	1.25	0.36	0.780	15.67	6.18	0.90	0.130

Table A.6.2: Deterioration Curve Coefficients for Climatic and Subgrade Zone 4, Pavement family A and Heavy Traffic.

Treatment Level	Pre-Treatment				Post-Treatment			
	Alpha	Rho	Beta	RMSE	Alpha	Rho	Beta	RMSE
PM	25.00	2.64	1.00	1.400	19.66	1.02	0.90	1.005
LRhb	55.00	3.00	0.62	1.990	16.00	0.75	0.75	1.390
MRhb	48.00	2.20	1.09	3.300	10.00	3.00	3.12	0.760
HRhb	50.00	1.63	1.00	2.570	20.00	10.00	0.75	1.740

Appendix B: Long Term-Effectiveness Measures

Table B.1: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Preventive Maintenance and Low Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.0	0	0
0.5	0.0	0.0	0.0	71	20
1.0	0.0	0.0	0.0	78	20
1.5	0.0	0.0	0.0	85	20
2.0	0.0	0.0	0.0	92	20
2.5	0.0	0.0	0.0	98	20
3.0	0.0	0.0	0.0	104	20
3.5	0.0	0.0	0.0	109	20
4.0	6.4	20.0	3.47	114	20
4.5	6.8	10.0	8.94	119	20
5.0	6.7	20.0	3.61	124	20
5.5	6.0	20.0	3.23	128	20
6.0	5.5	20.0	2.95	133	20
7.0	5.4	20.0	2.90	141	20
8.0	4.5	20.0	2.40	149	20
9.0	3.3	20.0	1.76	156	20
10.0	3.4	20.0	1.85	163	20
11.0	3.0	20.0	1.60	170	20
12.0	2.1	20.0	1.12	176	20

Table B.2: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Preventive Maintenance and Medium Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.0	0	0
0.5	0.0	0.0	0.0	36	20
1.0	0.0	0.0	0.0	44	20
1.5	0.0	0.0	0.0	52	20
2.0	0.0	0.0	0.0	58	20
2.5	0.0	0.0	0.0	65	20
3.0	0.0	0.0	0.0	71	20
3.5	0.0	0.0	0.0	77	20
4.0	4.8	20.0	2.58	82	20
4.5	5.1	20.0	2.77	87	20
5.0	5.4	20.0	2.93	93	20
5.5	5.7	20.0	3.08	97	20
6.0	5.0	20.0	2.68	102	20
7.0	3.6	20.0	1.95	111	20
8.0	2.6	20.0	1.40	119	20
9.0	1.9	20.0	1.03	127	20
10.0	1.4	20.0	0.74	135	20
11.0	0.8	20.0	0.43	142	20
12.0	0.4	20.0	0.22	148	20

Table B.3: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Preventive Maintenance and High Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.4	5.4	0.00	0	0
0.5	0.6	5.7	0.00	0	0
1.0	0.8	5.8	2.34	39	1
1.5	1.0	6.0	1.94	49	20
2.0	1.3	6.1	2.40	57	20
2.5	1.5	6.3	2.84	64	20
3.0	1.8	6.4	3.29	71	20
3.5	2.0	6.5	3.71	76	20
4.0	2.3	6.6	4.13	81	20
4.5	2.5	6.7	4.49	86	20
5.0	2.7	6.7	4.90	90	20
5.5	2.9	6.8	5.21	94	20
6.0	3.1	6.9	5.51	97	20
7.0	3.5	7.0	6.09	103	20
8.0	3.5	7.0	6.15	108	20
9.0	3.4	6.8	6.04	113	20
10.0	3.3	6.7	5.81	116	20
11.0	3.2	6.7	5.72	120	20
12.0	3.0	5.5	5.91	123	20

