Pavement Performance Curves: Modeling Pavement Deterioration for SCDOT

FINAL REPORT

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16. Abstract

The current SCDOT pavement performance models were formulated in 1989 by PMS Inc. (now known as Stantec) with assistance from SCDOT personnel, and they were based on engineering experience of pavement performance in South Carolina. Since their initial development, the parameters of the adopted sigmoidal, or S-shaped, function have not been updated. The purpose of this project was to evaluate the performance of these models using post 2000 pavement roughness and distress data collected by the SCDOT, and if they no longer reflect the pavement degradation behavior due to changes in materials and construction practices, determine the new parameter values that should be used. The model evaluation focused on the top five maintenance activities performed on interstates and the top five activities performed on primary routes in the last ten years in South Carolina. With different pavement types on the interstates and a separate model for pavement serviceability index (PSI) and pavement distress index (PDI), a total of 14 interstate models were evaluated using pavement roughness and distress data collected from 2000 to 2020 on 117 road sections that span 953 lane-miles. The SCDOT's maintenance records were supplemented with a search of paper records to determine the year in which a maintenance treatment was applied. All 14 interstate models were recommended to have their parameters updated based on the criterion that they yield at least 5% relative improvement. The average improvement in prediction accuracy of the recommended parameters compared to the current ones for the interstate models using the metric Mean Absolute Percentage Error (MAPE) is 46%. For primary routes, consisting of only asphalt pavements, a total of ten models (five for PSI and five for PDI) were evaluated using data from 294 road sections that span 1,116 lane-miles. As was the case with interstate models, all ten primary route models were recommended to have their parameters updated, with an average relative improvement of 58%.

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EXECUTIVE SUMMARY

The objectives of this research project were to: 1) validate and, if necessary, update the South Carolina Department of Transportation (SCDOT) existing PSI and PDI prediction models for new construction, existing pavements, and treatment types most frequently utilized by the SCDOT to preserve or rehabilitate pavements on the interstates and primary routes, and 2) supplement the Highway Pavement Maintenance Application (HMPA) with a search of paper records to determine when and what preservation or rehabilitation treatments were applied to the pavements.

Findings from the literature review indicated that the deterministic method is the most commonly used approach by State Departments of Transportation (DOTs) to predict pavement performance. The response variables of deterministic models developed and used by most DOTs include pavement roughness progression, pavement distress progression, pavement crack progression, ride quality, crack severity, wheel path cracking, and pavement condition index/rating. The explanatory variables of these models include pavement structural number (SN), annual average daily traffic (AADT), equivalent single axle load (ESAL), pavement age, pavement layer thickness, frost penetration gradient, slab length, cracking, rutting roughness, distress state, patching index, pavement type, and rehabilitation treatment type. The SCDOT's practice is similar to other DOTs in that it uses a deterministic, sigmoidal function to predict roughness progression (PSI) and distress progression (PDI). Unlike some other DOTs, the SCDOT's PSI and PDI models have only pavement age as their explanatory variable.

An online survey was conducted to understand the state-of-the-practice on the use of collected pavement data to predict pavement performance indices. A total of 14 DOTs responded to the online survey. Nine agencies indicated that they use the deterministic method, two use the probabilistic method, one uses the subjective method, two use a combination of deterministic and probabilistic methods, and one uses a combination of probabilistic and subjective methods. The top three characteristics used by these agencies to group their pavement performance models are: pavement type (13 agencies), highway system (8 agencies), and treatment type (seven agencies). The SCDOT's practice is similar to the majority of other DOTs in that it has a different pavement performance model for each combination of treatment type and pavement type. Unlike other DOTs, the SCDOT does not have a different model for each type of highway system. Rather, it has a different rehabilitation trigger value for different functional classes.

Due to the need to have a different model for each combination of treatment type, pavement type, and highway system, there are hundreds of unique models. However, only a small subset of these models is used. This project focused on evaluating those models that are associated with the top five maintenance activities performed on the interstates and the top five activities performed on primary routes in the last ten years in South Carolina. Given that there are four types of pavements on the interstates and there is a separate model for PSI and PDI, a total of 14 interstate models were evaluated using pavement roughness and distress data collected from 2000 to 2020 on 117 road sections that span 953 lane-miles. For primary routes, consisting of only asphalt pavements, a total of ten models (five for PSI and five for PDI) were evaluated using pavement roughness and distress data collected from 294 road sections that span 1,116 lane-miles.

An essential element of this project was the determination of the year and the type of treatment applied to a pavement. To this end, a search of paper records was conducted for each selected road section. The "start" year of a treatment was determined using a decision flowchart that weighs the agreement between paper records, HPMA, and trends in the PSI and PDI data provided by the SCDOT, with paper records deemed to have the highest fidelity, followed by observations in the data, and lastly, the date recorded in HPMA. The model evaluation process involved plotting the PSI and PDI data for each of the road sections by year (i.e., pavement age) for each activity/treatment type and applying the current SCDOT models and parameters to assess the goodness of fit using the metric Mean Absolute Percentage Error (MAPE). Nearly all of the current interstate and primary route models evaluated yielded MAPE values greater than 10%, which indicates that they do not have a very good fit. Hence, the optimal parameter values were determined for all interstate and primary route models. Three different approaches were taken to determine the optimal parameter values. The first was to use a translated SCDOT model which retained the *a*, *b*, *c* parameter values from the current SCDOT model but have the *O* (initial PSI value) parameter estimated from data. The second approach was to determine the values of *a*, *b*, *c*, and *O* parameters with minimal constraints on their bounds that gave the lowest sum of squared errors (referred to as optimized model 1 hereafter). To overcome the issue of optimized model 1 providing unrealistic remaining service life, the third approach used was to constrain the parameters such that the predicted remaining service life was not greater than 30 years. Among these three approaches/models, the one that yielded the lowest MAPE was the recommended one.

All 14 interstate models were recommended to have their parameters updated based on the criterion that they yield at least 5% relative improvement. The average improvement in prediction accuracy using the recommended models and parameters compared to the current ones for the interstate models is 46%. Similarly, for primary routes, all ten models were recommended to have their parameters updated. Using the recommended parameters yielded an average relative improvement of 58%. The calibrated models were then validated using a new set of data, not previously used to train the models. Nine out of 14 recommended interstate models yielded the same or lower Mean Square Error (MSE) for the test data compared to the training data which indicates that they were not overfitted to the training data. For primary routes, nine out of the ten recommended models have a higher MSE for the test data compared to the training data. However, their differences (except for one) are relatively small which suggests that the primary route models were not overfitted.

From the findings in this project, it is recommended that the SCDOT consider updating the parameters of the 14 interstate models and 10 primary route models shown above. Overall, the recommended PSI and PDI model parameters show a slower degradation rate compared to the current values for the first 10 years after receiving treatment. Therefore, adopting the recommended parameter values will enable the SCDOT to better identify those pavement candidates that are truly in need of repair and avoid making repairs to those that still have sufficient remaining service life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

The Federal Highway Administration defines pavement preservation as a long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations (FHWA, 2005). An integral element of the pavement preservation program is the pavement performance models which are used by state Departments of Transportation (DOTs) to predict future conditions of pavements. Specifically, they are used to identify sections of roadways that need to be rehabilitated. Also, pavement performance models are used to estimate and rationally allocate budget at the network level (Meegoda and Shengyan, 2014), evaluate the effectiveness of various rehabilitation treatments, and perform cost and benefit analyses (Chang et al., 2001).

The South Carolina Department of Transportation (SCDOT) pavement management system (PMS) relies on pavement performance models to estimate future pavement conditions. Their prediction accuracy is critical to the SCDOT in optimizing the scheduling of maintenance activities and budgeting for these activities to achieve a predetermined level of performance. The pavement performance models being used by the SCDOT were formulated in 1989 by PMS Inc. (now known as Stantec) with assistance from SCDOT personnel, and they were based on engineering experience of pavement performance in South Carolina. Since their initial development, the parameters of the adopted sigmoidal, or S-shaped, function have not been updated. The original model parameters may no longer reflect current pavement degradation trends due to changes in materials, construction practices, and traffic loads, as well as changes in the technology being used to collect pavement roughness and distress data. The purpose of this project is to evaluate the performance of these models using post 2000 pavement roughness and distress data collected by the SCDOT.

The fundamental form of the SCDOT's pavement serviceability index (PSI) and pavement distress index (PDI) prediction models is a sigmoidal, or S-shaped, function. The PSI model is shown in Equation 1.1. The PDI model has the exact same form.

$$PSI = O - e^{\left(a - b \times c^{t}\right)} \tag{1.1}$$

Presently, the values of *a*, *b*, *c,* and *O* parameters are predefined for each type of index (PSI or PDI), type of pavement (bituminous, concrete, continuously reinforced concrete, bituminous over concrete) and type of treatment (e.g., new construction, mill-and-replace two inches plus two-inch overlay). The scope of this project entails updating the parameter values using post 2000 roughness and distress data collected by the SCDOT without changing the model form and without considering other factors such as environment, traffic, pavement SN, and subgrade.

The specific objectives of this research project are to: 1) validate and, if necessary, update the SCDOT existing PSI and PDI prediction models for new construction, existing pavements, and treatment types most frequently utilized by the SCDOT to preserve or rehabilitate pavements on the interstates and primary routes, and 2) supplement the Highway Pavement Maintenance Application (HMPA) with a search of paper records to determine when and what preservation or rehabilitation treatments were applied to the pavements.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

From the onset of the project, the SCDOT indicated that the functional form of the PSI and PDI models will need to remain the same and only their parameters should be evaluated, and if necessary, updated. This is in part due to the lack of capability within HPMA to change the functional form of the pavement performance models, and in part due to the SCDOT's plan to change to a new asset management system in the future. The literature review conducted as part of this project covered all methods, but only the deterministic approach is discussed below since it is the one that the SCDOT currently uses and will most likely continue to use in the future as it transitions to a new asset management system. Most state agencies use deterministic pavement prediction models as shown in Table 2-1 due to its simplicity in model estimation and application. The aim of the following review is to highlight the explanatory variables/factors being used by other agencies in their deterministic models to illustrate how including other variables in addition to pavement age may improve the accuracy of the SCDOT models.

Table 2-1. Types of pavement prediction models being used by state agencies (source: FHWA, 2018)

Model type	Percent of responses*
Deterministic	74.1
Markov	12.0
Bayesian	0
Subjective (expert)	18.9
Not applicable	12.0

* a respondent can select more than one options

2.2 Pavement performance prediction using deterministic approach

Shahin et al. (1987) evaluated the applicability of three mathematical curve-fitting techniques for modeling pavement condition deterioration behavior: stepwise regression, B-spline approximation and constrained least-squares estimation. The technique they found to work best in modeling the relationship between pavement condition index (PCI) and age of a pavement was constrained least-squares estimation. The key idea of their estimation scheme is to keep the slope of the curve at any age negative or zero. Their deterioration model is a polynomial function of the form: $P(x) = \alpha_0 + \alpha_1 x + \alpha_2 x^2 + \ldots + \alpha_n x^n$ where x is age of the treated pavement.

George et al. (1989) conducted a study for the Mississippi Department of Transportation to develop pavement condition rating models for three types of asphalt pavements: pavements with no overlay, pavements with overlay, and composite pavements. The model for pavements with no overlay has the form: $PCR(t) = 90 - a\left[\exp\left(Age^b\right) - 1\right]\log\left[\frac{ESAL}{SNC^c}\right]$ where $PCR(t)$ is the pavement condition rating at time t, SNC is the modified structural number, a, b, and c are model parameters. Using data collected from 2,000 lane-miles of roads in northern Mississippi over a period of two years, the model parameters were found to be: a = 0.6349, b = 0.4203, and c = 2.7062. These values yielded a model R^2 of 0.75. In analyzing the results from all three models, the authors concluded that age is by far the most significant predictor of serviceability. AADT, ESALs, and the structural makeup of the pavement play only a secondary role in forecasting performance of pavements.

Chan et al. (1997) conducted a study for North Carolina DOT (NCDOT) to develop a model that could be used to predict pavement performance, specifically, Pavement condition rating (PCR). Their original intent was to develop a family of performance curves for roads categorized by pavement structure, date of last improvement, and traffic volume. However, the lack of data in key areas, forced them to change course and develop a performance model on individual sections. Their model has the form: $PCR = C_0 + C_1 \cdot Age^{C_2}$ where C_0, C_1, and C_2 are constants. C_0 determines the highest point of the flat portion of the curve, and the combination of C_1 and C_2 determines the rate of decline of the ratings, with C_2 playing a bigger role.

Gulen et al. (2001) conducted a study for Indiana DOT (INDOT) to develop simple pavement performance prediction models with the least number of explanatory (independent) variables required to predict the performance of various pavement types for future planning of rehabilitation or replacement. The authors used INDOT data collected in 1999 and 2000 to develop regression models for two pavement types, jointed concrete pavement and bituminous pavement, and for interstate and non-interstate roads. The response variable of their regression models is International Roughness Index (IRI), in inches per mile, and the explanatory variables consist of the age of pavement and current average annual daily traffic (AADT). The R^2 values of their regression models range from 0.27 to 0.9.

Abaza (2004) sought to develop a deterministic performance prediction model for use in rehabilitation and management of flexible pavements. His performance curve for a particular pavement section was estimated using an incremental analysis of the American Association of State Highway and Transportation Officials (AASHTO) basic design equation used in the design of flexible pavements. The outcome of the developed prediction model was the generation of a unique performance curve for a given pavement structure. An example curve presented has the form $PSI(t) = 4.4993 - 0.1246t$ where t is age of the treated pavement; this model was found to have an R^2 value of 0.9999.

Isa et al. (2005) conducted a study for the Malaysian Public Works Department (MPWD) to develop pavement performance models for their flexible pavement road network. Using data collected by MPWD, the authors developed and evaluated four regression models with the dependent variable being rut depth in millimeter. Among the four models, Model #4 was deemed best for its inclusion of expected variables and constant value. This particular model has log of rut depth as the dependent variable and roughness, AADT, and SN as explanatory variables. The R^2 value of this model is 0.723.

Jain et al. (2005) calibrated pavement deterioration models for a National Highway Network located in the Uttar Pradesh and Uttaranchal states of India. The authors selected eight pavement sections which did not have any kind of maintenance work performed on them for the entire 2002. The pavement condition data on these sections were collected at the beginning of 2002 and again by the end of 2002 using the same type of equipment and method. Using the collected data, they calibrated four distress progression models: cracking progression, raveling progression; pothole progression, and roughness progression. The explanatory variables of their roughness progression model include roughness at start of analysis (m/km IRI), age (since last overlay or reconstruction), adjusted structural number due to cracking at the end of the analysis year, annual number of equivalent standard axles (millions/lane), incremental change in area of total cracking during analysis year (percent), incremental change in standard deviation of rut depth during analysis year (mm), freedom to maneuver index based on lane width (in meter and AADT), number of potholes per km at start of analysis year, incremental change in number of potholes per km during analysis year, and time lapse factor depending upon frequency of pothole patching (default value = 1.0). The R^2 value obtained for the roughness progression model is 0.97 which indicates very good agreement between observed and predicted values.

Kim and Kim (2006) conducted a study for the Georgia Department of Transportation (GDOT) to develop a set of asphalt pavement performance prediction models for flexible pavement in the state of Georgia. The authors developed three regression models using Pavement Condition Evaluation System (PACES) data from each GDOT district. Model A included only one explanatory variable: service year. Model B included two variables: service year and interaction of service year and AADT. Model C included three variables: service year, AADT, and interaction of service year and AADT. The R^2 of Model A is between 0.58 to 0.73 for the seven districts evaluated, Model B is between 0.59 and 0.75, and Model C is between 0.59 and 0.76. The authors concluded that all three models are effective when PACES Rating is above 70 with the pavement losing about 2.5 to 3 points per year which means that pavement rehabilitation is required every 6 to 8 years.

Luo and Chou (2006) proposed the use of clusterwise regression. Unlike the traditional regression method, in which data are fitted to one curve, the clusterwise regression method fits the data to more than one curve. This technique was applied to a pavement condition rating (PCR) deterioration function with the pavement age as the explanatory variable. The functional form they chose for the PCR model is the sigmoidal, S-shape, function, identical to that of the SCDOT's PSI and PDI models. Using data from Ohio Department of Transportation's Pavement Management Information System, they found that the traditional regression method yielded an R^2 of 0.55, whereas the R^2 of the three-cluster model was 0.89. It should be noted that the clusterwise regression model is actually a nonlinear optimization problem. The difficulty in solving the model increases as the number of unknowns involved is increased.

Sadeghi and Fathali (2007) sought to understand the influence of overloading on the operational life of flexible pavements by developing a deterioration model for pavement and a ticketing formulation for overweight vehicles. Their proposed deterioration model has the form $F = C_1C_2C_3C_4 f(P)$ where F is the operational life reduction factor for a flexible pavement when an axle with excess load of ΔP is applied, $f(P)$ is the deterioration formula for a pavements with C_1, C_2, C_3, and C_4 being coefficients which are functions of asphalt layer thickness, pavements temperature, subgrade CBR, and vehicle speed, respectively. The authors found that the revenue collected from fines by the road authorities is inadequate compensation for the pavement damages predicted by the model, particularly if the magnitude of the excess load is more than 20% of the allowable loads.

Prozzi and Hong (2008) proposed a flexible and statistically rigorous methodology for the simultaneous estimation of transportation infrastructure deterioration models. They proposed a deterioration model of the form $p_t = a + bN_t^c + \mu_t$ where p_t is the pavement performance at time t, N_t is some measure of traffic until time t, a is a parameter representing initial performance; b is a parameter representing the deterioration rate, c is a parameter representing the curvature; and μ_t is the error term. To ensure the parameter *b* is positive, they proposed an exponential form for the deterioration rate, which include factors such as asphalt binder type, Marshall asphalt mix design, thickness of surface layer, thickness of base layer, and thickness of subbase layer. The observed versus fitted roughness data were found to be in good agreement.

Tsai et al. (2012) conducted a study for the Georgia Department of Transportation to enhance its life-cycle cost analysis (LCCA) in pavement design which require knowing how long the pavements will last. The authors used the Gompertz growth curve to model the probability of pavements being rehabilitated as a function of pavement age. The survival curve of a pavement is then computed by subtracting the Gompertz Growth Curve from 100% as follows: $survival = 100\% - A \times \exp\left[-\exp\left(\frac{\mu \times \exp(1)}{A}(\lambda - t) + 1\right)\right] \times 100$ where t is the pavement age in years, A is the maximum of the growth curve, μ is the maximum slope of the growth curve, and λ is the lag phase, which indicates how long the growth curve remained at 0%. Using this model, pavement service life based on data collected from the 839 surveyed miles of interstates was found to vary from 10 to 29 years.

Xu et al. (2014) conducted a study for the Kentucky Transportation Cabinet (KTC) to develop pavement prediction models using linear regression and artificial neural networks (ANN). The dependent variable of their regression model is the extent (or severity) of wheel path cracking for next year and the explanatory variables include nine cracking index variables, pavement age, average daily traffic (ADT) and international roughness index (IRI). The authors evaluated eight different regression functions, with some being linear and some polynomial. Using data collected by KTC on 5,146 road segments over 11 years, the authors estimated the parameters of the developed models. It was found the best regression model has a linear form with age, extent of wheel path cracking and severity of wheel path cracking as explanatory variables. This model has an R^2 of 0.877 and its average squared error is comparable to that of the ANN model. For this reason, the authors recommended that KTC adopt the regression model in its practice.

Rahman et al. (2017) developed pavement performance models for Asphalt Concrete (AC) pavements and Jointed Plain Concrete Pavements (JPCP) using data from primary routes and interstates in South Carolina. For AC and JPCP pavements, four different regression models were developed with the dependent variable being PSI, PDI, IRI, and Pavement Quality Index (PQI). The explanatory variables considered in all models include AADT, Free Flow Speed (FFS), precipitation, temperature, and soil type (soil Type A from Blue Ridge and Piedmont Region, and soil Type B from Coastal Plain and Sediment Region). Estimated results indicated that AADT, FFS, and precipitation have statistically significant effects on PSI and IRI for both JPCP and AC pavements. Temperature showed significant effect only on PDI and PQI for AC pavements. Type B soil has a greater effect on PDI and PQI compared to Type A soil on AC pavements; whereas Type B soil has a greater effect on IRI and PSI compared to Type A soil on JPCP pavements.

2.3 State DOTs Survey

As part of this study, an online survey was conducted to understand how other state agencies are using the collected pavement data to predict pavement condition. The survey was distributed to other state DOTs on June 1, 2019, and a response was requested by June 30, 2019. A total of 14 state DOTs responded to the survey. The following summary first lists the questions in *italics* followed by a summary of the responses.

1. *What pavement management software is your agency currently using?*

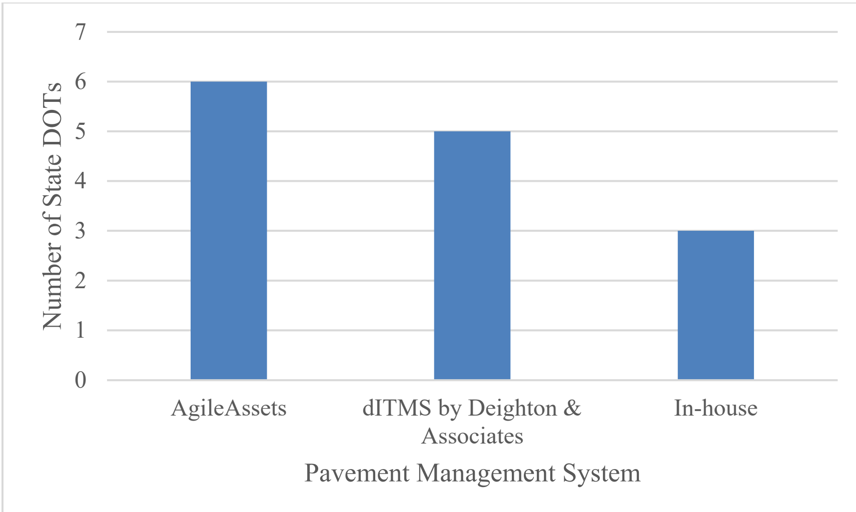

Figure 2-1. Pavement management system used by state agencies

As shown in Figure 2-1, AgileAsset is used by six agencies and dITMS is used by five agencies. The remaining three use an in-house PMS.

2. *Who collects pavement roughness and distress data for your agency?*

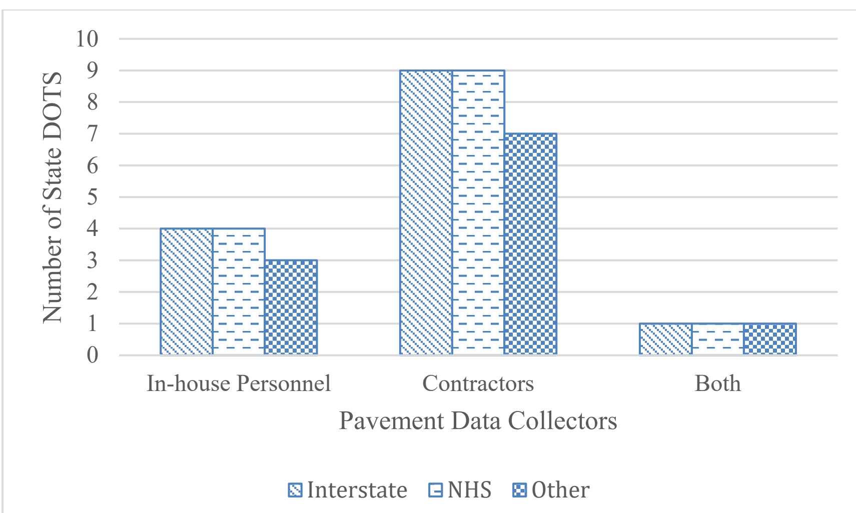

Figure 2-2. Party responsible for collecting pavement data

As shown in Figure 2-2, nine agencies indicated that they outsource the pavement data collection on interstates and NHS to contractors, four agencies use in-house personnel, and one agency uses both. For "Other" road type that is lower in functional classification than interstates and NHS, seven agencies use contractors, three use in-house staff, and one uses both. These responses indicate that three agencies do not collect pavement data for lower functional class roads.

3. *What type of mathematical model does your agency use to predict pavement performance indices (such as pavement serviceability index or pavement distress index)?*

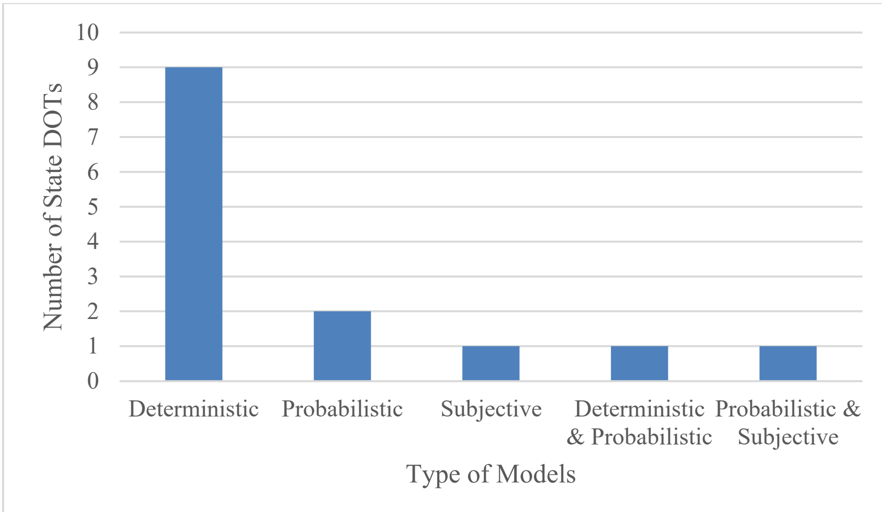

Figure 2-3. Type of models used by State DOTs for predicting pavement condition

As shown in Figure 2-3, the majority of state agencies use the deterministic approach. Examples of deterministic approach include regression and the sigmoidal function that the SCDOT currently uses. Two agencies indicated that they use a probabilistic approach, one uses a subjective (expert) approach, one uses a combination of deterministic and probabilistic, and one uses a combination of probabilistic and subjective.

4. *What characteristics are used to group pavement performance models into "families"?*

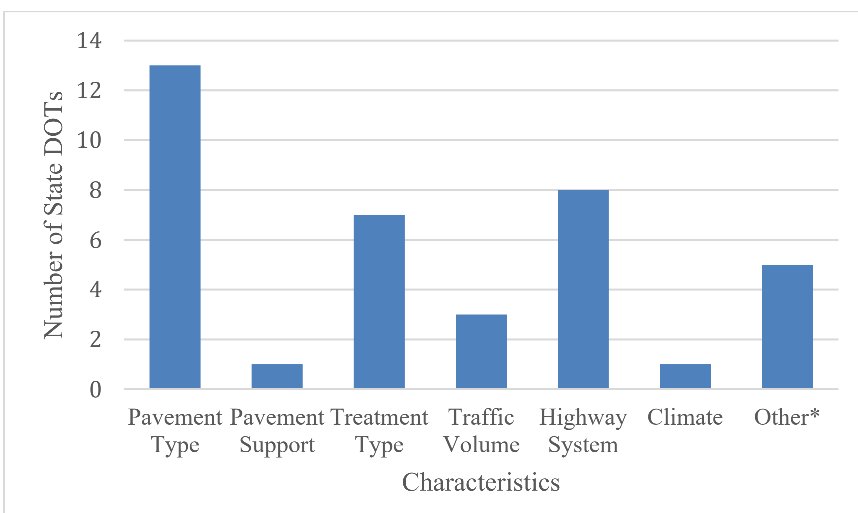

Figure 2-4. Characteristics used by State DOTs to group their pavement performance models

As shown in Figure 2-4, the top three characteristics used by these agencies to group their pavement performance models are pavement type (13 agencies), highway system (eight agencies), and treatment type (seven agencies). Pavement support (one agency), traffic volume (three agencies), and climate (one agency) are also used. Several agencies indicated that they also group their models based on truck level, functional class, 2-lane system by truck weight, condition prior to last work, and district. These findings indicate that the SCDOT's practice is similar to the majority of other DOTs in that it has a different pavement performance model for each combination of treatment type and pavement type. Unlike other DOTs, the SCDOT does not have a different model for each type of highway system. Rather, it has a different rehabilitation trigger value for different functional classes.

5. *Is your agency updating pavement performance models using high resolution 3D pavement data?*

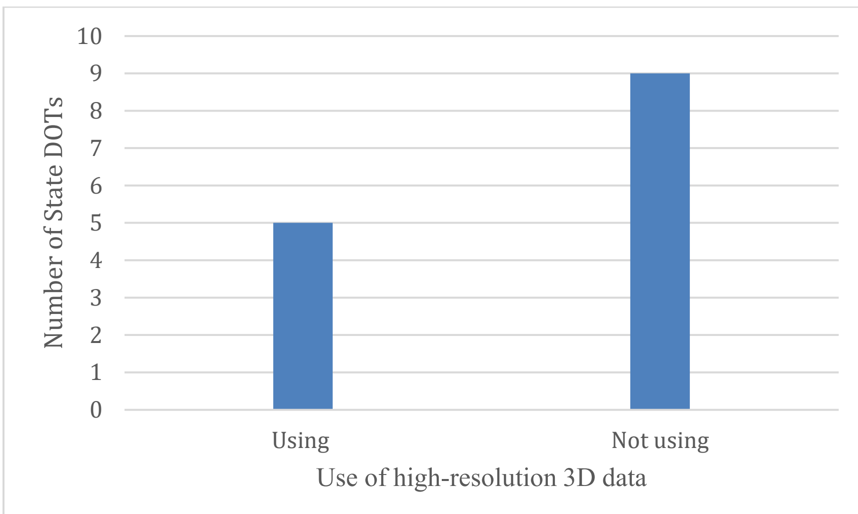

Figure 2-5. Use of High-Resolution 3D pavement data to update performance models

The SCDOT procured two vehicles equipped with Laser Crack Measurement System (LCMS) at the start of this project. The aim of this question was intended to understand how many agencies make use of such data in their pavement performance models. As shown in Figure 2-5, the majority (nine agencies) do not. About a third of the respondents do use high-resolution data. Thus, the SCDOT should investigate the use of such data in the future given the ability to implement regression type of models in the new asset management system.

6. *Is your agency updating pavement performance models using traffic speed deflectometer (TSD) data?*

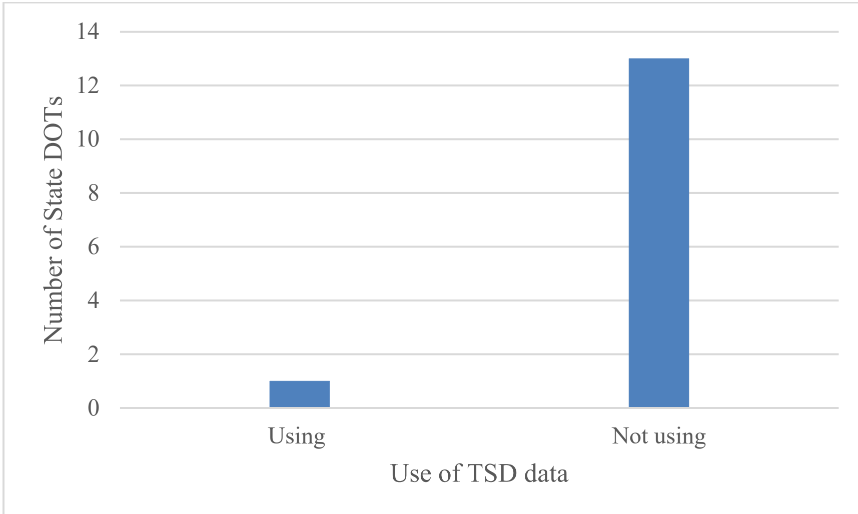

Figure 2-6. Use of TSD data to update pavement performance models

The SCDOT is among the first agencies in the U.S. to investigate the use of TSD data to better identify candidates for preservation or rehabilitation. The aim of this question was intended to understand how many agencies make use of such data in their pavement performance models. As shown in Figure 2-6, the majority (13 agencies) do not. With one agency using TSD data and one agency grouping their performance models by pavement support type (Figure 2-4), it suggests that there is opportunity to improve upon current practice with the use of TSD data that the SCDOT intends to collect in the future.

7. *Is your agency planning to update pavement performance models using high resolution 3D pavement data?*

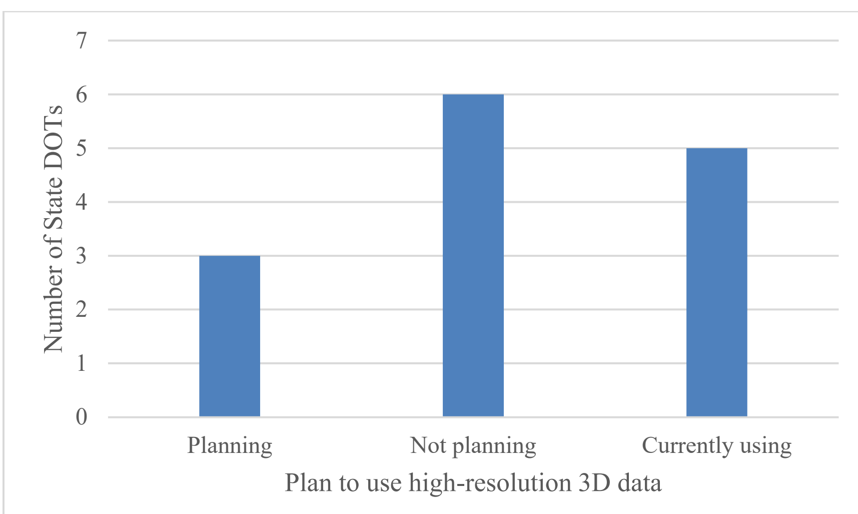

Figure 2-7. Plan to use high-resolution 3D pavement data to update performance models

As shown in Figure 2-7, among the nine agencies that are not currently using high-resolution 3D data to update their performance models, three indicated that they plan to use them in the future while six indicated that they do not plan to.

8. *Is your agency planning to update pavement performance models using traffic speed deflectometer (TSD) data?*

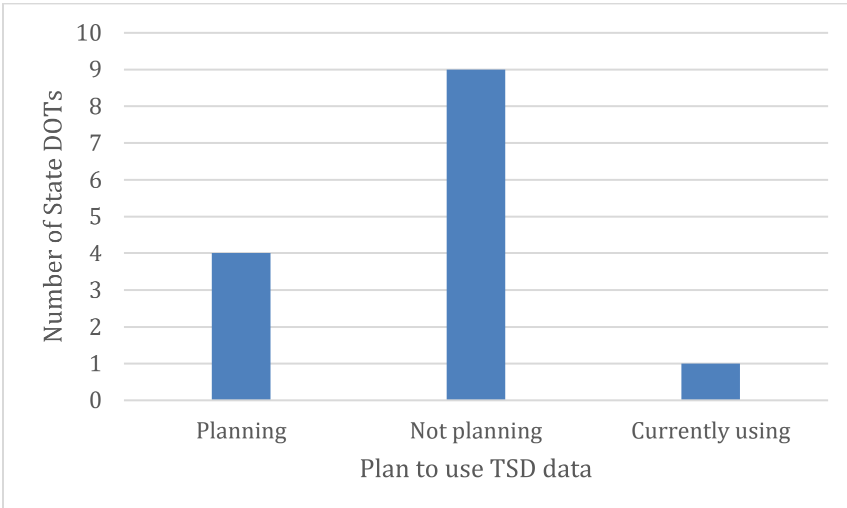

Figure 2-8. Plan to use TSD data to update performance models

As shown in Figure 2-8, among the 13 agencies that are not currently using TSD data, four indicated that they plan to in the future while nine indicated that they do not plan to.

9. *Is your agency willing to share pavement performance data to assist the South Carolina Department of Transportation in updating its pavement performance models?*

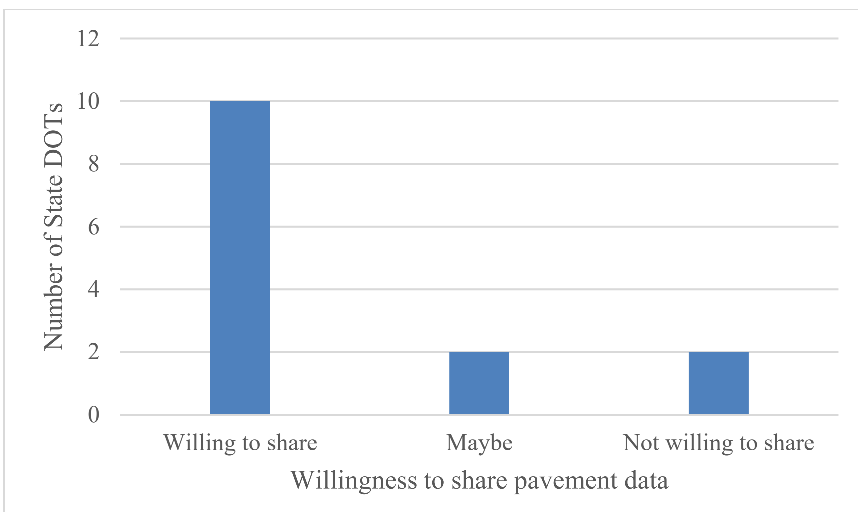

Figure 2-9. Willingness to share pavement data with SCDOT

The aim of this question was to gauge the willingness of other agencies to share their pavement data with the SCDOT, which in the absence of sufficient data for model evaluation, would be needed from environmentally similar regions outside of South Carolina. As shown in Figure 2-9, ten agencies indicated that they were willing to do so, with two indicating “may be,” and two indicating that they will not be able to share. During the course of this project, it was decided jointly with the PSIC that external data was not needed for the following reasons: 1) for each of the 14 interstate models and for each of the 10 primary route models, there was a sufficient sample size for model estimation; 2) the method used by nearby agencies (NCDOT, GDOT, and TDOT) to rate individual distresses may be different from that of the SCDOT which would lead to very different PDI values; 3) other agencies may have different pavement design methods and construction practices which may result in different pavement degradation behavior; and 4) all else being similar, roads in other states may be subject to different AADTs and ESALs than those in South Carolina which may lead to different remaining service life for pavements.

CHAPTER 3: METHODOLOGY

3.1 Introduction

To evaluate the pavement serviceability index (PSI) and pavement distress index (PDI) models and parameters, their predicted values are compared against measured data for the applicable treatment type and pavement type. The difference is quantified using the metric Mean Absolute Percentage Error (MAPE); a low MAPE value suggests a good fit whereas a high MAPE value suggests a poor fit. The data points used for the assessment consist of average PSI or PDI of all 0.1-mile PSI or PDI values over the entire pavement section. Each data point has an "age" associated with it, where "age" is the number of years since the section was last repaired. The year and the type of treatment applied to a selected pavement section are determined using a combination of information available in HPMA, paper records, and trends in measured data. To determine the optimal parameter values for each model, MATLAB's built-in curve fitting function and constrained optimization function are used. The robustness of these parameters is validated using a new data set and the mean squared error is used to determine if the model has been overfitted to the training data.

3.2 PSI and PDI data

The SCDOT collects PSI and PDI data annually for the interstate system, every two years for federal aid roadways, every three years for non-federal aid roadways and those that have AADT > 400, and every six years for roadways with AADT < 400. These data, dating back to 2000, were used for model evaluation and validation. The PSI and PDI data that were calculated from measured pavement condition data were available at every 0.1 mile along a pavement section. Information provided for each section include County ID, route type (interstate, US route, or SC route), route number, direction, beginning mile point, ending mile point, pavement type (bituminous, bituminous over concrete, concrete, or continuously reinforced concrete), rehabilitation activity, rehabilitation year, maintenance activity, and maintenance year.

3.3 Selection of activities and associated models for evaluation

In HPMA, 142 different pavement maintenance activities are listed, with each having an associated deterioration model and unique parameter values. Many of these activities are not routinely applied by the SCDOT. Given the need to search paper records for each road section, it was determined jointly with the PSIC that the model evaluation should focus on the top five activities most frequently applied to interstates and the top five activities most frequently applied to primary routes in the last 10 years. The top five activities performed on interstates based on count and lane-miles are shown in Table 3-1.

Table 3-1. Top five maintenance activities on interstates in South Carolina

Interstate maintenance activity	Pavement type	Lane-miles	Number of road sections
MR 2-4"+OL 200 PSY	BIT	98.68	15
	BOC	103.68	15
MR 1-2"+OL 400 PSY	BIT	154.73	16
	BOC	137.21	16
General Rehab CON	CON	227.36	24

Interstate maintenance activity	Pavement type	Lane-miles	Number of road sections
General Rehab CRC	CRC	138.63	20
Original Construction	CON	92.48	11
	Total	952.77	117

The mill-and-replace plus 200 pounds per square yard (PSY) overlay (MR 2-4"+OL 200 PSY) treatment is applied to both asphalt (BIT) and asphalt over concrete (BOC) pavements. Similarly, the MR 1-2"+OL 400 PSY treatment is applied to both BIT and BOC pavements. The General Rehab CON treatment is applied to only concrete (CON) pavements, and the General Rehab CRC treatment is applied to only continuously reinforced concrete (CRC) pavements. Original Construction is applied to both CON and BIT pavements. However, for interstates, it is most frequently applied to CON pavements. It can be seen in Table 3-1 that there are seven combinations of treatment type and pavement type. For each combination, there is a separate PSI and PDI model. Thus, there is a total of 14 models for interstates. The locations where these treatments were applied in the last ten years in South Carolina are shown in Figure 3-1. The measured PSI and PDI data, between 2000 to 2020, from 117 pavement sections spanning 953 lane-miles were used to evaluate the respective interstate models. Note that the selected locations cover all interstates in South Carolina, and they are spatially distributed throughout the state.

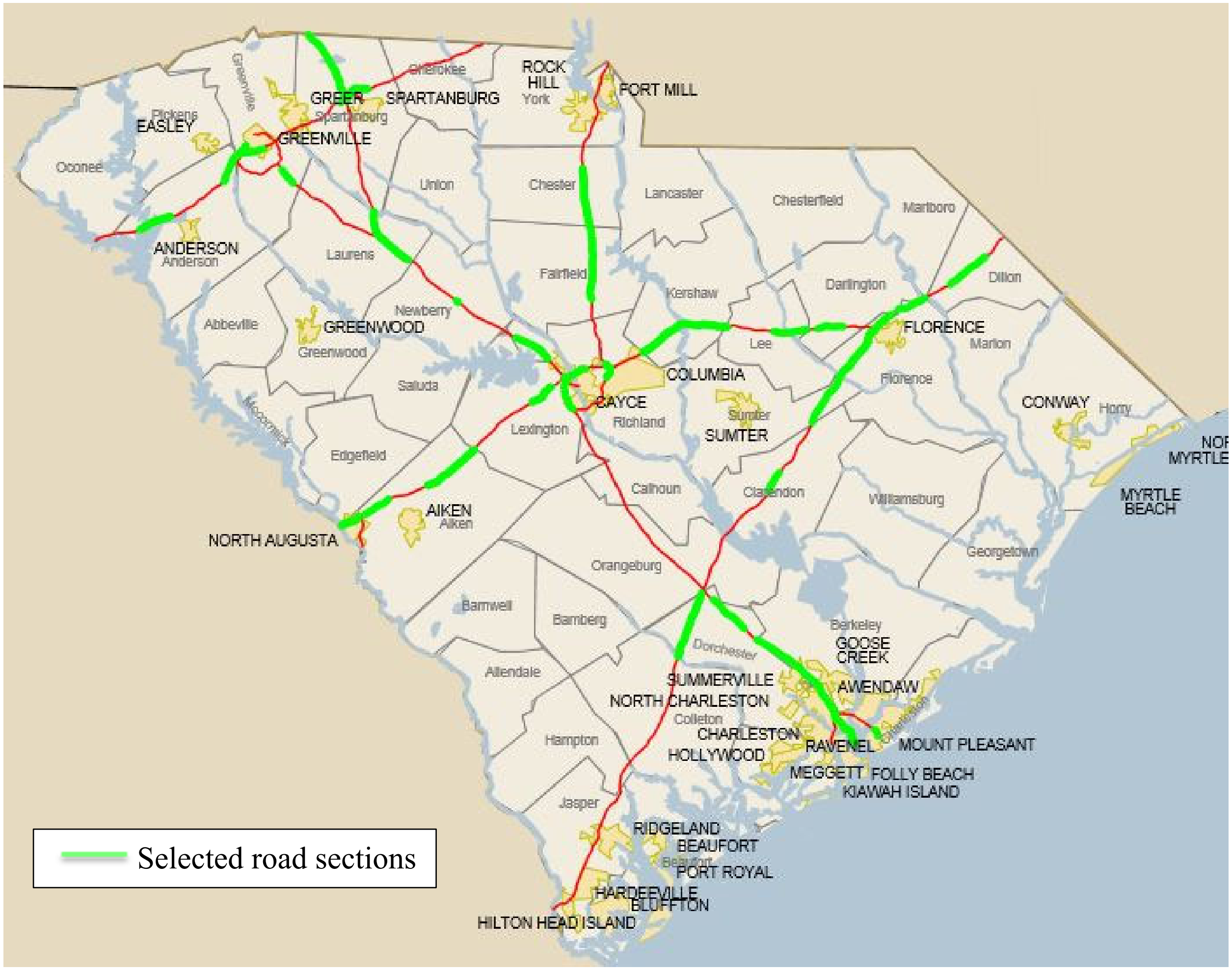

Figure 3-1. Locations of interstate sections with top five maintenance activities (source: SCDOT ITMS)

The top five activities performed on primary routes based on count and lane-miles are shown in Table 3-2. In South Carolina, most primary routes are constructed with asphalt pavements. For each of the five different treatments, there is a separate PSI and PDI model. Thus, there is a total of 10 models for primary routes. The locations where these treatments were applied in the last ten years in South Carolina are shown in Figure 3-2. The measured PSI and PDI data, between 2000 to 2020, from 294 pavement sections spanning 1,116 lane-miles were used to evaluate the respective primary route models. Note that the selected locations are spatially distributed throughout the state.