Table B.4: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Light Rehabilitation and Low Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.0	0	0
0.5	0.0	0.0	0.0	308	20
1.0	0.0	0.0	0.0	320	20
1.5	0.0	0.0	0.0	329	20
2.0	0.0	0.0	0.0	337	20
2.5	0.0	0.0	0.0	343	20
3.0	0.0	0.0	0.0	349	20
3.5	0.0	0.0	0.0	354	20
4.0	0.0	0.0	0.0	359	20
4.5	8.7	20.0	0.79	363	20
5.0	9.1	20.0	0.83	367	20
5.5	9.5	20.0	0.86	370	20
6.0	9.9	20.0	0.89	373	20
7.0	10.5	20.0	0.95	379	20
8.0	11.1	20.0	1.00	384	20
9.0	11.2	20.0	1.01	388	20
10.0	10.6	20.0	0.96	392	20
11.0	10.0	20.0	0.90	395	20
12.0	9.5	20.0	0.86	398	20
13.0	9.1	20.0	0.82	401	20
14.0	8.8	20.0	0.79	404	20
15.0	8.4	20.0	0.76	406	20
16.0	8.1	20.0	0.73	408	20
17.0	8.3	20.0	0.75	410	20
18.0	8.1	20.0	0.73	412	20
19.0	7.5	20.0	0.68	414	20
20.0	7.3	20.0	0.66	416	20

Table B.5: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Light Rehabilitation and Medium Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.0	0	0
0.5	0.0	0.0	0.0	292	20
1.0	0.0	0.0	0.0	306	20
1.5	0.0	0.0	0.0	318	20
2.0	9.2	20.0	0.83	330	20
2.5	9.8	20.0	0.88	340	20
3.0	10.3	20.0	0.93	350	20
3.5	10.8	20.0	0.98	359	20
4.0	11.3	20.0	1.02	368	20
4.5	11.7	20.0	1.05	376	20
5.0	12.1	20.0	1.09	384	20
5.5	12.4	20.0	1.12	392	20
6.0	12.7	20.0	1.15	399	20
7.0	13.3	20.0	1.20	413	20
8.0	13.8	20.0	1.25	425	20
9.0	14.3	20.0	1.29	437	20
10.0	14.7	20.0	1.32	448	20
11.0	14.6	20.0	1.32	459	20
12.0	14.3	20.0	1.29	469	20
13.0	14.0	20.0	1.26	478	20
14.0	13.6	20.0	1.23	487	20
15.0	13.3	20.0	1.20	496	20
16.0	13.1	20.0	1.18	504	20
17.0	12.9	20.0	1.16	512	20
18.0	12.6	20.0	1.14	520	20
19.0	12.4	20.0	1.12	527	20
20.0	12.3	20.0	1.12	534	20

Table B.6: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Light Rehabilitation and High Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.00	0	0
0.5	0.0	0.0	0.00	375	20
1.0	0.0	0.0	0.00	393	20
1.5	0.0	0.0	0.00	408	20
2.0	10.3	20.0	0.93	422	20
2.5	10.7	20.0	0.97	434	20
3.0	11.1	20.0	1.00	446	20
3.5	11.4	20.0	1.03	457	20
4.0	11.7	20.0	1.06	465	20
4.5	12.0	20.0	1.08	474	20
5.0	12.2	20.0	1.11	482	20
5.5	12.5	20.0	1.13	489	20
6.0	12.6	20.0	1.14	496	20
7.0	13.0	20.0	1.17	509	20
8.0	13.2	20.0	1.20	521	20
9.0	13.5	20.0	1.22	531	20
10.0	13.7	20.0	1.23	540	20
11.0	13.8	20.0	1.25	549	20
12.0	14.0	20.0	1.26	557	20
13.0	14.1	20.0	1.27	564	20
14.0	13.2	20.0	1.19	571	20
15.0	13.1	20.0	1.18	578	20
16.0	13.0	20.0	1.17	584	20
17.0	12.9	20.0	1.16	589	20
18.0	12.7	20.0	1.15	595	20
19.0	12.6	20.0	1.14	600	20
20.0	12.4	20.0	1.12	604	20