Table 3-2. Top five maintenance activities on primary routes in South Carolina

Primary route maintenance activity	Pavement type	Lane mile	Number of road sections
MR 1-2"	BIT	112.693	37
MR 1-2"+OL 200 PSY	BIT	124.7	40
Crack Seal	BIT	393.33	64
OL>100<200 PSY	BIT	210.697	68

Microsurfacing	BIT	274.2	85
	Total	1115.62	294

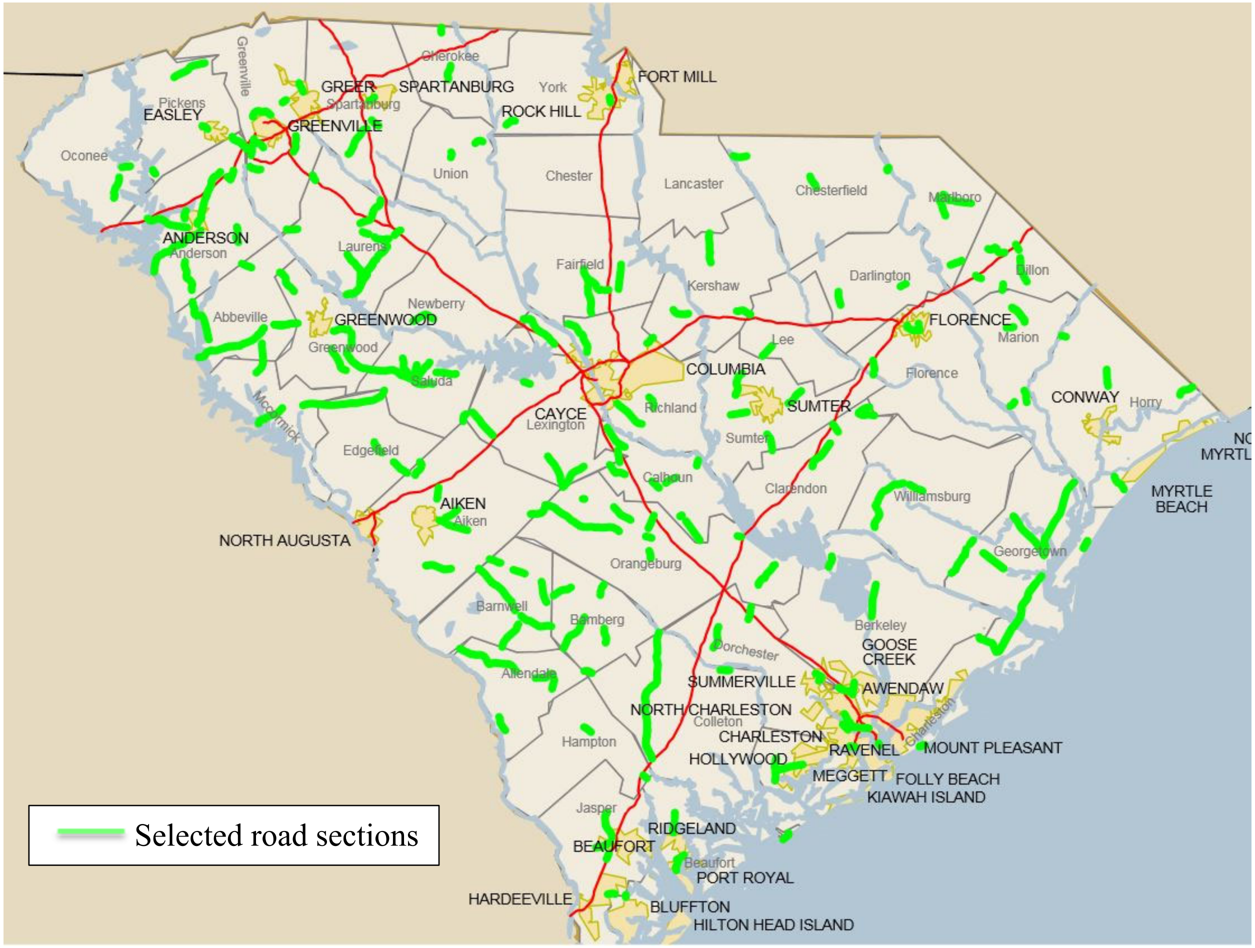

Figure 3-2. Location of sections with top five primary route activities (source: SCDOT ITMS)

3.4 Determination of pavement age

When a pavement section receives a rehabilitation treatment, the "age" of that pavement associated with that particular treatment is considered to be zero. If PSI and PDI data are collected on that section two years later, then the "age" of the pavement is two years. The decline of the measured PSI and PDI represent the deterioration of the pavement over that period. The essence of this project is to assess how well the current models and parameters capture the pavement degradation trend for each type of pavement and activity/treatment. Thus, it is necessary that the age of the selected pavement section is correctly identified.

This project utilized three sources of information to determine the age of the treated pavement, specifically, the completion date of the treatment. The first source is HPMA. The maintenance activities and dates are provided by the Director of Maintenance Office and these data are manually entered in HPMA by Pavement Management staff. The provided data have completeness issues resulting in gaps/errors, especially prior to 2013. For this reason, the PSIC indicated that it is necessary to search paper records to verify and to supplement activity and dates recorded in

HPMA. Hence, the second source of information used to determine age of treated pavement is paper records which were made available on ProjectWise. The PSIC Chair provided training to research assistants tasked with finding relevant information. Figure 3-3 shows a sample posting advice with relevant information identified. This particular task is laborious due to the need to review one PDF document at a time. The third source of information used to determine pavement age is the PSI and PDI data themselves. Given that their values are expected to get lower over time, a significant increase in value followed by higher values relative to prior years suggest that a preservation or rehabilitation treatment has been applied.

The age of the treated pavement was determined using the decision flowchart shown in Figure 3-4 that weighs the agreement between paper records, HPMA, and trends in the PSI and PDI data, with paper records deemed to have the highest fidelity, followed by observations in the data, and lastly, the date recorded in HPMA. Which source to use depends on the answers to the following questions:

1. Is the HPMA rehabilitation year the same as paper records rehabilitation year? If yes, go to question 2A; otherwise, go to question 2B.

2A. Do PSI or PDI support the rehabilitation year indicated by paper records? If yes, use paper records rehabilitation year and mile points; otherwise, go to question 3A.

2B. Do PSI or PDI support the rehabilitation year indicated by HPMA or paper records? If yes, Use HPMA/paper records rehabilitation year; otherwise, go to question 3B.

3A. Is there an increase in PSI (>1) and the PSI after increase is above 3.5 between HPMA and paper records rehabilitation year? If yes, use rehabilitation year indicated by increase in PSI; otherwise, use paper records rehabilitation year and mile points.

3B. Is there an increase in PSI (>1) and the PSI after increase is above 3.5? If yes, use rehabilitation year indicated by increase in PSI; otherwise, use paper records rehabilitation year and mile points.

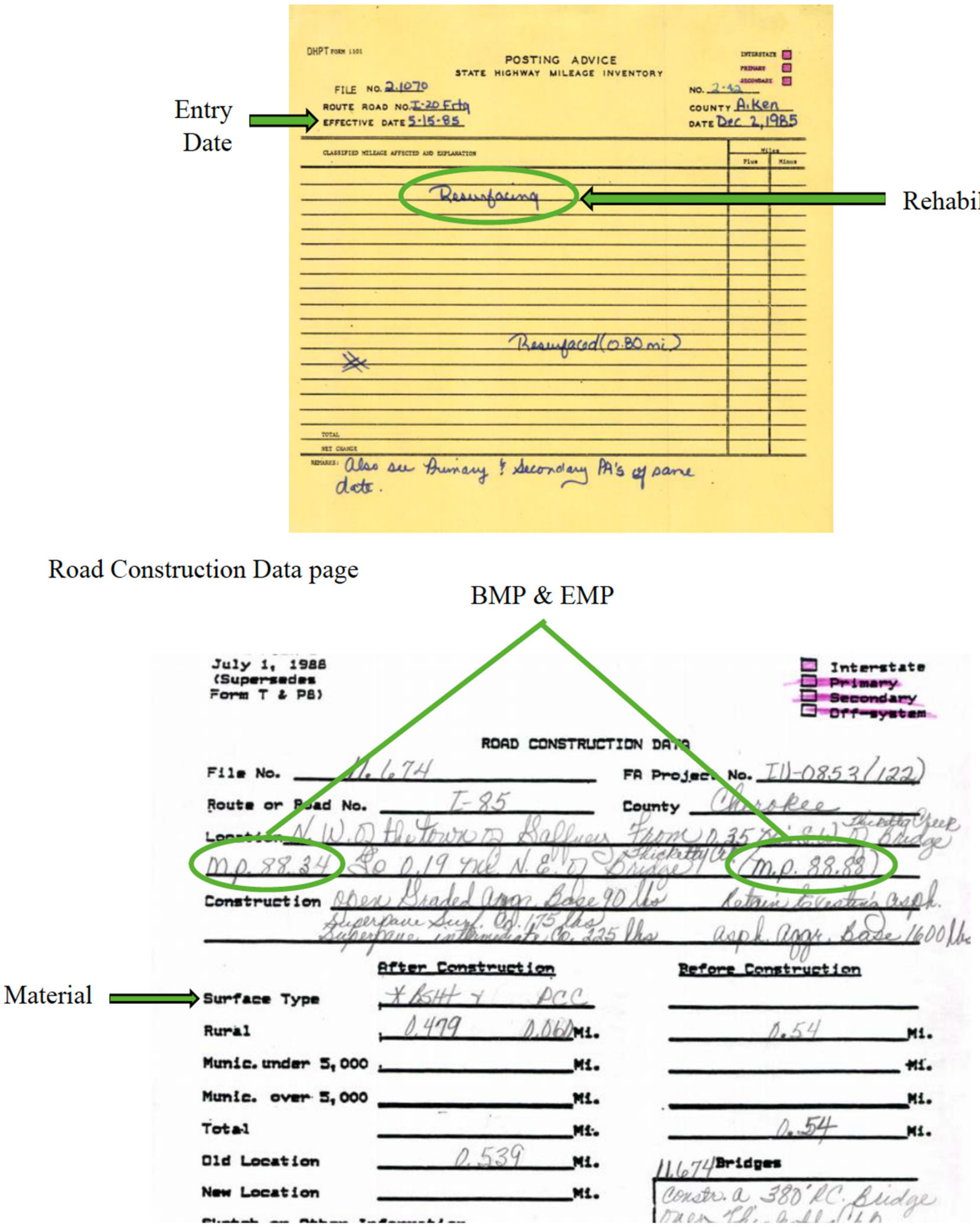

Figure 3-3. Posting advice with relevant maintenance information

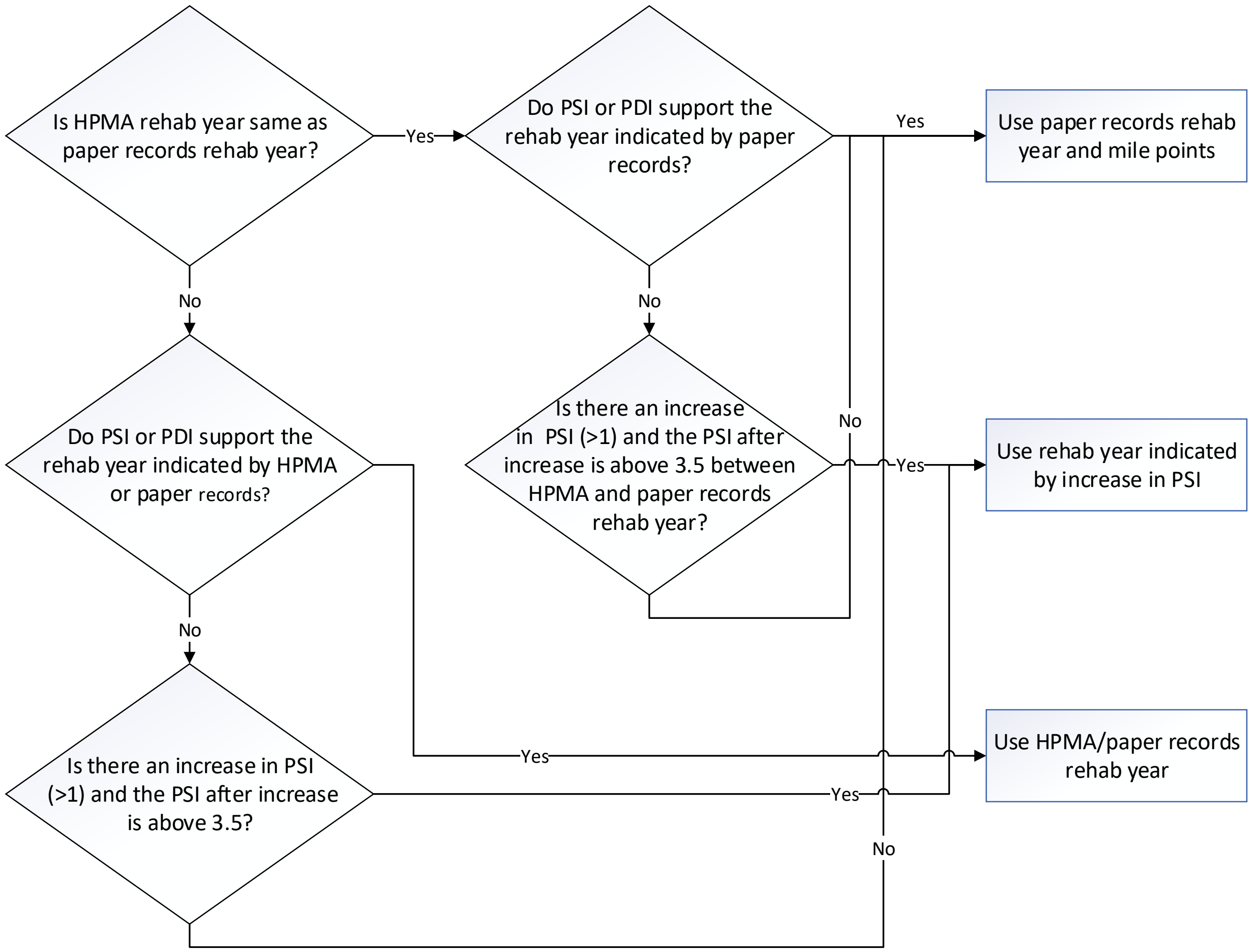

Figure 3-4. Age of treated pavement decision flowchart

3.5 PSI and PDI data cleaning

Prior to using the PSI and PDI data for model evaluation, some data points were removed to eliminate potential outliers. For all selected pavement sections, both interstate and primary routes, the PSI and PDI reported for the first 0.1-mile and last 0.1-mile segment were removed. Given the length of each section and that data are collected at every 0.1 mile, eliminating two data points before the average is taken does not introduce any error since the sample size is sufficiently large. This approach eliminates potential outliers due to collection instrument adjustment at the start and end of the section. When a reported PSI or PDI value is not for a 0.1-mile segment as in this scenario observed for US-278 with the following beginning mile point and ending mile point, 19.7-19.8, 19.72-19.76, and 19.8-19.9, the value for segment 19.72-19.76 is removed if it is significantly lower or higher (by more than one) compared to the prior and following year's data at the same location. The removal of such data eliminates potential outliers due to: 1) GIS-based collection instrument adjustments, 2) distance measurement instrumentation adjustments, and 3) presence of bridges (SCDOT does not collect distress data on bridges).

3.6 PSI and PDI model evaluation

Equation 3.1 shows the current form of the SCDOT's PSI prediction model. As shown, the future PSI value depends on the initial PSI value and age of the treated pavement. The term $ln(1/x_i)$

allows the model to adapt to the rate of deterioration of a pavement section. As explained, for each pavement type and treatment type, there is a unique set of values for parameters *a*, *b*, *c*, and *O*.

$$\mathrm{PSI}_i = O - e^{\left(a - b_1 \times c^{ln\left(\frac{1}{x_i}\right)}\right)} \quad (3.1)$$

where,

PSI_i	= PSI in future year *i*
O	= PSI in year 0
a, *b*, and *c*	= model coefficients
x_i	= age of treated pavement

To evaluate the performance of a model and its associated parameters, the predicted PSI values (from Equation 3.1) are compared against the reported PSI values for the same pavement type and treatment type. To quantify the error, the MAPE metric is used, which is calculated using Equation 3.2.

$$MAPE = \left(\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\left|PSI_{i,act} - PSI_{i,pred}\right|}{PSI_{i,act}}\right)\right) \times 100 \quad (3.2)$$

where,

N = number of observations
$PSI_{i,act}$ = actual/measured PSI in year *i*
$PSI_{i,pred}$ = predicted PSI in year *i*

The PDI prediction model has the same functional form as the PSI model shown above but with different values for parameters *a*, *b*, *c*, and *O*. Its evaluation is the same as that of PSI.

3.7 PSI and PDI model updating

It was determined jointly with the PSIC that if the MAPE (Equation 3.2) of a current SCDOT PSI or PDI model is high or if updating its parameter values will yield at least a 5% relative improvement, then the model should be updated. Relative improvement is defined and calculated as follows.

$$\text{Relative Improvement} = \left(\frac{MAPE_{original} - MAPE_{proposed}}{MAPE_{original}}\right) \times 100 \quad (3.3)$$

Three different approaches were taken to determine the optimal parameter values. The first was to use a translated SCDOT model which retained the *a*, *b*, *c* parameter values from the current SCDOT model but have the *O* (initial PSI value) parameter estimated from data. The second approach was to determine the values of *a*, *b*, *c*, and *O* parameters with minimal constraints on their bounds that gave the lowest sum of squared errors (referred to as optimized model 1 hereafter). To overcome the issue of optimized model 1 providing unrealistic remaining service life, the third approach used was to constrain the parameters *a*, *b*, *c*, and *O* such that the predicted remaining service life was not greater than 30 years. Among these three approaches/models, the one that yielded the lowest MAPE was the recommended one.

To determine the optimal values for parameters *a*, *b*, *c*, and *O*, MATLAB's curve fitting function was used. The upper bound of parameters *a*, *b*, *c*, and *O* is set not to exceed the respective maximum value currently used by the SCDOT. The lower bound of parameters *b* and *O* are set to zero, while the lower bound of parameters *a* and *c* are set to one. With these constraints, in some instances, the model yielded unrealistic remaining service life for a pavement section. The literature indicates that 30 years is the maximum expected service life of a pavement. Therefore, it is set as a constraint in optimized model 2. Note that optimized model 2 is estimated only if optimized model 1 predicts a service life greater than 30 years. The exact value used as the upper bound on the service life differs depending on the scenario. If the data range exceeds the current SCDOT model's predicted service life, then the upper bound on service life is set to be the data range plus 3 years. On the other hand, if the data range is less than the current SCDOT model's predicted service life, then the upper bound on the service life is set to be the current SCDOT model's predicted service life plus three years. The reason for padding an additional three years is due to the data showing a slower deterioration rate compared to the current SCDOT models. Three is chosen as a conservative estimate.

3.8 PSI and PDI model validation

To validate the calibrated PSI and PDI models, they were evaluated on a new set of data, not previously used to estimate the parameters. The aim was to evaluate how well the calibrated models perform on newer data. Another aim was to verify that the calibrated models were not overfitted to training data. Five pavement sections were selected for each interstate model and ten pavement sections were selected for each primary route model. For each section, at least five years of historical pavement condition data is available.

To determine if the models were overfitted, the mean squared error (MSE) was calculated for each model using Equation 3-4.

$$MSE = \frac{\sum_{i=1}^{N} \left[PSI_{i,act} - PSI_{i,pred} \right]^2}{N} \tag{3.4}$$

If the MSE of the model applied to the test dataset is fairly close to the MSE of the training dataset, then it can be concluded that the model was not overfitted, and thus, it will likely perform well on unseen data.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The individual interstate model evaluation and validation results are provided in the following appendices.

- Appendix A – general rehabilitation for concrete pavement (GR CON)
- Appendix B – general rehabilitation for continuously reinforced concrete pavement (GR CRC)
- Appendix C – original construction for concrete pavement (OC CON)
- Appendix D – mill-and-replace 2 to 4 inches + 200 PSY overlay for asphalt pavement (MR 2-4" + 200 PSY BIT)
- Appendix E – mill-and-replace 2 to 4 inches + 200 PSY overlay for asphalt over concrete pavement (MR 2-4" + 200 PSY BOC)
- Appendix F – mill-and-replace 1 to 2 inches + 400 PSY overlay for asphalt pavement (MR 1-2" + 400 PSY BIT)
- Appendix G – mill-and-replace 1 to 2 inches + 400 PSY overlay for composite pavement (MR 1-2" + 400 PSY BOC)

The individual primary route model evaluation and validation results are provided in the following appendices.

- Appendix H – mill-and-replace 1 to 2 inches for asphalt pavement (MR 1-2" BIT)
- Appendix I – mill-and-replace 1 to 2 inches + 200 PSY overlay for asphalt pavement (MR 1-2" + 200 PSY BIT)
- Appendix J – crack seal for asphalt pavement (Crack Seal BIT)
- Appendix K – 100 to 200 PSY overlay for asphalt pavement (OL 100-200 PSY BIT)
- Appendix L – micro-surfacing for asphalt pavement (Micro-surfacing BIT)

Within each appendix, four sets of results are provided: 1) PSI model evaluation results using training data, 2) PSI model validation results using test data, 3) PDI model evaluation results using training data, and 4) PDI model validation results using test data. Each set of results includes a plot of the average reported PSI or PDI per pavement section per year as shown in Figure 4-1. Some sections received more than one treatment during the analysis period. Thus, these sections have more than one "datasets." For example, if a section received two treatments from 2000 to 2020, then it has two datasets. The provided plots show the number of road sections and datasets used for model evaluation and validation. The number of data points is the number of datasets multiplied by their respective length in years. Also provided on the plots are the performance curves of the current SCDOT model and the ones evaluated in this project. Among the three approaches evaluated (translated SCDOT model, optimized model 1, and optimized model 2), the recommended one is indicated in the results table. In most cases, optimized model 1 is recommended one because it has the lowest MAPE value; however, if its project pavement service life is unrealistic, then optimized model 2 is recommended. Figure 4-2 shows an example of a treatment (MR 1-2" + 200 PSY BIT) where optimized model 1 projected a pavement service life of 84.21 years. Using the recommended optimized model 2, a service life of 17.28 years is expected.