Table B.7: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Medium Rehabilitation and Low Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.00	0	0
0.5	0.0	0.0	0.00	480	20
1.0	0.0	0.0	0.00	491	20
1.5	0.0	0.0	0.00	501	20
2.0	0.0	0.0	0.00	509	20
2.5	0.0	0.0	0.00	517	20
3.0	17.8	20.0	1.17	525	20
3.5	18.4	20.0	1.21	532	20
4.0	18.9	20.0	1.25	539	20
4.5	19.3	20.0	1.27	545	20
5.0	19.7	20.0	1.30	551	20
5.5	19.9	20.0	1.31	557	20
6.0	20.1	20.0	1.33	563	20
9.0	20.9	20.0	1.38	592	20
10.0	21.0	20.0	1.39	601	20
11.0	21.1	20.0	1.39	609	20
12.0	21.2	20.0	1.40	616	20
13.0	21.3	20.0	1.40	624	20
14.0	21.4	20.0	1.41	631	20
15.0	21.4	20.0	1.41	637	20
20.0	21.5	20.0	1.42	666	20
30.0	21.6	20.0	1.43	712	20
40.0	21.7	20.0	1.43	747	20

Table B.8: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Medium Rehabilitation and Medium Traffic.

Year of Treatment	**Ride Score**			**Distress Score**	
	Benefit	**Extended Service life**	**Cost-Effectiveness**	**Benefit**	**Extended Service life**
0.0	0.0	0.0	0.0	0	0
0.5	0.0	0.0	0.0	385	20
1.0	0.0	0.0	0.0	397	20
1.5	0.0	0.0	0.0	407	20
2.0	0.0	0.0	0.0	416	20
2.5	0.0	0.0	0.0	425	20
3.0	17.1	20.0	1.13	432	20
3.5	17.8	20.0	1.17	440	20
4.0	18.4	20.0	1.22	447	20
4.5	19.0	20.0	1.25	453	20
5.0	19.5	20.0	1.28	459	20
5.5	19.9	20.0	1.31	465	20
6.0	20.2	20.0	1.33	471	20
10.0	21.9	20.0	1.44	509	20
11.0	22.1	20.0	1.46	517	20
12.0	22.3	20.0	1.47	525	20
13.0	22.5	20.0	1.48	533	20
14.0	22.6	20.0	1.49	539	20
15.0	22.8	20.0	1.50	546	20
20.0	23.2	20.0	1.53	575	20
30.0	23.6	20.0	1.56	621	20
40.0	23.8	20.0	1.57	655	20

Table B.9: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Medium Rehabilitation and High Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.00	0	0
0.5	0.0	0.0	0.00	554	20
1.0	0.0	0.0	0.00	575	20
1.5	0.0	0.0	0.00	594	20
2.0	0.0	0.0	0.00	609	20
2.5	4.5	13.5	0.53	622	20
3.0	4.9	13.7	0.57	633	20
3.5	5.3	13.8	0.60	643	20
4.0	5.6	13.9	0.64	652	20
4.5	5.9	14.0	0.66	659	20
5.0	6.1	14.1	0.68	666	20
5.5	6.4	14.2	0.70	672	20
6.0	6.6	14.2	0.73	678	20
10.0	6.6	20.0	0.44	709	20
11.0	6.8	20.0	0.45	714	20
12.0	7.0	20.0	0.46	719	20
13.0	7.3	20.0	0.48	723	20
14.0	7.5	20.0	0.50	727	20
15.0	8.7	20.0	0.57	730	20
20.0	8.4	20.0	0.55	743	20
30.0	9.1	20.0	0.60	759	20
40.0	9.8	20.0	0.65	768	20