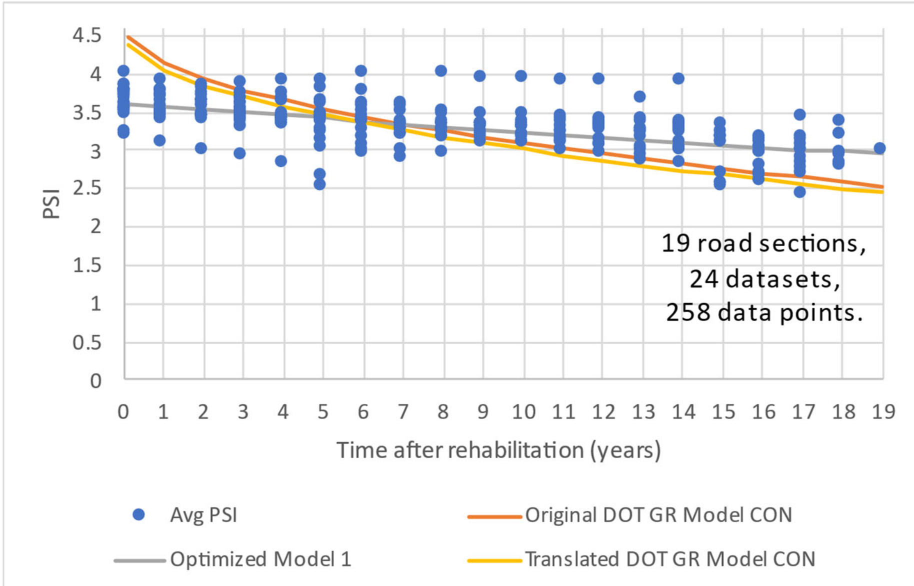

Figure 4-1. Performance curves for GR CON treatment vs. reported PSI data

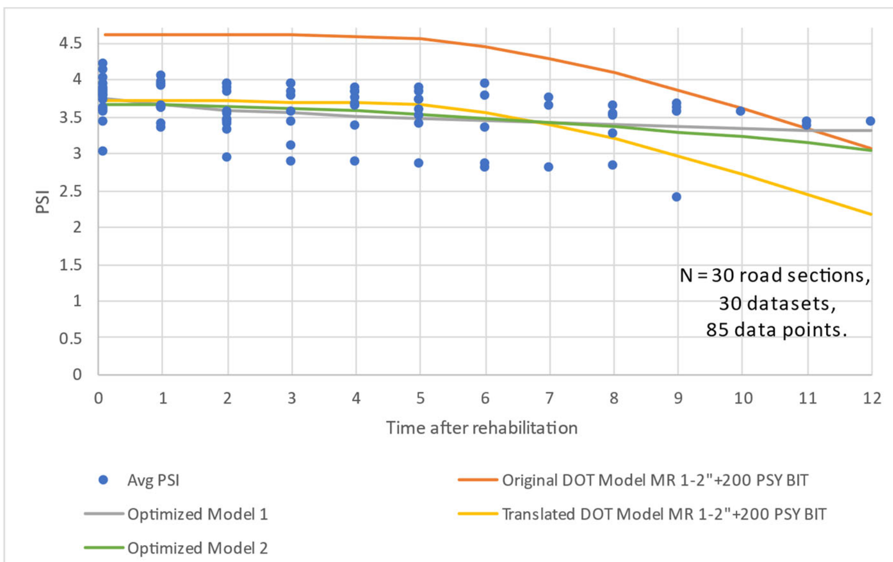

Figure 4-2. Performance curves for MR 1-2" + 200 PSY BIT treatment vs. reported PSI data

4.2 Interstate PSI and PDI model evaluation

Table 4-1 shows the results of the current interstate PSI and PDI models in terms of MAPE. As the term "error" suggests, the lower the MAPE value, the better the model is in capturing the pavement degradation trend. Generally, a MAPE value less than 10% is considered to be acceptable. Based on this criterion, among the current PSI models, only the MR 1-2" + 400 PSY BOC model yielded acceptable results. The rest are marginal since they are close to 10%, except for the OC CON model which has a MAPE of 26.64%. Among the PDI models, two yielded acceptable results (GR CRC and MR 2-4" + 200 PSY BOC) and two yielded marginal results (MR 2-4" + 200 PSY BIT and MR 1-2" + 400 PSY BOC). The other three yielded poor results.

Table 4-1. Interstate model evaluation results

Treatment / Pavement type	Mean Absolute Percentage Error (%)	
	Current PSI Model	**Current PDI Model**
GR CON	10.20	17.46
GR CRC	11.19	9.53
OC CON	26.64	34.80
MR 2-4" + 200 PSY BIT	12.71	10.35
MR 2-4" + 200 PSY BOC	10.28	8.08
MR 1-2" + 400 PSY BIT	12.78	87.68
MR 1-2" + 400 PSY BOC	8.89	12.68

4.3 Interstate PSI and PDI model updating

In consultation with the PSIC, it was determined that if the MAPE value of the current PSI or PDI model is above 10% or if updating its parameter values will yield at least a 5% relative improvement, then the model should be updated. Based on these criteria, all seven interstate PSI models and all seven interstate PDI models were updated. Table 4-2 shows the recommended model and its parameter values. When the optimized model 2 is recommended over the optimized model 1, it is because the latter yielded an unrealistic pavement service life. The reason why optimized model 1 produced an unrealistic pavement service life is that the reported PSI and PDI data showed nearly a "flat line" over a very long period. A possible explanation for this is that one or more maintenance activity was performed but not recorded.

Table 4-2. Interstate model updating results

Variable / Treatment / Pavement Type	Recommended Model	Recommended Parameter Values (*a*, *b*, *c*, and *O*)
PSI GR CON	Optimized model 1	(45.540, 48.710, 1.020, 3.6)
PSI GR CRC	Optimized model 2	(55.468, 63.285, 1.044, 3.8)
PSI OC CON	Optimized model 2	(1.715, 4.339, 1.406, 3.9)
PSI MR 2-4" + 200 PSY BIT	Optimized model 2	(53.056, 63.286, 1.067, 4.029)
PSI MR 2-4" + 200 PSY BOC	Optimized model 2	(57.123, 63.295, 1.035, 4.1)
PSI MR 1-2" + 400 PSY BIT	Optimized model 1	(1.133, 31.530, 3.113, 4.1)
PSI MR 1-2" + 400 PSY BOC	Optimized model 1	(2.177, 21.176, 2.194, 4.1)
PDI GR CON	Optimized model 2	(56.239, 63.286, 1.042, 4.3)
PDI GR CRC	Optimized model 1	(2.282, 6.603, 1.445, 4.3)
PDI OC CON	Optimized model 2	(1.715, 11.143, 2.263, 5.0)
PDI MR 2-4" + 200 PSY BIT	Optimized model 1	(1.133, 17.370, 3.417, 4.6)
PDI MR 2-4" + 200 PSY BOC	Optimized model 1	(28.830, 34.860, 1.097, 4.5)
PDI MR 1-2" + 400 PSY BIT	Optimized model 1	(1.935, 22.66, 3.711, 4.422)
PDI MR 1-2" + 400 PSY BOC	Optimized model 1	(2.282, 7.406, 1.83, 4.429)

Table 4-3 shows the relative improvement in MAPE when the recommended parameter values are used compared to the current ones. Among the seven interstate PSI models, the relative improvement ranges between 36.74% and 75.80%, and among the seven interstate PDI models, the relative improvement ranges between 7.76% and 80.72%. Four out of the seven proposed PSI models have MAPE values below 5% and two below 10%. The MAPE value of the worst-performing PSI model (OC CON) is reduced from 26.64% to 14.44% when the optimal parameter values are used. One of the seven proposed PDI models have MAPE values below 5%, two below 10%, and three below 15%. Only one model (OC CON) has a MAPE above 20%. This is due to the reported PDI data showing nearly a “flat line” over 38 years.

Table 4-3. Interstate model relative improvement

Treatment / Pavement Type	Mean Absolute Percentage Error (%)				Relative Improvement	
	Current PSI model	Proposed PSI model	Current PDI model	Proposed PDI model	PSI (%)	PDI (%)
GR CON	10.20	5.23	17.46	12.33	48.71	29.35
GR CRC	11.19	7.08	9.53	7.16	36.74	24.85
OC CON	26.64	14.44	34.80	28.91	45.78	16.91
MR 2-4"+200 PSY BIT	12.71	3.74	10.35	4.85	70.56	53.12
MR 2-4"+200 PSY BOC	10.28	3.09	8.08	7.41	69.94	8.32
MR 1-2"+400 PSY BIT	12.78	3.09	87.68	16.90	75.80	80.72
MR 1-2"+400 PSY BOC	8.89	2.57	12.68	11.69	71.06	7.76

4.4 Interstate PSI and PDI model validation

Table 4-4 shows the results of the recommended PSI and PDI models and parameters when applied to a new set of data, not previously used to estimate the parameters. All seven of the proposed PSI models have MAPE values below 10%, with three having MAPE below 5%. Five of the seven proposed PDI models have MAPE values below 10%, and the other two have MAPE values below 20%. Collectively, the MAPE values obtained from the test dataset are comparable to those of the training dataset. This finding suggests that the recommended models are robust and the same model performance can be expected in future applications.

Table 4-4. Interstate model validation results

Treatment / Pavement Type	Mean Absolute Percentage Error (%)				Relative Improvement	
	Current PSI	Proposed PSI	Current PDI	Proposed PDI	PSI (%)	PDI (%)
GR CON	9.77	7.00	16.30	10.15	28.37	37.72
GR CRC	13.32	8.26	11.70	6.00	38.03	48.75
OC CON	14.99	6.34	11.56	4.36	57.72	62.27
MR 2-4" + 200 PSY BIT	12.92	4.66	10.29	4.48	63.91	56.47
MR 2-4" + 200 PSY BOC	12.13	3.06	9.83	8.40	74.79	14.55
MR 1-2" + 400 PSY BIT	16.08	5.48	21.13	17.21	65.92	18.55
MR 1-2" + 400 PSY BOC	9.99	3.84	8.16	6.74	61.54	17.42

Table 4-5 shows the calculated mean squared error (MSE) to assess whether the proposed interstate PSI and PDI models have been overfitted to data. Overfitted models perform well only on the training data and not on other unseen data. This is not the case as indicated by the MAPE results. The MSE results indicate that nine out of the 14 proposed interstate models have about the same or lower Mean Square Error (MSE) for the test data compared to the training data which indicates that they were not overfitted to the training data. Therefore, similar model performance can be expected of the proposed models on other unseen data.

Table 4-5. Interstate model robustness results

Treatment / Pavement Type	Proposed PSI Model		Proposed PDI Model	
	Training MSE	Validation MSE	Training MSE	Validation MSE
GR CON	0.0564	0.1079	0.3205	0.2159
GR CRC	0.0944	0.1255	0.1347	0.0716
OC-CON	0.2828	0.0767	2.2450	0.1042
MR 2-4" + 200 PSY BIT	0.0381	0.0437	0.0659	0.0618
MR 2-4" + 200 PSY BOC	0.0242	0.0249	0.1429	0.2001
MR 1-2" + 400 PSY BIT	0.0260	0.0923	0.1958	0.6733
MR 1-2" + 400 PSY BOC	0.0172	0.0470	0.2826	0.1299

4.5 Interstate pavement deterioration rate

Table 4-6 shows a comparison of the projected pavement roughness deterioration rates between the current PSI and proposed PSI models per five-year interval. In the first five years, the proposed PSI models project a lower degradation rate compared to the current models, except for MR 1-2" + 400 PSY BIT. The same result applies to the second five-year interval. In the third five-year interval, the proposed PSI models project a lower degradation rate compared to the current models, except for MR 1-2" + 400 PSY BOC. Compared to MR 2-4" + 200 PSY BIT, the MR 1-2" + 400 PSY BIT treatment has a higher degradation rate in the first 10 years. From the proposed PSI models, three treatments have a higher deterioration rate in the third five-year interval compared to the first two: MR 2-4" + 200 PSY BIT, MR 1-2" + 400 PSY BIT, and MR 1-2" + 400 PSY BOC. From the proposed PSI model, concrete pavements with the original construction have a higher deterioration rate in the second five-year interval compared to the first and third.

Table 4-6. Interstate roughness deterioration rate in percent based on PSI

Treatment / Pavement Type	Current PSI model			Proposed PSI model		
	1st 5 years	2nd 5 years	3rd 5 years	1st 5 years	2nd 5 years	3rd 5 years
GR CON	-18.83	-8.50	-6.57	-3.86	-3.47	-3.31
GR CRC	-18.83	-8.50	-6.57	-0.58	-2.96	-5.91
OC CON	-7.55	-9.87	-10.76	-4.78	-7.66	-5.59
MR 2-4" + 200 PSY BIT	-0.25	-17.24	-25.89	-0.21	-3.56	-13.17
MR 2-4" + 200 PSY BOC	-2.39	-11.41	-7.10	-1.03	-3.74	-2.40
MR 1-2" + 400 PSY BIT	-0.01	-5.69	-19.81	-0.40	-6.47	-8.31

Treatment / Pavement Type	Current PSI model			Proposed PSI model		
	1st 5 years	2nd 5 years	3rd 5 years	1st 5 years	2nd 5 years	3rd 5 years
MR 1-2" + 400 PSY BOC	-17.70	-11.93	-6.65	-0.46	-5.63	-8.87

Table 4-7 shows a comparison of the projected pavement distress deterioration rates between the current PDI and proposed PDI models per five-year interval. In the first five years, the proposed PDI models project a lower degradation rate compared to the current models, except for MR 2-4" + 200 PSY BIT and MR 1-2" + 400 PSY BIT. In the second five-year interval, the proposed PDI models project a higher degradation rate compared to the current models, except for GR CON and GR CRC. In the third five-year interval, the proposed PSI models project a higher degradation rate compared to the current models, except for GR CRC and MR 2-4" + 200 PSY BIT. From the proposed PDI models, all treatments (except GR CON) have a higher deterioration rate in the second five-year interval compared to the first and third. Also, from the proposed PDI models, all treatments have a higher deterioration rate in the third five-year interval compared to the first.

Table 4-7. Interstate distress deterioration rate in percent based on PDI

Treatment / Pavement Type	Current PDI Model			Proposed PDI Model		
	1st 5 years	2nd 5 years	3rd 5 years	1st 5 years	2nd 5 years	3rd 5 years
GR CON	-24.77	-10.55	-7.40	-1.02	-4.62	-8.75
GR CRC	-12.59	-8.90	-7.47	-5.19	-6.41	-5.47
OC-CON	-16.23	-12.33	-9.82	-5.84	-15.97	-11.95
MR 2-4" + 200 PSY BIT	-0.09	-17.07	-35.62	-3.37	-17.14	-11.56
MR 2-4" + 200 PSY BOC	-17.28	-14.78	-15.96	-4.11	-29.29	-16.54
MR 1-2" + 400 PSY BIT	-0.02	-6.00	-20.55	-9.07	-37.32	-25.15
MR 1-2" + 400 PSY BOC	-19.96	-15.58	-13.55	-12.16	-18.88	-14.89

4.6 Interstate pavement service life

Table 4-8 shows a comparison of the projected pavement service life (PSL) for interstates between the current and proposed PSI models using a rehabilitation trigger value of 2.7. For all treatments, the proposed PSI models project a longer PSL compared to the current models, ranging from three to ten years. The treatment that has the biggest difference is GR CON. The three treatments with the smallest difference (+3 years) are OC CON, MR 2-4" + 200 PSY BIT, and MR 2-4" + 200 PSY BOC.

Table 4-8. Interstate pavement service life (in years) based on PSI models

Treatment / Pavement Type	Current PSI model	Proposed PSI model	Difference (years)
GR CON	16.1	27.04	+10.94
GR CRC	16.1	22.00	+5.90
OC CON	19.49	22.49	+3.00
MR 2-4" + 200 PSY BIT	13.46	16.46	+3.00

MR 2-4" + 200 PSY BOC	20.31	23.32	+3.01
MR 1-2" + 400 PSY BIT	18.05	25.19	+7.14
MR 1-2" + 400 PSY BOC	13.88	22.32	+8.44

Table 4-9 shows a comparison of the projected pavement service life (PSL) for interstates between the current and proposed PDI models using a rehabilitation trigger value of 2.7. For four treatments, the proposed PDI models project a longer PSL compared to the current models, ranging from three to five years. For the other three treatments, the proposed PDI models project a shorter PSL compared to the current models, ranging from two to 10 years. The treatment with the largest negative difference is MR 1-2" + 400 PSY BIT. Based on the proposed PDI models, the expected service life for a BOC treatment is shorter than that of a BIT treatment (MR 2-4" + 200 PSY BOC vs. MR 2-4" + 200 PSY BIT). This finding is counterintuitive. Also, a service life of less than nine years for MR 2-4" + 200 PSY BOC and MR 1-2" + 400 PSY BIT does not correspond to expectation. A possible explanation for this is the use of open graded friction course (OGFC) by SCDOT on interstates which has been known to have asphalt binder prematurely oxidizes and cause raveling.

Table 4-9. Interstate pavement service life (in years) based on PDI models

Treatment / Pavement Type	Current PDI Model	Proposed PDI Model	Difference (years)
GR CON	16.68	22.00	+5.32
GR CRC	28.7	33.86	+5.16
OC CON	19.32	22.32	+3
MR 2-4" + 200 PSY BIT	13.05	17.71	+4.66
MR 2-4" + 200 PSY BOC	15.22	9.79	-5.43
MR 1-2" + 400 PSY BIT	18.55	8.40	-10.15
MR 1-2" + 400 PSY BOC	13.68	11.05	-2.63

4.7 Primary route PSI and PDI model evaluation

Table 4-10 shows the results of the current primary route PSI and PDI models in terms of MAPE. None of the current PSI models yield acceptable predictive performance (< 10%). The same is true with the current PDI models. The reason why two models are listed for Crack Seal in Table 4-10 is that currently in HPMA, the US/SC route default model is used in place of the Crack Seal model for those pavement sections that received the crack seal treatment. Hence, both the Crack Seal and the US/SC default models were evaluated against the reported PSI and PDI.

Table 4-10. Primary route model evaluation results

Treatment / pavement type		Mean Absolute Percentage Error (%)	
		Current PSI model	Current PDI model
MR 1-2" BIT		32.70	14.33
MR 1-2"+200 PSY BIT		28.06	37.18
Crack Seal	Crack Seal BIT	32.13	60.50
	US/SC default	40.70	91.49
OL 100-200 PSY BIT		29.39	11.51

Microsurfacing BIT	36.29	38.92

4.8 Primary route PSI and PDI model updating

Given that all of the current PSI and PDI models yielded MAPE values above 10%, their parameters were updated. Table 4-11 shows the recommended model and its parameter values. As was the case with interstate models, when the optimized model 2 is recommended over the optimized model 1, it is because the latter yielded an unrealistic pavement service life. The four treatments where optimized model 2 are recommended are PSI MR 1-2" + 200 PSY BIT, PSI Crack Seal, PSI OL 100-200 PSY, and PSI Microsurfacing BIT. Note that the Crack Seal models were calibrated using data obtained from pavement sections that received the crack seal treatment.

Table 4-11. Primary route model updating results

Variable / Treatment / Pavement Type	Recommended Model	Recommended Parameter Values (***a***, ***b***, ***c***, and ***O***)
PSI MR 1-2" BIT	Optimized model 1	(2.646, 15.692, 2.611, 3.7)
PSI MR 1-2" + 200 PSY BIT	Optimized model 2	(1.994, 40.910, 3.711, 3.7)
PSI Crack Seal BIT	Optimized model 2	(58.317, 66.770, 1.057, 3.3)
PSI OL 100-200 PSY	Optimized model 2	(58.3, 62.799, 1.031, 3.7)
PSI Micro-surfacing BIT	Optimized model 2	(25.9, 79.019, 1.618, 3.3)
PDI MR 1-2" BIT	Optimized model 1	(2.646, 15.692, 2.611, 4.2)
PDI MR 1-2" + 200 PSY BIT	Optimized model 1	(2.470, 50.166, 3.711, 3.7)
PDI Crack Seal BIT	Optimized model 1	(1.133, 3.90, 1.333, 2.7)
PDI OL 100-200 PSY	Optimized model 1	(49.1, 52.62, 1.041, 4.5)
PDI Micro-surfacing BIT	Optimized model 1	(1.133, 3.603, 2.343, 3.8)

Table 4-12 shows the relative improvement in MAPE when the recommended parameter values are used compared to the current ones. Among the five primary route PSI models, the relative improvement ranges between 72.79% and 85.25%, and among the five primary route PDI models, the relative improvement ranges between 51.69% and 75.11%. All five of the proposed PSI models have MAPE values below 10%. Two of the five proposed PDI models have MAPE values below 10% and two below 20%. The proposed PDI model for Crack Seal has a MAPE above 20%. This is due to the reported PDI data showing nearly a "flat line" over 8 years, but this treatment is expected to have a much shorter pavement service life.

Table 4-12. Primary route model relative improvement

		Mean Absolute Percentage Error (%)				**Relative Improvement**	
Treatment / Pavement Type		**Current PSI**	**Proposed PSI**	**Current PDI**	**Proposed PDI**	**PSI (%)**	**PDI (%)**
MR 1-2" BIT		32.70	7.22	14.33	6.60	77.92	53.97
MR 1-2" + 200 PSY BIT		28.06	7.63	37.18	14.60	72.79	60.73
Crack Seal	Crack Seal BIT	32.13	7.84	60.50	22.77	75.61	62.37

	US/SC default	40.70	7.84	91.49	22.77	80.75	75.11
OL 100-200 PSY BIT		29.39	4.34	11.51	5.56	85.25	51.69
Micro-surfacing BIT		36.29	6.34	38.92	16.76	82.54	56.95

4.9 Primary route PSI and PDI model validation

Table 4-13 shows the results of the recommended PSI and PDI models and parameters when applied to a new set of data, not previously used to estimate the parameters. Four of the five proposed PSI models have MAPE values below 10%, except for MR 1-2"+200 PSY BIT which has a MAPE value of 18.27%. Two of the five proposed PDI models have MAPE values below 10%, two below 20%, and one with a fairly high MAPE value at 35.99% (Crack Seal model).