Table B.10: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Heavy Rehabilitation and Low Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.00	0	0
0.5	0.0	0.0	0.00	685	20
1.0	0.0	0.0	0.00	702	20
1.5	0.0	0.0	0.00	714	20
2.0	0.0	0.0	0.00	724	20
2.5	0.0	0.0	0.00	732	20
3.0	34.7	20.0	20.00	738	20
3.5	35.7	20.0	20.00	743	20
4.0	36.5	20.0	20.00	748	20
4.5	37.3	20.0	20.00	752	20
5.0	37.9	20.0	20.00	755	20
5.5	38.5	20.0	20.00	758	20
6.0	39.0	20.0	20.00	761	20
10.0	41.8	20.0	20.00	776	20
11.0	42.2	20.0	20.00	778	20
12.0	42.6	20.0	20.00	780	20
13.0	42.9	20.0	20.00	782	20
14.0	43.2	20.0	20.00	784	20
15.0	43.4	20.0	20.00	786	20
20.0	44.3	20.0	20.00	791	20
30.0	45.3	20.0	20.00	798	20
40.0	45.8	20.0	20.00	802	20

Table B.11: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Heavy Rehabilitation and Medium Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.0	0	0
0.5	0.0	0.0	0.0	584	20
1.0	0.0	0.0	0.0	596	20
1.5	0.0	0.0	0.0	606	20
2.0	0.0	0.0	0.0	614	20
2.5	0.0	0.0	0.0	622	20
3.0	27.0	20.0	20.00	629	20
3.5	28.0	20.0	20.00	636	20
4.0	28.8	20.0	20.00	642	20
4.5	29.6	20.0	20.00	647	20
5.0	30.2	20.0	20.00	652	20
5.5	30.8	20.0	20.00	657	20
6.0	31.3	20.0	20.00	662	20
8.0	33.0	20.0	20.00	678	20
10.0	34.2	20.0	20.00	692	20
11.0	34.6	20.0	20.00	698	20
12.0	35.0	20.0	20.00	704	20
13.0	35.4	20.0	20.00	709	20
14.0	35.7	20.0	20.00	714	20
15.0	36.0	20.0	20.00	719	20
20.0	36.9	20.0	20.00	739	20
30.0	38.0	20.0	20.00	768	20
40.0	38.5	20.0	20.00	789	20

Table B.12: Calculated Long Term-Effectiveness Measures for Ride and Distress Scores due to Heavy Rehabilitation and High Traffic.

Year of Treatment	Ride Score			Distress Score	
	Benefit	Extended Service life	Cost-Effectiveness	Benefit	Extended Service life
0.0	0.0	0.0	0.0	0	0
0.5	0.0	0.0	0.0	651	20
1.0	0.0	0.0	0.0	671	20
1.5	0.0	0.0	0.0	688	20
2.0	12.3	20.0	20.00	701	20
2.5	13.1	20.0	20.00	712	20
3.0	13.7	20.0	20.00	722	20
3.5	14.2	20.0	20.00	730	20
4.0	14.7	20.0	20.00	737	20
4.5	15.2	20.0	20.00	743	20
5.0	15.6	20.0	20.00	749	20
5.5	16.0	20.0	20.00	754	20
6.0	16.3	20.0	20.00	759	20
7.0	17.0	20.0	20.00	767	20
10.0	18.4	20.0	20.00	785	20
11.0	18.8	20.0	20.00	789	20
12.0	19.2	20.0	20.00	793	20
13.0	19.5	20.0	20.00	797	20
14.0	19.8	20.0	20.00	800	20
15.0	20.0	20.0	20.00	803	20
20.0	21.1	20.0	20.00	815	20
30.0	22.0	20.0	20.00	829	20
40.0	23.2	20.0	20.00	838	20

Vita

Daniel Saenz was born in Ciudad Juarez, Mexico in 1988, the third son of Eduardo Saenz Cardenas and Julieta Palmira Flores de Saenz. In the fall of 2011, he earned his Bachelor of Science in Civil Engineering degree at the University of Texas at El Paso (UTEP). In the spring of 2012, he joined the Civil Engineering Master's Program at UTEP. While partaking his undergraduate and graduate studies, he became involved in pavement management related research under the supervision of Dr. Carlos M. Chang. The research included project 0-6673 "Improvement in Pavement Ride, Distress and Condition Based on Different Treatment Types" for the Texas Department of Transportation and the calibration of contractor performance monitoring equipment.

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