Table 4-13. Primary route model validation results

		Mean Absolute Percentage Error (%)				Relative Improvement	
Treatment / Pavement Type		Current PSI	Proposed PSI	Current PDI	Proposed PDI	PSI (%)	PDI (%)
MR 1-2" BIT		31.24	8.55	11.82	6.46	72.63	45.34
MR 1-2"+200 PSY BIT		45.85	18.27	23.05	16.65	60.15	27.76
Crack Seal	Crack Seal BIT	37.29	7.32	80.93	35.99	80.37	55.53
	US/SC default	33.84	7.32	123.09	35.99	78.37	70.76
OL 100-200 PSY		38.80	9.53	7.95	4.45	75.44	44.02
Micro-surfacing BIT		29.31	8.58	32.93	16.24	70.73	50.68

Table 4-14 shows the calculated mean squared error (MSE) to assess whether the proposed primary route PSI and PDI models have been overfitted to data. The results indicate that nine out of the ten proposed models have a lower MSE for the test data compared to the training data; however, the difference is relatively small, except for Crack Seal. Overall, these results suggest that the primary route models were not overfitted.

Table 4-14. Primary route model robustness results

	Proposed PSI Model		Proposed PDI Model	
Treatment / Pavement Type	Training MSE	Validation MSE	Training MSE	Validation MSE
MR 1-2" BIT	0.1148	0.1217	0.1137	0.1907
MR 1-2" + 200 PSY BIT	0.1111	0.3766	0.2902	0.6062
Crack Seal BIT	0.1031	0.1208	0.3616	0.5659
OL 100-200 PSY	0.0380	0.1289	0.0808	0.0552
Micro-surfacing BIT	0.0660	0.1353	0.3760	0.4154

4.10 Primary route pavement deterioration rate

Table 4-15 shows a comparison of the projected pavement roughness deterioration rates for primary routes between the current PSI and proposed PSI models per five-year interval. In the first five years, the proposed PSI models project a lower degradation rate compared to the current models, except for MR 1-2"+200 PSY BIT. In the second five-year interval, all of the proposed PSI models project a lower degradation rate compared to the current models. In the third five-year interval, all of the proposed PSI models project a lower degradation rate compared to the current models, except for Crack Seal. For Micro-surfacing, the deterioration rate is not provided in the third five-year interval because the projected PSI value is negative by that time. From the proposed PSI models, not counting Micro-surfacing, all treatments have a higher deterioration rate in the second five-interval compared to the first, and the third compared to the second. This finding suggests that the deterioration of alphalt pavements on primary routes accelerates as they age.

Table 4-15. Primary route roughness deterioration rate in percent based on PSI

Treatment / Pavement type	Current PSI Model			Proposed PSI Model		
	1st 5 years	2nd 5 years	3rd 5 years	1st 5 years	2nd 5 years	3rd 5 years
MR 1-2" BIT	-10.11	-41.81	-36.51	-4.94	-6.47	-6.98
MR 1-2" + 200 PSY BIT	-1.05	-21.20	-25.27	-2.55	-6.60	-9.56
Crack Seal BIT	-48.43	-17.56	-12.82	-1.26	-12.46	-35.38
OL 100-200 PSY BIT	-10.11	-41.81	-36.51	-4.76	-12.31	-17.83
Micro-surfacing BIT	-20.82	-61.17	N/A	0.00	-20.70	N/A

Table 4-16 shows a comparison of the projected pavement distress deterioration rates for primary routes between the current PDI and proposed PDI models per five-year interval. In the first five years, three of the proposed PDI models project a higher degradation rate compared to the current models; the exceptions are Crack Seal and Micro-surfacing. In the second five-year interval, all of the proposed PDI models project a lower degradation rate compared to the current models, except for OL 100-200 PSY BIT. In the third five-year interval, three of the five models cannot be accessed due to the projected PDI value being negative by that time; for MR 1-2" BIT, the deterioration will be higher, and for MR 1-2" + 200 PSY BIT the deterioration rate will be lower. From the proposed PDI models, three of the five treatments have higher deterioration rate in the first five-year interval, followed by the second, and then the third.

Table 4-16. Primary route distress deterioration rate in percent based on PDI

Treatment / pavement type	Current PDI model			Proposed PDI model		
	1st 5 years	2nd 5 years	3rd 5 years	1st 5 years	2nd 5 years	3rd 5 years
MR 1-2" BIT	-10.11	-41.81	-36.51	-15.06	-39.02	-55.50
MR 1-2" + 200 PSY BIT	-0.55	-23.05	-36.04	-23.38	-19.98	-6.71
Crack Seal BIT	-42.45	-45.28	N/A	-5.40	-2.83	-1.99
OL 100-200 PSY BIT	-10.11	-41.81	-36.51	-16.30	-48.78	N/A
Micro-surfacing BIT	-30.90	-45.20	N/A	-25.37	-11.29	-5.58

4.11 Primary route pavement service life

Table 4-17 shows a comparison of the projected pavement service life (PSL) for primary routes between the current and proposed PSI models using a rehabilitation trigger value of 2.5. For all treatments, the proposed PSI models project a longer PSL compared to the current models, ranging from three to nine years. The treatment that has the biggest difference (+ nine years) is MR 1-2" BIT. The three treatments with the smallest difference (+ three years) are MR 1-2"+200 PSY BIT, OL 100-200 PSY BIT, and Microsurfacing BIT.

Table 4-17. Primary route pavement service life (in years) based on PSI models

Treatment / Pavement Type	Current PSI Model	Proposed PSI Model	Difference (years)
MR 1-2" BIT	9.48	18.94	+9.46
MR 1-2"+200 PSY BIT	14.28	17.28	+3.00
Crack Seal BIT	2.07	11	+8.93
OL 100-200 PSY BIT	9.48	12.48	+3.00
Micro-surfacing BIT	6.79	10.00	+3.21

Table 4-18 shows a comparison of the projected pavement service life (PSL) for primary routes between the current and proposed PDI models using a rehabilitation trigger value of 2.5. For all five treatments, the proposed PDI models project a shorter PSL compared to the current models, ranging from -0.62 to -6.78 years. The treatment with the largest negative difference (-6.78 years) is MR 1-2"+200 PSY BIT.

Table 4-18. Primary route pavement service life (in years) based on PDI models

Treatment / Pavement Type	Current PDI Model	Proposed PDI Model	Difference (years)
MR 1-2" BIT	9.48	8.36	-1.12
MR 1-2" + 200 PSY BIT	13.6	6.82	-6.78
Crack Seal BIT	5.03	4.41	-0.62
OL 100-200 PSY BIT	9.48	7.94	-1.54
Micro-surfacing BIT	6.45	5.32	-1.13

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This project evaluated pavement performance models corresponding to the top five maintenance activities performed on interstates and the top five activities for primary routes in the last 10 years in South Carolina. Considering different pavement types, treatment types, and a separate model for PDI and PSI, there were a total of 14 interstate models. None of the current 14 models have MAPE values less than 5%, indicating that none has excellent predictive performance. However, eleven of these 14 models have MAPE values greater than 10%, indicating the majority have subpar predictive performance. All 14 models were calibrated to fit the reported PSI and PDI data collected from 2000 to 2020. The calibrated models reduces the number of subpar models from eleven to five and increase the number of excellent performing models from zero to six. Each of the calibrated models was validated using an independent test dataset and the obtained MAPE values are comparable to those obtain from the training dataset. These results combined with the calculated MSE values confirm that the models were not overfitted; hence, they can be expected to perform equally well on future unseen data. The calibrated models indicate lower degradation rate, which translates to a longer projected pavement service life for 11 of the 14 models, except for three PDI model: MR 2-4" + 200 PSY BOC, MR 1-2" + 400 PSY BIT, and MR 1-2" + 400 PSY BOC. A possible explanation for this is the use of OGFC on the interstates which has been known to have the asphalt binder prematurely oxidizing and cause raveling.

For the top five maintenance activities performed on primary routes, with only asphalt pavements to consider in the data and a separate model for PSI and PDI, there were a total of 10 primary route models. The SCDOT currently uses a US/SC route default model for pavement sections that received the Crack Seal treatment. For this reason, the US/SC default model was also evaluated, making the total evaluated twelve. None of the 10 models have MAPE values less than 5% and all 10 models have MAPE values greater than 10%. Using data from the top five treatments, the corresponding 10 models were calibrated to fit the reported PSI and PDI data collected from 2000 to 2020. The calibrated models reduce the number of subpar models from ten to three. The model validation yielded comparable MAPE values but the MSE values on the test dataset were higher than the training dataset for nine out of the ten models. However, the difference is relatively small; thus, it can be concluded that the primary route models were not overfitted. The calibrated primary route PSI models indicate lower degradation rate, which translates to a longer projected pavement service life for all five models. However, all five of the calibrated primary route PDI models indicate a higher degradation rate which translated to shorter projected pavement service life. A possible explanation for this is that there is a greater amount of reflective cracking on primary routes than there are on interstates which is affected by how well the pavement was rehabilitated prior to overlay.

5.2 Recommendations

From the findings in this project, it is recommended that the SCDOT consider updating the parameters of the 14 interstate models and 10 primary route models. Overall, the recommended PSI and PDI model parameters show a slower degradation rate compared to the current values for the first 10 years after receiving treatment. Therefore, adopting the recommended parameter values will enable the SCDOT to better identify those pavement candidates that are truly in need of repair and avoid making repairs to those that still have sufficient remaining service life.

5.3 Implementation Plan

The procedure for updating model parameters in HPMA is straighforward. The primary steps are illustrated in Figure 5-1 and described below.

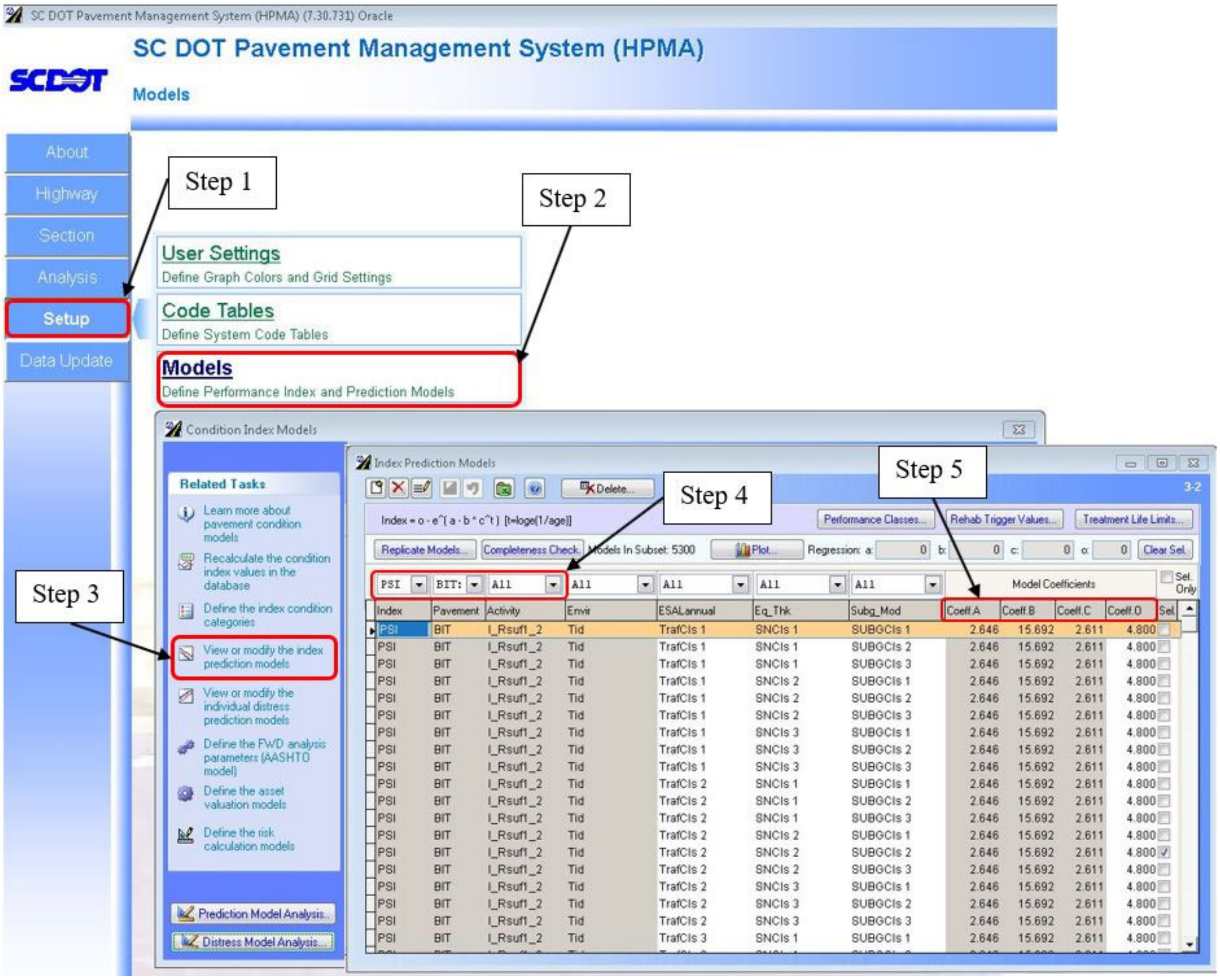

Figure 5-1. Screenshot of HPMA with primary steps to update model parameters outlined

- Step 1. Click on the "Setup" option on the left panel.
- Step 2. Select "Models" among the available choices.
- Step 3. Click on "View or modify the individual distress prediction models" option on the left panel.
- Step 4. Indicate the model to be updated by selecting the appropriate index (PSI or PDI), pavement type (BIT, CON, CRC or BOC), and activity/treatment type. The activities are abbreviated in HPMA. Their descriptions are provided in Table 5.1.
- Step 5. Click on each cell corresponding to coefficients *a*, *b*, *c*, and *O*, and input the recommended values shown in Tables 4-2 and 4-11.
- Step 6. Click on the disk icon on the toolbar to save the input.

Table 5-1. HPMA activity code, abbreviation, and description

ID code	Abbreviation	Description
1	I_Rsuf1_2	Mill-and-Replace (MR) 1"-2"
3	MO2200	MR 1-2" + Overlay (OL) 200 PSY
4	MO4200	MR 2-4" + OL 200 PSY
5	MO2400	MR 1-2" + OL 400 PSY
12	GR	General Rehabilation
16	OC-CON	Original CON Construction
56	CrkSeal	Crack Seal
70	D-USSC	US/SC Default Model
80	0150	OL 100-200 PSY
84	MicroSurf	Micro-surfacing

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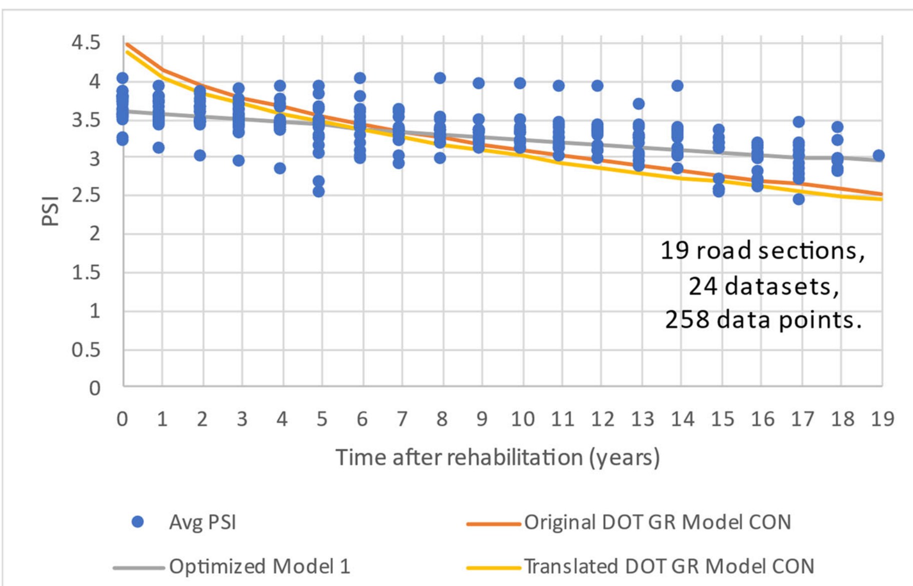
APPENDIX A (GR CON)

[General rehabilitation for concrete pavement]

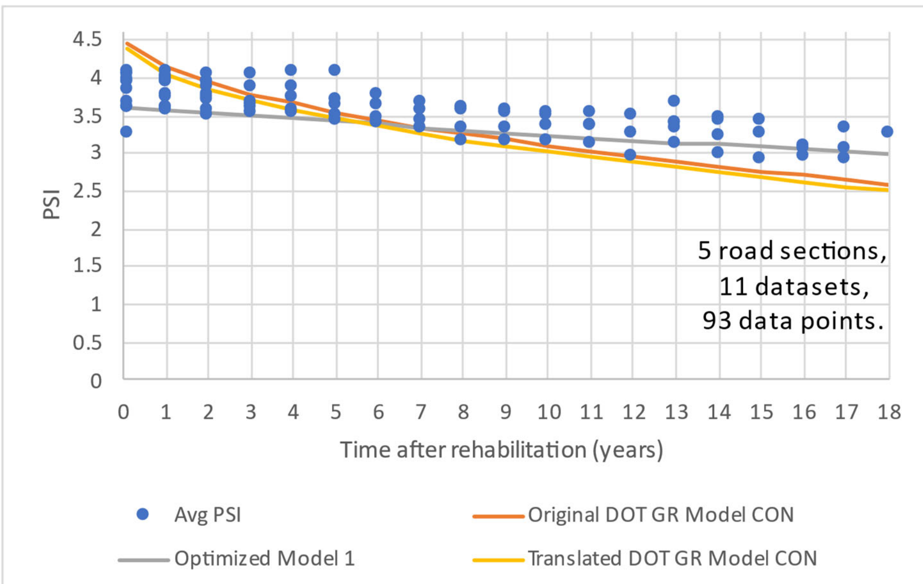
[PSI model evaluation using training data.]

PSI Coef. (Training model)	Original DOT GR Model CON	Optimized Model 1 (recommended)	Translated DOT GR Model CON
a	25.706	45.540	25.706
b	26.482	48.710	26.482
c	1.02	1.020	1.02
o	4.6	3.6	4.5
SSE	51.1167	15.1274	49.2242
RMSE	0.4367	0.2376	0.4286
MSE	0.1907	0.0564	0.1837
MAPE (%)	10.20	5.23	10.28
Expected rehab year	16.10	27.04	14.67
Rehab threshold	2.7	2.7	2.7
1st 5 years average slope (%)	-18.83	-3.86	-18.83
2nd 5 years average slope (%)	-8.50	-3.47	-8.50
3rd 5 years average slope (%)	-6.57	-3.31	-6.57
Relative improvement (%)		48.71	



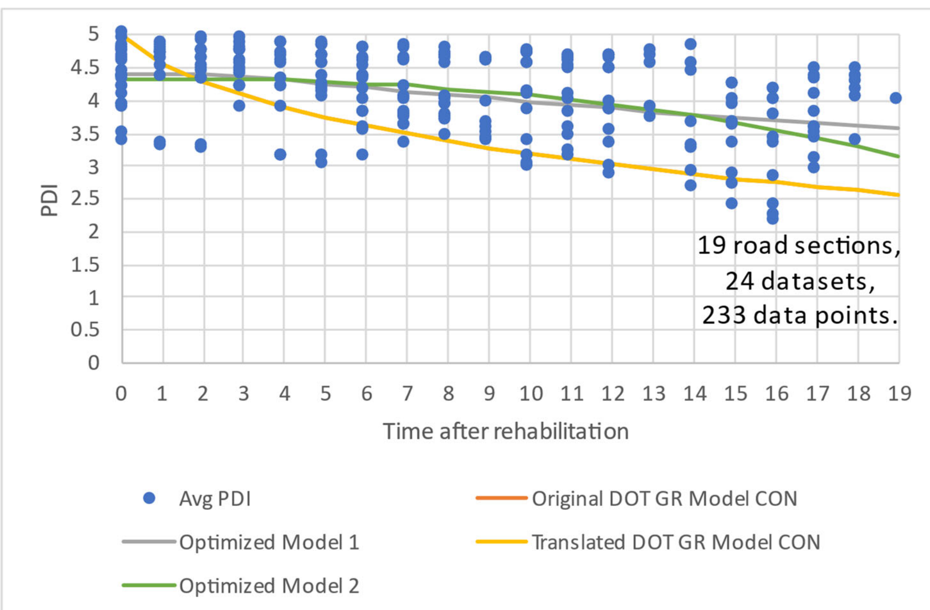
[PSI model evaluation using validation data.]

PSI Coef. (Validation model)	Original DOT GR Model CON	Optimized Model 1 (recommended)	Translated DOT GR Model CON
a	25.706	45.540	25.706
b	26.482	48.710	26.482
c	1.02	1.020	1.02
o	4.6	3.6	4.5
SSE	18.9116	10.7881	21.4599
RMSE	0.4349	0.3285	0.4633
MSE	0.1891	0.1079	0.2146
MAPE (%)	9.77	7.00	10.54
Expected rehab year	16.10	27.04	14.67
Rehab threshold	2.7	2.7	2.7
Relative improvement (%)		28.37	



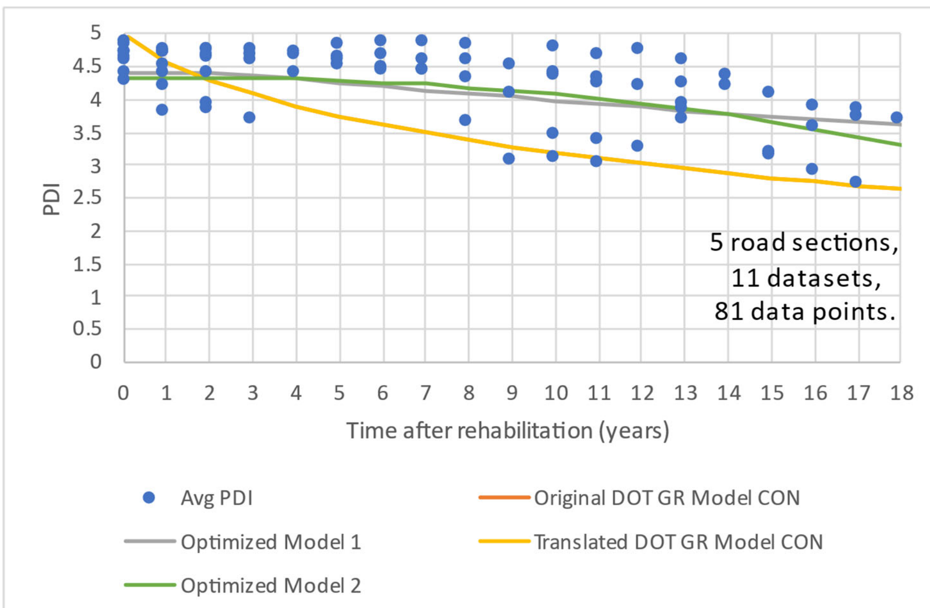
[PDI model evaluation using training data.]

PDI Coef. (Training model)	Original DOT GR Model CON	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT GR Model CON
a	2.964	1.715	56.239	2.964
b	3.825	7.570	63.286	3.825
c	1.231	1.608	1.042	1.231
o	5	4.4	4.3	5
SSE	180.4307	70.6540	74.6747	180.4307
RMSE	7.6358	0.2983	0.8735	7.6358
MSE	0.7744	0.3032	0.3205	0.7744
MAPE (%)	17.46	12.00	12.33	17.46
Expected rehab year	16.68	50.71	22.00	16.68
Rehab threshold	2.7	2.7	2.7	2.7
1st 5 years average slope (%)	-24.77	-3.34	-1.02	-24.77
2nd 5 years average slope (%)	-10.55	-5.52	-4.62	-10.55
3rd 5 years average slope (%)	-7.40	-4.85	-8.75	-7.40
Relative improvement (%)			29.35	



[PDI model evaluation using validation data.]

PDI Coef. (Validation model)	Original DOT GR Model CON	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT GR Model CON
a	2.964	1.715	56.239	2.964
b	3.825	7.570	63.286	3.825
c	1.231	1.608	1.042	1.231
o	5	4.4	4.3	5
SSE	57.0849	17.1394	17.4840	57.0849
RMSE	4.9703	1.2375	1.5477	4.9703
MSE	0.7048	0.2116	0.2159	0.7048
MAPE (%)	16.30	9.84	10.15	16.30
Expected rehab year	16.68	50.71	22.00	16.68

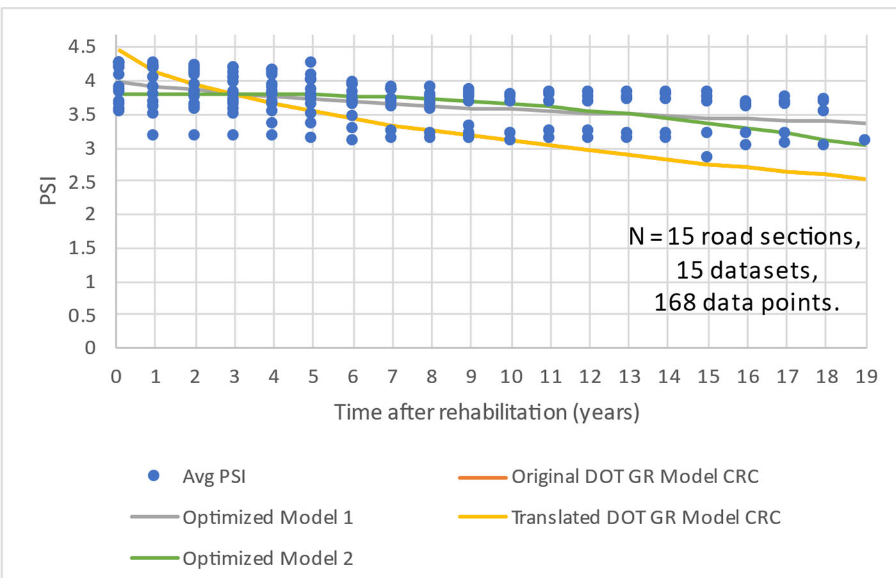


APPENDIX B (GR CRC)

[General rehabilitation for continuously reinforced concrete pavement]

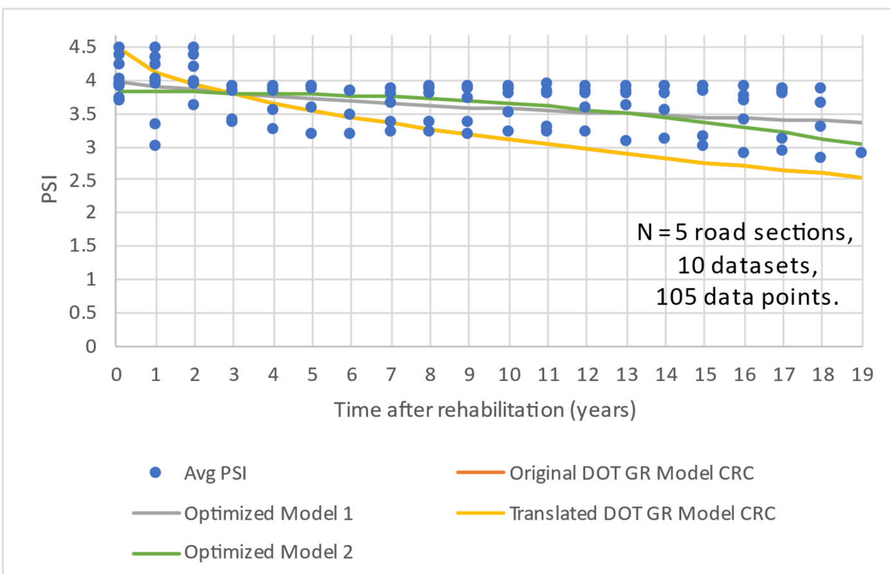
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original DOT GR Model CRC	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT GR Model CRC
a	25.706	2.066	55.468	25.706
b	26.482	5.030	63.285	26.482
c	1.02	1.253	1.044	1.02
o	4.6	4.0	3.8	4.6
SSE	42.6322	14.2220	15.8673	42.6322
RMSE	0.5038	0.2910	0.3073	0.5037
MSE	0.2538	0.0847	0.0944	0.2538
MAPE (%)	11.19	6.93	7.08	11.19
Expected rehab year	16.10	88.64	22.00	16.10
Rehab threshold	2.7	2.7	2.7	2.7
1st 5 years average slope (%)	-18.83	-4.84	-0.58	-18.83
2nd 5 years average slope (%)	-8.50	-3.03	-2.96	-8.50
3rd 5 years average slope (%)	-6.57	-2.31	-5.91	-6.57
Relative improvement (%)			36.77	



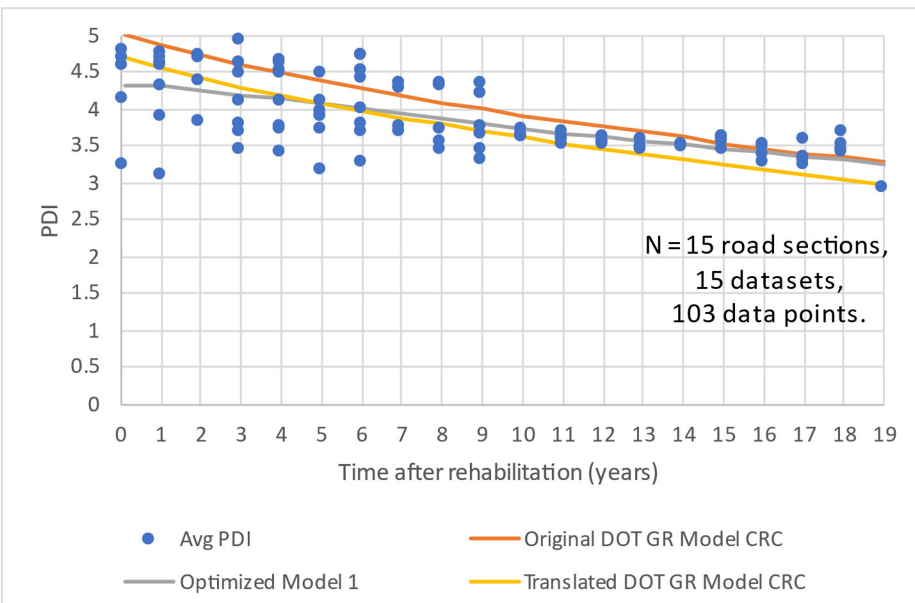
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original DOT GR Model CRC	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT GR Model CRC
a	25.706	2.066	55.4684	25.706
b	26.482	5.03	63.2846	26.482
c	1.02	1.253	1.0443	1.02
o	4.6	4.0	3.8	4.6
SSE	38.7602	11.5159	13.1795	38.7602
RMSE	0.6076	0.3312	0.3543	0.6076
MSE	0.3692	0.1097	0.1255	0.3692
MAPE (%)	13.32	7.82	8.26	8.17
Expected rehab year	16.10	88.64	22.00	16.10
Rehab threshold	2.7	2.7	2.7	2.7
Relative improvement (%)			38.03	



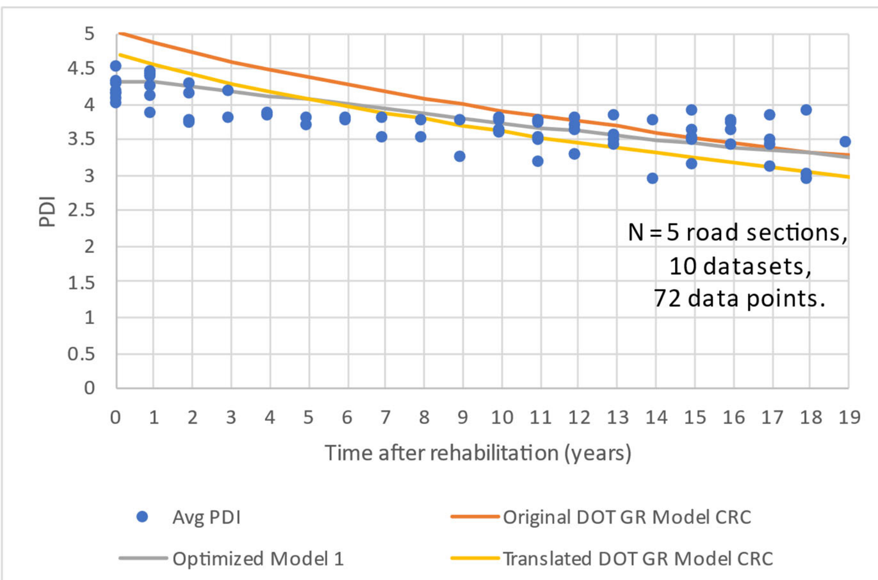
[PDI model evaluation using training data]
*Exception for GR CRC PDI model: Optimized model 1 is recommended for this model because its expected rehab year is almost identical to the optimized model 2 expected rehab year.

PDI Coef. (Training model)	Original DOT GR Model CRC	Optimized Model 1 (recommended)	Optimized Model 2	Translated DOT GR Model CRC
a	6.711	2.282	16.370	6.711
b	8.625	6.603	44.779	8.625
c	1.121	1.445	1.336	1.121
o	5	4.3	3.6	4.7
SSE	24.3116	13.8749	31.0857	17.1138
RMSE	2.7044	0.1089	2.7148	0.3403
MSE	0.2360	0.1347	0.3018	0.1662
MAPE (%)	9.53	7.16	9.49	8.06
Expected rehab year	28.70	33.86	31.70	23.36
Rehab threshold	2.7	2.7	2.7	2.7
1st 5 years average slope (%)	-12.59	-5.19	0.00	-12.59
2nd 5 years average slope (%)	-8.90	-6.41	-0.03	-8.90
3rd 5 years average slope (%)	-7.47	-5.47	-0.37	-7.47
Relative improvement (%)		24.85	0.43	



[PDI model evaluation using validation data]

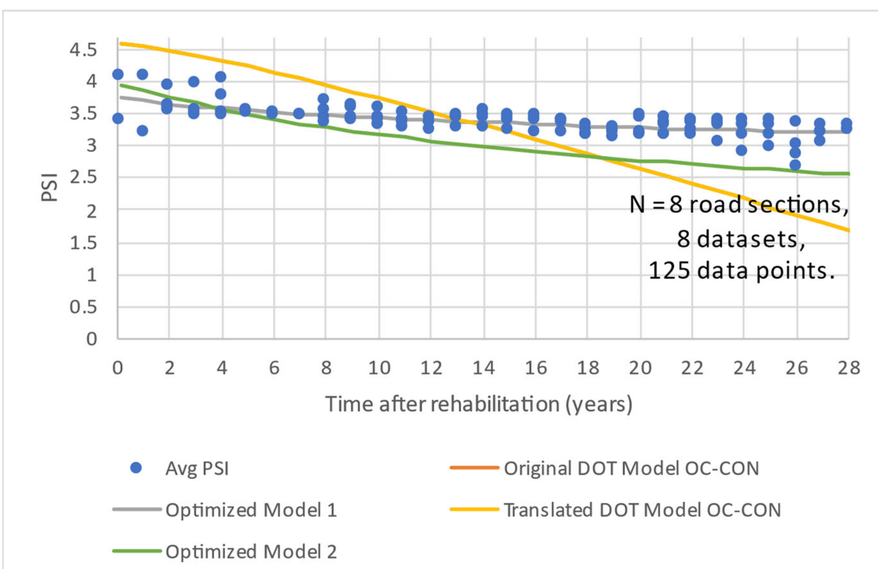
PDI Coef. (Validation model)	Original DOT GR Model CRC	Optimized Model 1 (recommended)	Optimized Model 2	Translated DOT GR Model CRC
a	6.711	2.282	16.370	6.711
b	8.625	6.603	44.779	8.625
c	1.121	1.445	1.336	1.121
o	5	4.3	3.6	4.7
SSE	18.7610	5.0130	9.8449	9.8045
RMSE	3.0392	0.7066	1.0705	0.5292
MSE	0.2680	0.0716	0.1406	0.1401
MAPE (%)	11.70	6.00	7.79	8.26
Expected rehab year	28.70	33.86	31.70	23.36
Rehab threshold	2.7	2.7	2.7	2.7
Relative improvement (%)		48.75	33.38	



APPENDIX C (OC CON)
[Original construction for concrete pavement]

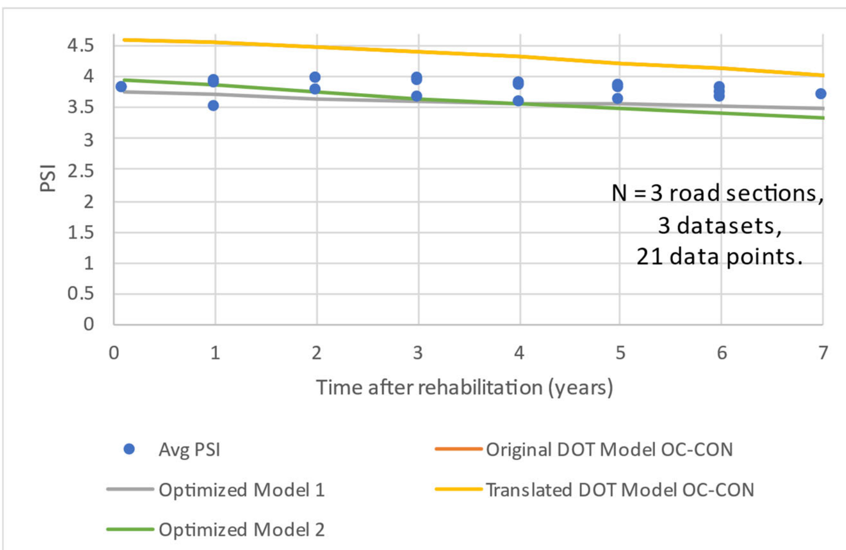
[PSI model evaluation using training data]

PSI Coef. (Training Model)	Original DOT Model OC-CON	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model OC-CON
a	60.322	1.7157	1.715	60.322
b	63.295	4.6443	4.339	63.295
c	1.02	1.234	1.4063	1.02
o	4.6	3.8	3.9	4.6
SSE	155.4499	3.1663	35.35	155.4499
RMSE	1.1152	0.1592	0.5318	1.1152
MSE	1.2436	0.0253	0.2828	1.2436
MAPE (%)	26.64	3.61	14.44	26.64
Expected rehab year	19.49	131.82	22.49	19.49
Rehab threshold	2.7	2.7	2.7	2.7
1st 5 years average slope (%)	-7.55	-4.08	-9.24	-7.55
2nd 5 years average slope (%)	-9.87	-2.20	-6.02	-9.87
3rd 5 years average slope (%)	-10.76	-1.63	-4.34	-10.76
Relative improvement (%)			45.78	



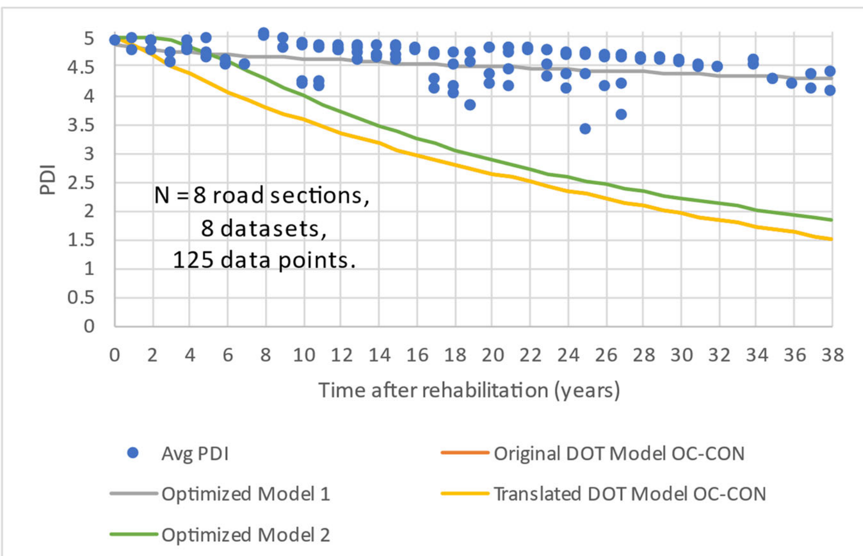
[PSI model evaluation using validation data]

PSI Coef. (Validation Model)	Original DOT Model OC-CON	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model OC-CON
a	60.322	1.7157	1.715	60.322
b	63.295	4.6443	4.339	63.295
c	1.02	1.234	1.4063	1.02
o	4.6	3.8	3.9	4.6
SSE	7.4010	0.7769	1.61	7.4010
RMSE	0.5937	0.1923	0.2769	0.5937
MSE	0.3524	0.0370	0.0767	0.3524
MAPE (%)	14.99	4.31	6.34	14.99
Expected rehab year	19.49	131.82	22.49	19.49
Rehab threshold	2.7	2.7	2.7	2.7
Relative improvement (%)			57.72	



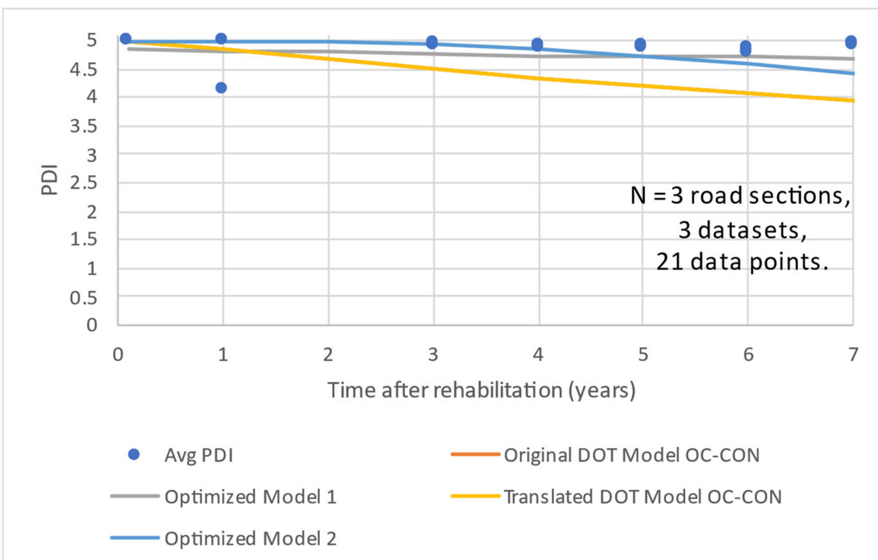
[PDI model evaluation using training data]

PDI Coef. (Training Model)	Original DOT Model OC-CON	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model OC-CON
a	3.611	17.343	1.715	3.611
b	5.638	20.564	11.143	5.638
c	1.27	1.039	2.263	1.27
o	5	4.9	5.0	5
SSE	345.1649	8.0754	257.08	345.1649
RMSE	1.7555	0.2685	1.5150	1.7555
MSE	3.0818	0.0751	2.2450	3.0818
MAPE (%)	34.80	4.86	28.91	34.80
Expected rehab year	19.32	288.57	22.32	19.32
Rehab threshold	2.7	2.7	2.7	2.7
1st 5 years average slope (%)	-16.23	-2.64	-5.68	-16.23
2nd 5 years average slope (%)	-12.33	-1.73	-14.86	-12.33
3rd 5 years average slope (%)	-9.82	-1.48	-12.16	-9.82
Relative improvement (%)			16.91	



[PDI model evaluation using validation data]

PDI Coef. (Training Model)	Original DOT Model OC-CON	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model OC-CON
a	3.611	1.715	1.474	3.611
b	5.638	6.541	12.933	5.638
c	1.27	1.341	2.631	1.27
o	5	4.9	5.0	5
SSE	7.8546	0.7740	1.98	7.8546
RMSE	0.6430	0.2018	0.3228	0.6430
MSE	0.4134	0.0407	0.1042	0.4134
MAPE (%)	11.56	2.82	4.36	11.56
Expected rehab year	19.32	288.57	22.32	19.32
Rehab threshold	2.7	2.7	2.7	2.7
Relative improvement (%)			62.27	

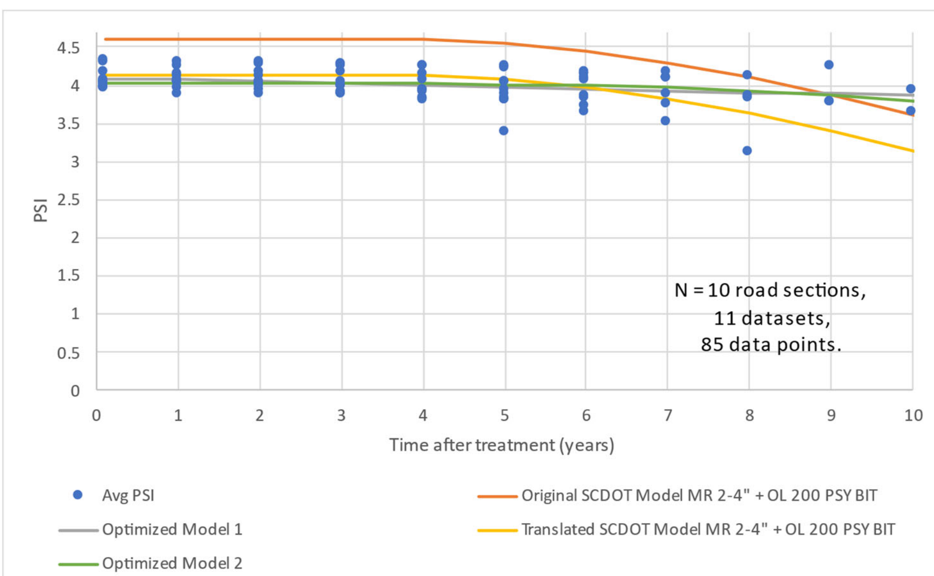


APPENDIX D (MR 2-4" + 200 PSY BIT)

[Mill and Replace 2 to 4 inches + OL 200 PSY for asphalt pavement]

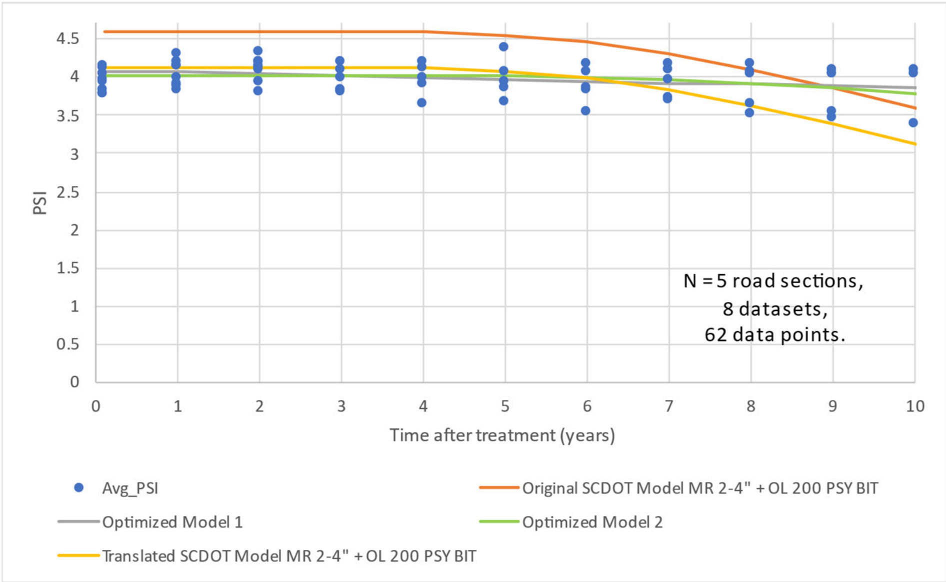
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original SCDOT Model MR 2-4" + OL 200 PSY BIT	Optimized Model 1	Optimized Model 2 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BIT
a	1.994	1.133	53.056	1.994
b	40.91	5.689	63.286	40.91
c	3.711	1.393	1.067	3.711
o	4.6	4.1	4.029	4.1
SSE	24.9581	3.0715	3.2425	5.2597
RMSE	0.5419	0.1901	0.1953	0.2488
MSE	0.2936	0.0361	0.0381	0.0619
MAPE (%)	12.71	3.81	3.74	4.84
Expected rehab year	13.47	358.81	16.46	11.65
Rehab threshold	2.7	2.7	2.7	2.7
1st 5 years average slope (%)	-0.25	-2.19	-0.21	-0.25
2nd 5 years average slope (%)	-17.24	-2.22	-3.56	-17.24
3rd 5 years average slope (%)	-25.89	-1.77	-13.17	-25.89
15 years average slope (%)	-14.62	-2.08	-5.48	-14.62
Relative improvement (%)			70.56	



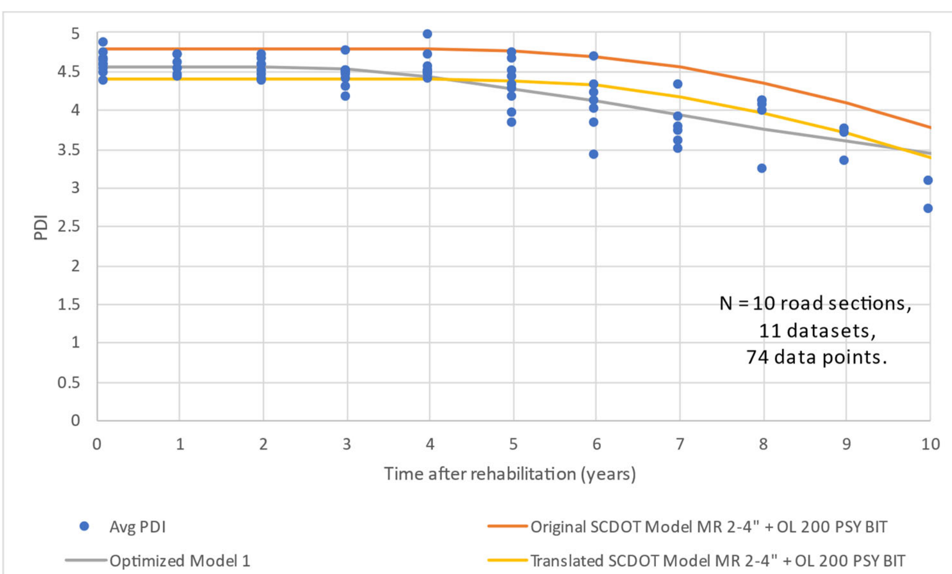
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original SCDOT Model MR 2-4" + OL 200 PSY BIT	Optimized Model 1	Optimized Model 2 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BIT
a	1.994	1.133	53.056	1.994
b	40.91	5.689	63.286	40.91
c	3.711	1.393	1.067	3.711
o	4.6	4.1	4.0	4.1
SSE	18.7758	2.8727	2.7068	6.1790
RMSE	0.5503	0.2153	0.2090	0.3157
MSE	0.3028	0.0463	0.0437	0.0997
MAPE (%)	12.92	4.70	4.66	5.84
Expected rehab year	13.47	358.81	16.46	11.65
Rehab threshold	2.7	2.7	2.7	2.7
Relative improvement (%)			63.91	



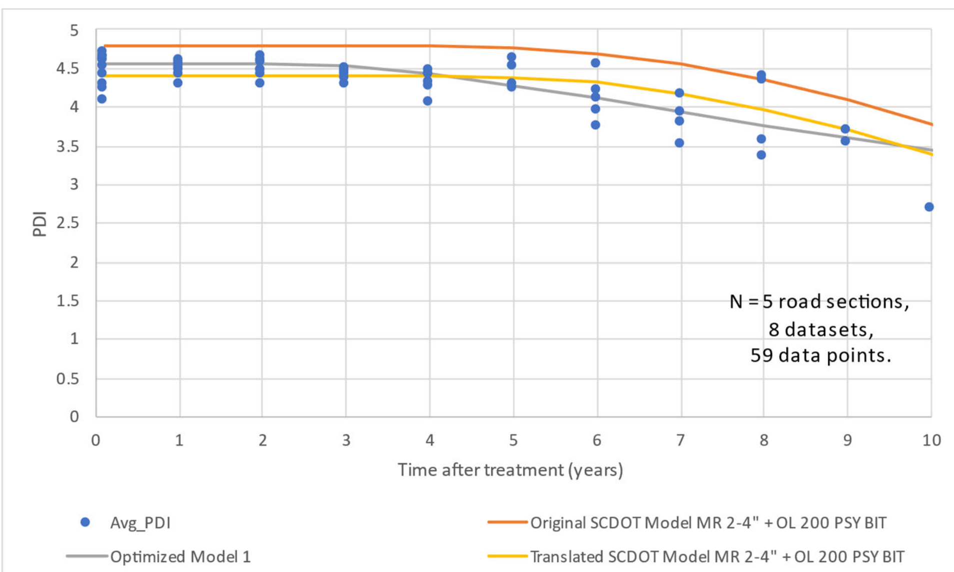
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original SCDOT Model MR 2-4" + OL 200 PSY BIT	Optimized Model 1 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BIT
a	2.47	1.133	2.47
b	50.166	17.37	50.166
c	3.711	3.417	3.711
o	4.8	4.6	4.4
SSE	18.2466	4.8732	6.2436
RMSE	0.4966	0.2566	0.2905
MSE	0.2466	0.0659	0.0844
MAPE (%)	10.35	4.85	5.43
Expected rehab year	13.05	17.71	11.99
Rehab threshold	2.7	2.7	2.7
1st 5 years average slope (%)	-0.09	-3.37	-3.73
2nd 5 years average slope (%)	-17.07	-17.14	-22.32
3rd 5 years average slope (%)	-35.62	-11.56	-45.65
15 years average slope (%)	-17.59	-11.33	-23.87
Relative improvement (%)		53.12	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original SCDOT Model MR 2-4" + OL 200 PSY BIT	Optimized Model 1 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BIT
a	2.47	1.133	2.47
b	50.166	17.37	50.166
c	3.711	3.417	3.711
o	4.8	4.6	4.4
SSE	13.6978	3.6472	3.6380
RMSE	0.4818	0.2486	0.2483
MSE	0.2322	0.0618	0.0617
MAPE (%)	10.29	4.48	4.74
Expected rehab year	13.05	17.71	11.99
Rehab threshold	2.7	2.7	2.7
Relative improvement (%)		56.47	

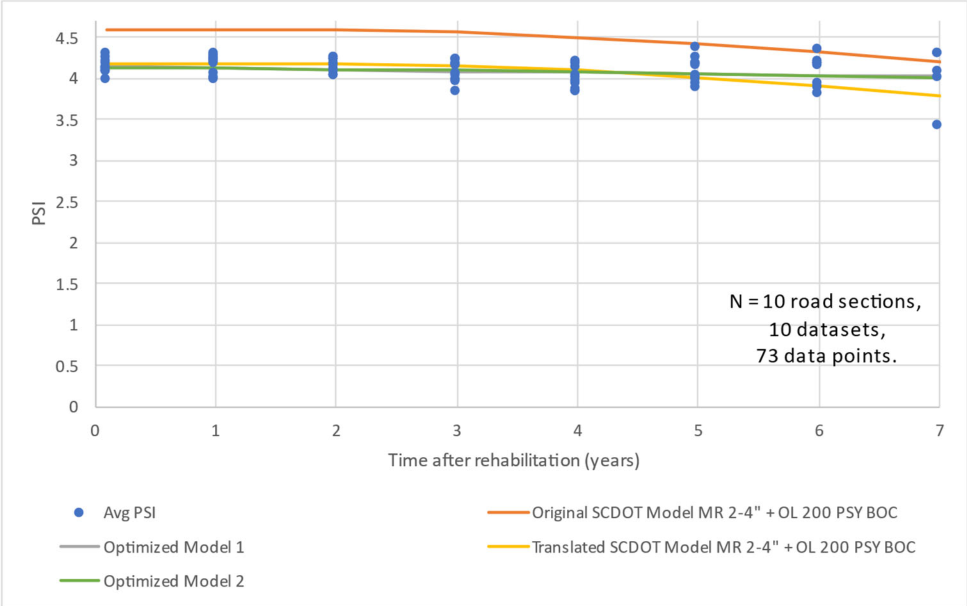


APPENDIX E (MR 2-4" + 200 PSY BOC)

[Mill and Replace 2 to 4 inches + OL 200 PSY for asphalt over concrete pavement]

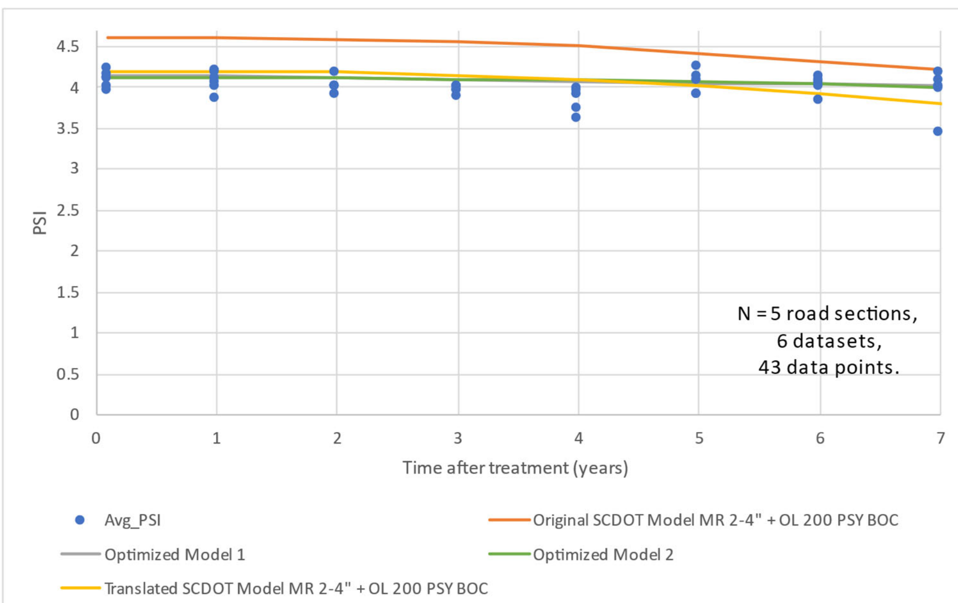
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original SCDOT Model MR 2-4" + OL 200 PSY BOC	Optimized Model 1	Optimized Model 2 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BOC
a	2.109	1.181	57.123	2.109
b	11.632	5.239	63.295	11.632
c	1.989	1.28	1.035	1.989
o	4.6	4.2	4.1	4.2
SSE	14.5419	1.6786	1.7668	2.3014
RMSE	0.4463	0.1516	0.1556	0.1776
MSE	0.1992	0.0230	0.0242	0.0315
MAPE (%)	10.28	3.02	3.09	3.36
Expected rehab year	20.31	1943.24	23.32	16.25
Rehab threshold	2.7	2.7	2.7	2.7
1st 5 years average slope (%)	-2.39	-2.01	-1.03	-2.39
2nd 5 years average slope (%)	-11.41	-1.47	-3.74	-11.41
3rd 5 years average slope (%)	-12.06	-1.12	-6.39	-12.06
15 years average slope (%)	-8.91	-1.52	-3.74	-8.91
Relative improvement (%)			69.94	



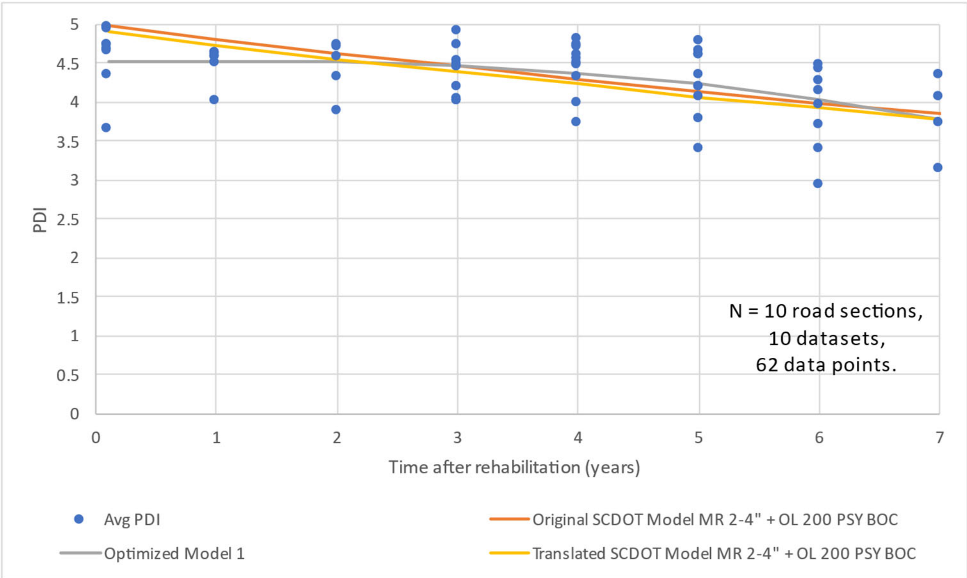
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original SCDOT Model MR 2-4" + OL 200 PSY BOC	Optimized Model 1	Optimized Model 2 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BOC
a	2.109	1.181	57.123	2.109
b	11.632	5.239	63.295	11.632
c	1.989	1.28	1.035	1.989
o	4.6	4.2	4.1	4.2
SSE	11.4202	1.1920	1.0720	1.7785
RMSE	0.5154	0.1665	0.1579	0.2034
MSE	0.2656	0.0277	0.0249	0.0414
MAPE (%)	12.13	3.21	3.06	4.46
Expected rehab year	20.31	1943.24	23.32	16.25
Rehab threshold	2.7	2.7	2.7	2.7
Relative improvement (%)			74.79	



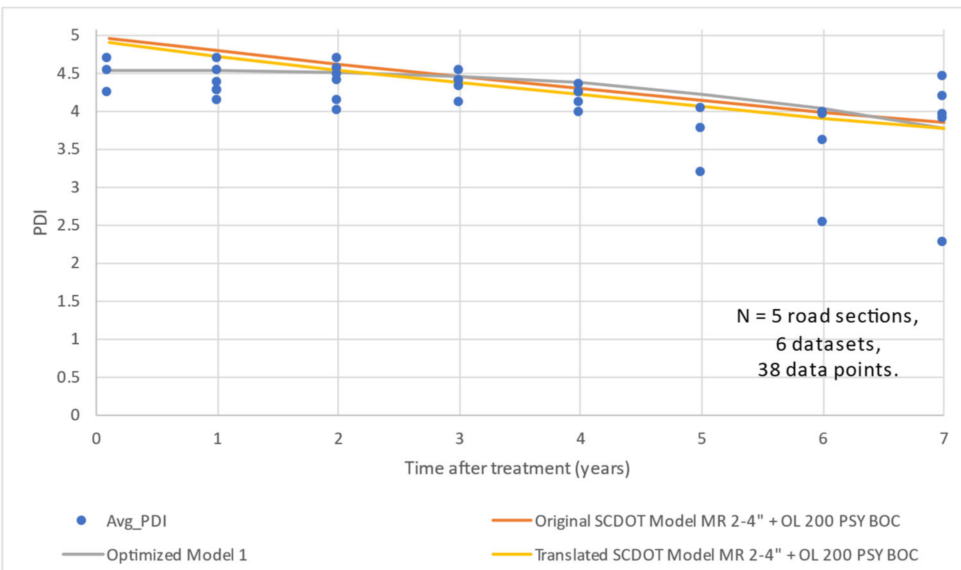
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original SCDOT Model MR 2-4" + OL 200 PSY BOC	Optimized Model 1 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BOC
a	45.434	28.83	45.434
b	47.072	34.86	47.072
c	1.02	1.097	1.02
o	5	4.5	4.9
SSE	10.8664	8.8566	10.5643
RMSE	0.4187	0.3780	0.4128
MSE	0.1753	0.1429	0.1704
MAPE (%)	8.08	7.41	8.05
Expected rehab year	15.22	9.79	14.67
Rehab threshold	2.7	2.7	2.7
1st 5 years average slope (%)	-17.28	-4.11	-4.19
2nd 5 years average slope (%)	-14.78	-29.29	-30.14
3rd 5 years average slope (%)	-13.79	-66.55	-68.76
15 years average slope (%)	-15.21	-33.11	-34.14
Relative improvement (%)		8.32	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original SCDOT Model MR 2-4" + OL 200 PSY BOC	Optimized Model 1 (recommended)	Translated SCDOT Model MR 2-4" + OL 200 PSY BOC
a	45.434	28.83	45.434
b	47.072	34.86	47.072
c	1.02	1.097	1.02
o	5	4.5	4.9
SSE	9.4711	7.6029	7.7504
RMSE	0.4992	0.4473	0.4516
MSE	0.2492	0.2001	0.2040
MAPE (%)	9.83	8.40	8.71
Expected rehab year	15.22	9.79	14.67
Rehab threshold	2.7	2.7	2.7
Relative improvement (%)		14.55	

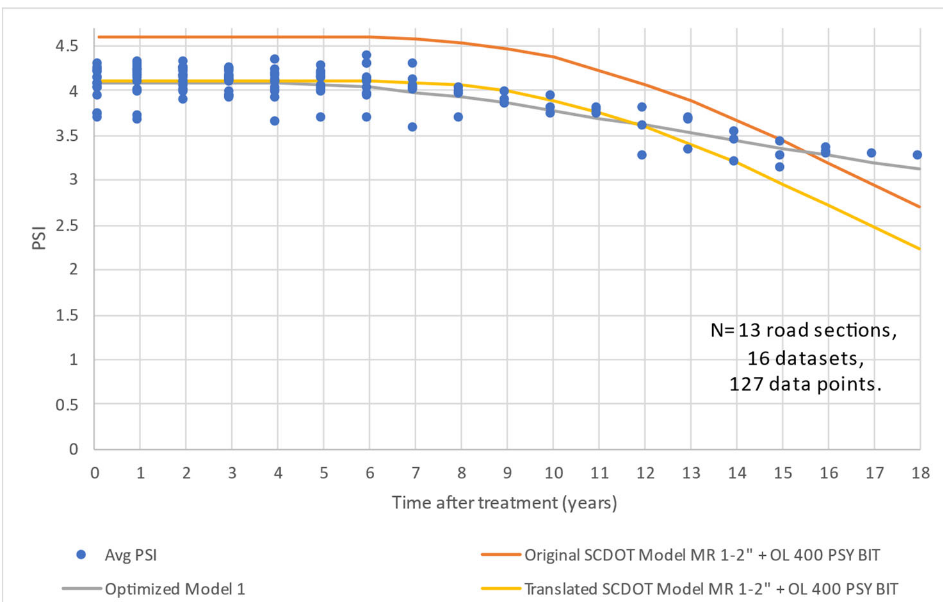


APPENDIX F (MR 1-2" + 400 PSY BIT)

[Mill and Replace 1 to 2 inches + OL 400 PSY for asphalt pavement]

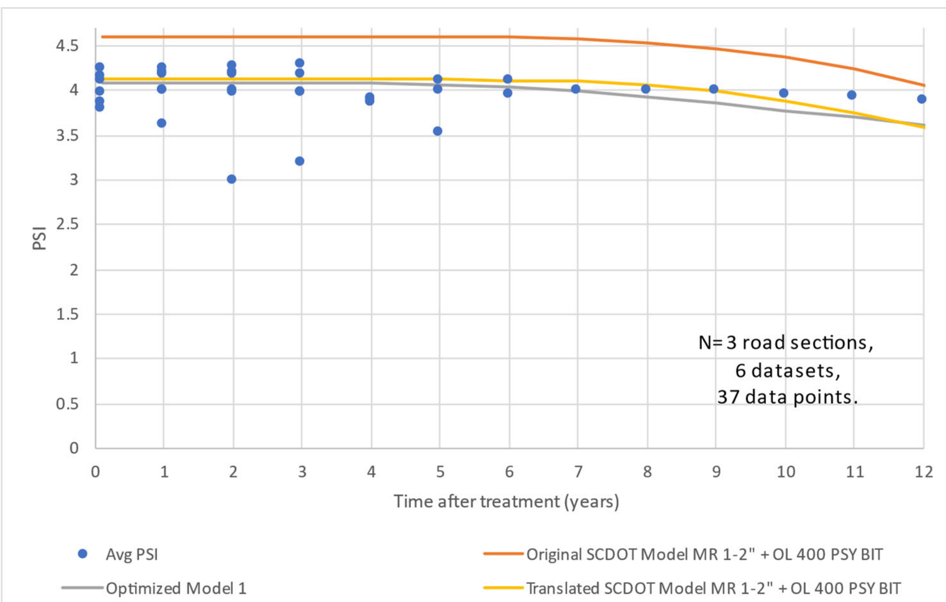
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original SCDOT Model MR 1-2" + OL 400 PSY BIT	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2" + OL 400 PSY BIT
a	2.435	1.133	2.435
b	79.662	31.530	79.662
c	3.711	3.113	3.711
o	4.6	4.1	4.1
SSE	36.3772	3.3082	6.7719
RMSE	5.4444	0.1823	0.1903
MSE	0.2864	0.0260	0.0533
MAPE (%)	12.78	3.09	4.21
Expected rehab year	18.05	25.19	16.09
Rehab threshold	2.7	2.7	2.7
1st 5 years average slope (%)	-0.01	-0.40	-0.01
2nd 5 years average slope (%)	-5.69	-6.47	-5.69
3rd 5 years average slope (%)	-19.81	-8.31	-19.81
Relative improvement (%)		75.80	



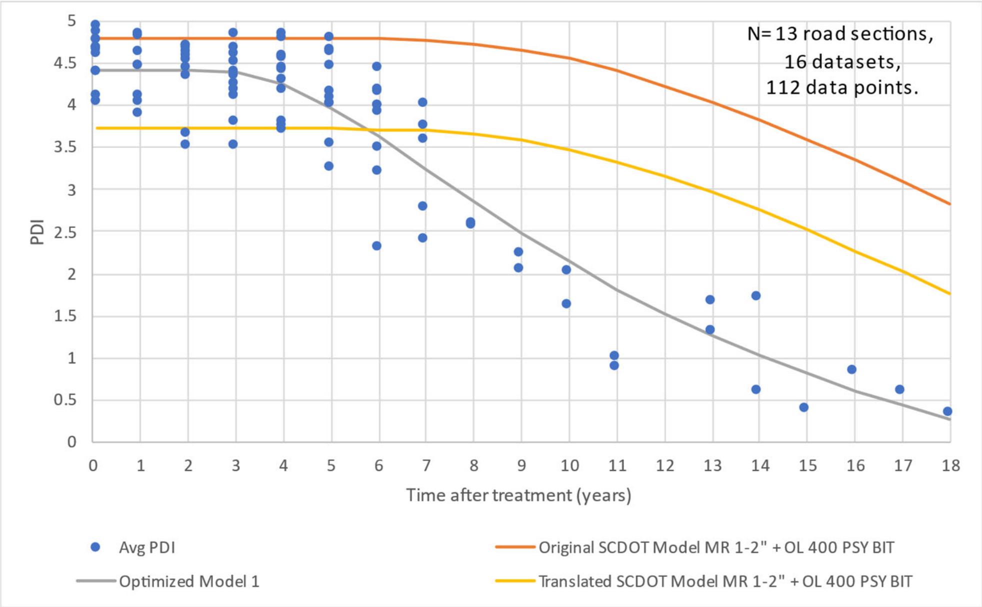
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original SCDOT Model MR 1-2" + OL 400 PSY BIT	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2" + OL 400 PSY BIT
a	2.435	1.133	2.435
b	79.662	31.530	79.662
c	3.711	3.113	3.711
o	4.6	4.1	4.1
SSE	16.8138	3.4136	3.4596
RMSE	3.7161	0.5971	0.6747
MSE	0.4544	0.0923	0.0935
MAPE (%)	16.08	5.48	5.49
Expected rehab year	18.05	25.19	16.09
Rehab threshold	2.7	2.7	2.7
Relative improvement (%)		65.92	



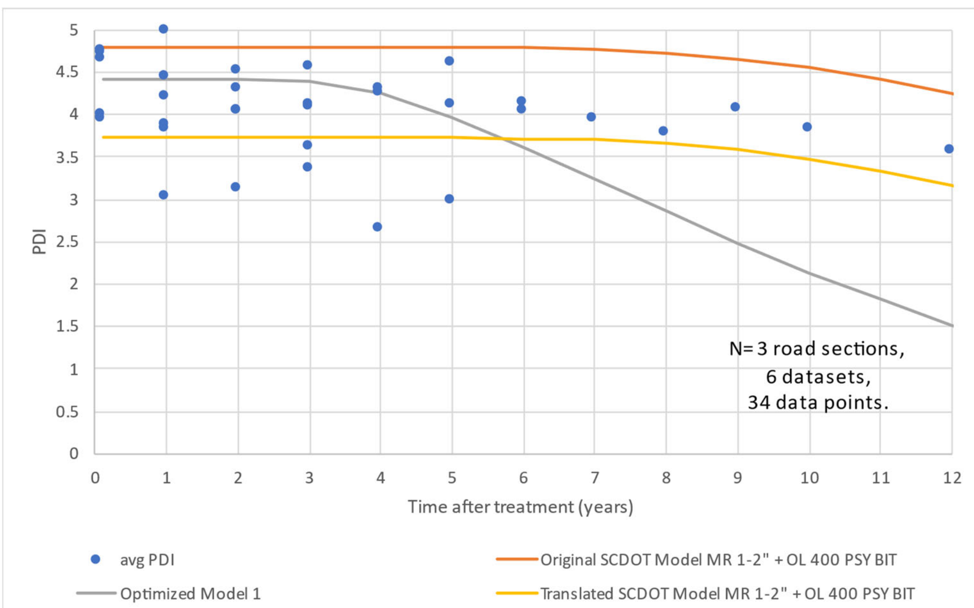
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original SCDOT Model MR 1-2" + OL 400 PSY BIT	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2" + OL 400 PSY BIT
a	2.458	1.935	2.458
b	79.024	22.66	79.024
c	3.711	3.711	3.711
o	4.8	4.422	3.7
SSE	238.1713	21.9326	108.5356
RMSE	11.3886	0.2320	0.2527
MSE	2.1265	0.1958	0.9691
MAPE (%)	87.68	16.90	56.66
Expected rehab year	18.55	8.40	14.21
Rehab threshold	2.7	2.7	2.7
1st 5 years average slope (%)	-0.02	-9.07	-0.02
2nd 5 years average slope (%)	-6.00	-37.32	-6.00
3rd 5 years average slope (%)	-20.55	-25.15	-20.55
Relative improvement (%)		80.72	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original SCDOT Model MR 1-2" + OL 400 PSY BIT	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2" + OL 400 PSY BIT
a	2.458	1.935	2.458
b	79.024	22.66	79.024
c	3.711	3.711	3.711
o	4.8	4.422	3.7
SSE	28.2404	22.8918	13.4590
RMSE	4.3593	0.1086	2.0548
MSE	0.8306	0.6733	0.3959
MAPE (%)	21.13	17.21	13.84
Expected rehab year	18.55	8.40	14.21
Rehab threshold	2.7	2.7	2.7
Relative improvement (%)		18.55	

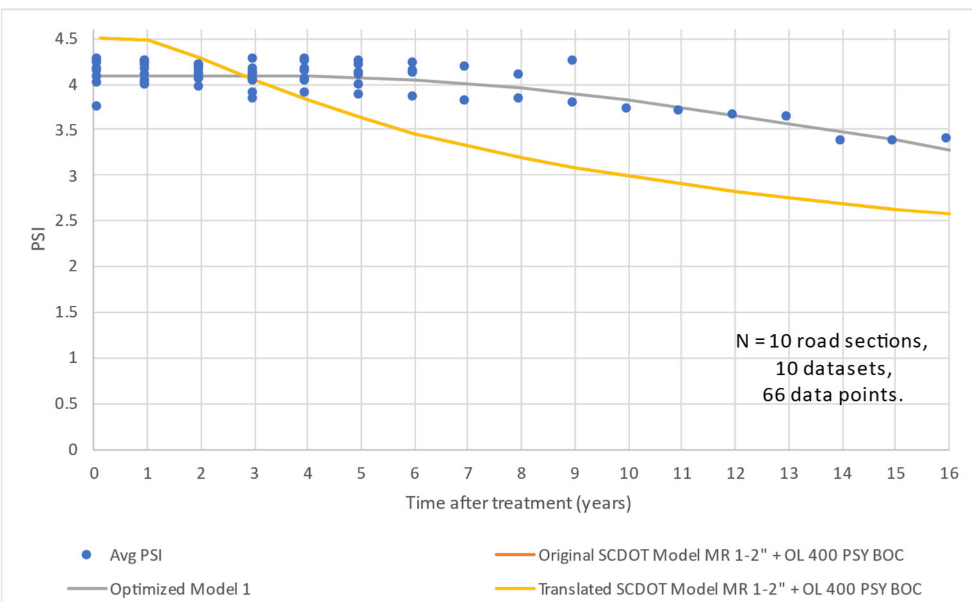


APPENDIX G (MR 1-2" + 400 PSY BOC)

[Mill and Replace 1 to 2 inches + OL 400 PSY for asphalt over concrete pavement]

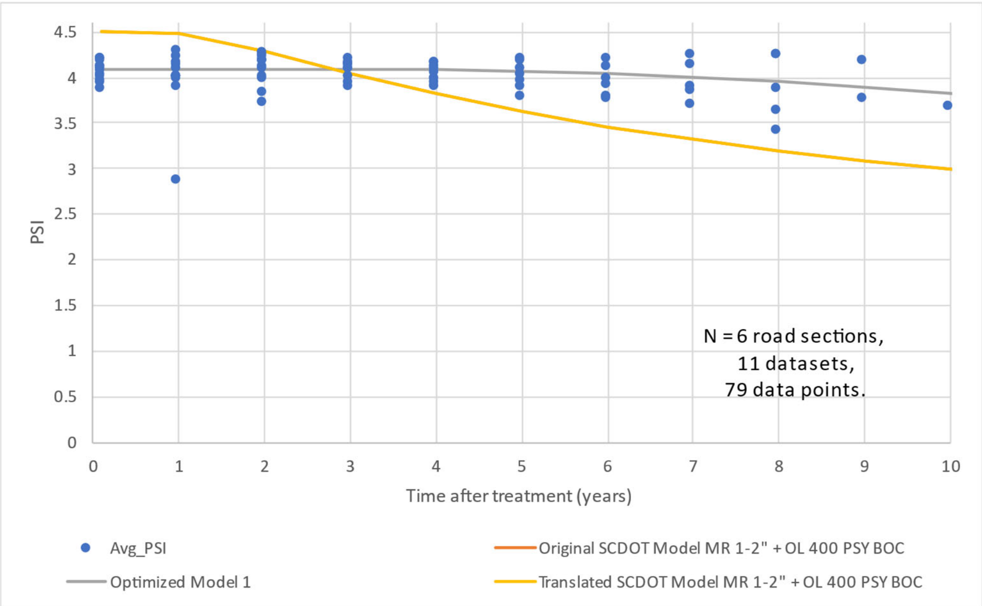
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original SCDOT Model MR 1-2" + OL 400 PSY BOC	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2" + OL 400 PSY BOC
a	1.181	2.177	1.181
b	4.686	21.176	4.686
c	2.194	2.194	2.194
o	4.5	4.1	4.5
SSE	11.1167	1.0337	11.1167
RMSE	0.5651	0.0502	0.5651
MSE	0.1853	0.0172	0.1853
MAPE (%)	8.89	2.57	10.09
Expected rehab year	13.88	22.32	13.88
Rehab threshold	2.7	2.7	2.7
1st 5 years average slope (%)	-17.70	-0.46	-17.70
2nd 5 years average slope (%)	-11.93	-5.63	-11.93
3rd 5 years average slope (%)	-6.65	-8.87	-6.65
Relative improvement (%)		71.06	



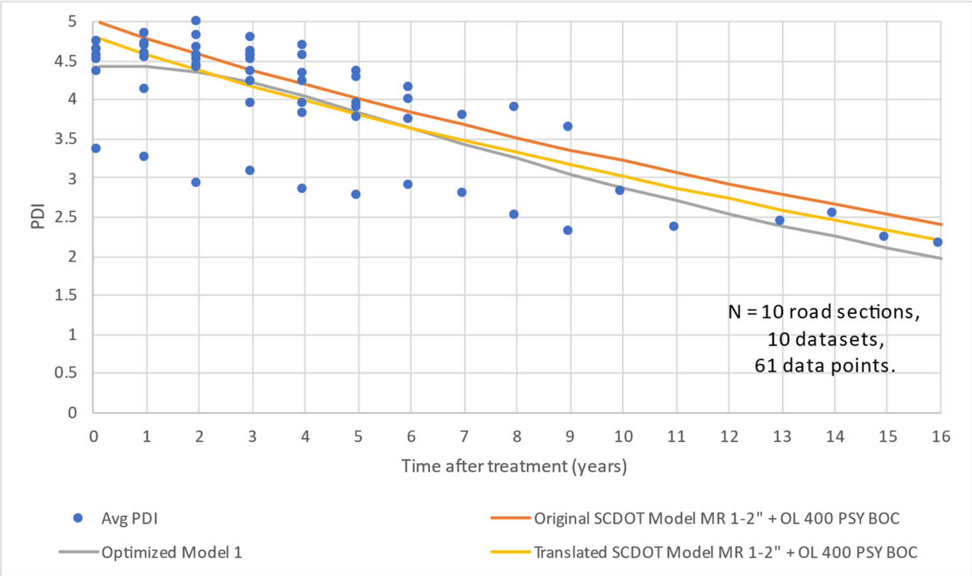
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original SCDOT Model MR 1-2"+400 PSY BOC	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2"+400 PSY BOC
a	1.181	2.177	1.181
b	4.686	21.176	4.686
c	2.194	2.194	2.194
o	4.5	4.1	4.5
SSE	18.1873	3.7132	18.1873
RMSE	0.2215	0.6201	0.2215
MSE	0.2302	0.0470	0.2302
MAPE (%)	9.99	3.84	9.99
Expected rehab year	13.88	22.32	13.88
Rehab threshold	2.7	2.7	2.7
Relative improvement (%)		61.54	



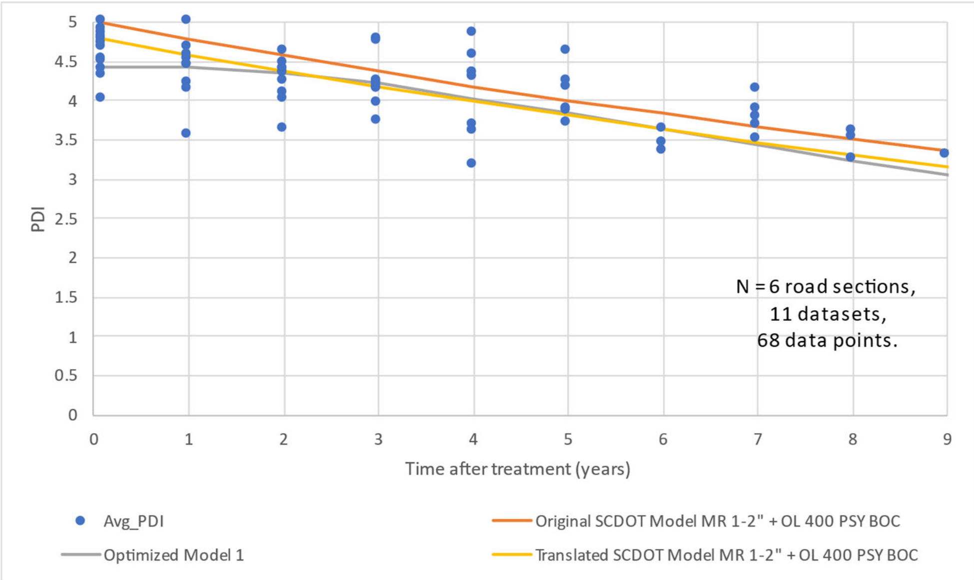
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original SCDOT Model MR 1-2" + OL 400 PSY BOC	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2" + OL 400 PSY BOC
a	8.701	2.282	8.701
b	10.241	7.406	10.241
c	1.106	1.83	1.106
o	5	4.429	4.803
SSE	20.7674	15.5450	17.1469
RMSE	1.9621	0.1988	0.4789
MSE	0.3776	0.2826	0.3118
MAPE (%)	12.68	11.69	11.93
Expected rehab year	13.68	11.05	12.23
Rehab threshold	2.7	2.7	2.7
1st 5 years average slope (%)	-19.96	-12.16	-19.96
2nd 5 years average slope (%)	-15.58	-18.88	-15.58
3rd 5 years average slope (%)	-13.55	-14.89	-13.55
Relative improvement (%)		7.76	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original SCDOT Model MR 1-2" + OL 400 PSY BOC	Optimized Model 1 (recommended)	Translated SCDOT Model MR 1-2" + OL 400 PSY BOC
a	8.701	2.282	8.701
b	10.241	7.406	10.241
c	1.106	1.83	1.106
o	5	4.429	4.803
SSE	11.7500	8.8311	9.0472
RMSE	0.4157	0.6975	0.0196
MSE	0.1728	0.1299	0.1331
MAPE (%)	8.16	6.74	6.64
Expected rehab year	13.68	11.05	12.23
Rehab threshold	2.7	2.7	2.7
Relative improvement (%)		17.42	

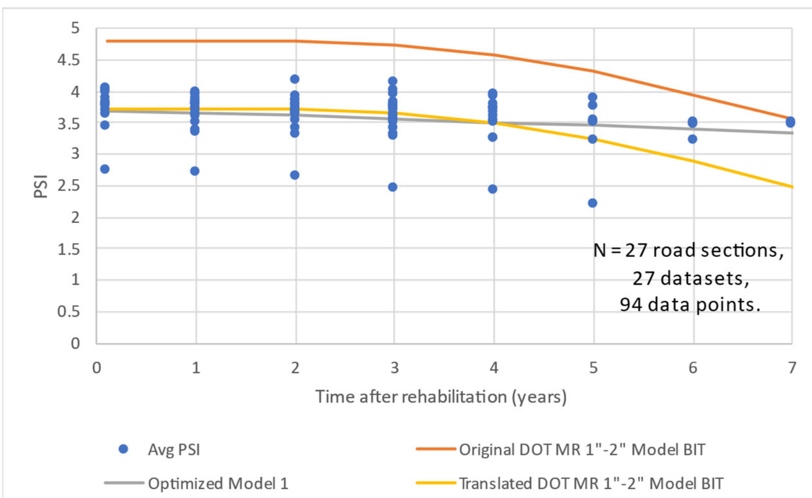


APPENDIX H (MR 1-2" BIT)

[Mill and Replace 1 to 2 inches for asphalt pavement]

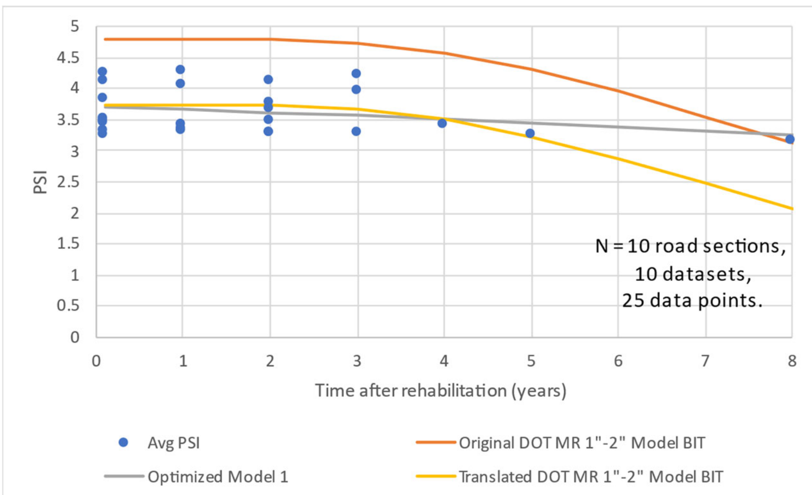
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original DOT MR 1"-2" Model BIT	Optimized Model 1 (recommended)	Translated DOT MR 1"-2" Model BIT
a	2.646	29.85	2.646
b	15.692	33.3	15.692
c	2.611	1.04	2.611
o	4.8	3.7	3.7
SSE	121.1644	10.7070	10.9729
RMSE	1.1734	0.3488	0.3531
MSE	1.3769	0.1217	0.1247
MAPE (%)	32.70	7.22	7.38
Expected rehab year	9.48	18.94	6.95
Rehab threshold	2.5	2.5	2.5
1st 5 years average slope (%)	-10.11	-4.94	-10.11
2nd 5 years average slope (%)	-41.81	-6.47	-41.81
3rd 5 years average slope (%)	-36.51	-6.98	-19.91
Relative improvement (%)		77.92	



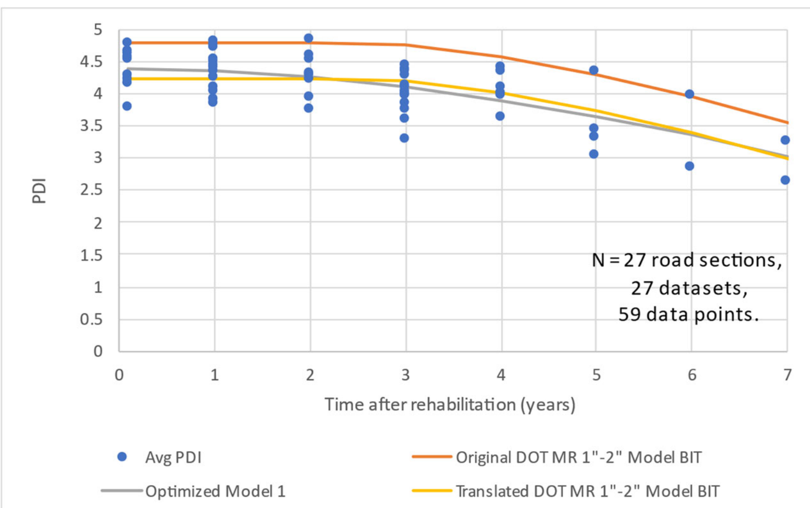
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original DOT MR 1"-2" Model BIT	Optimized Model 1 (recommended)	Translated DOT MR 1"-2" Model BIT
a	2.646	29.85	2.646
b	15.692	33.3	15.692
c	2.611	1.04	2.611
o	4.8	3.7	3.7
SSE	33.9533	3.0436	4.1954
RMSE	1.1654	0.3489	0.4097
MSE	1.3581	0.1217	0.1678
MAPE (%)	31.24	8.55	9.63
Expected rehab year	9.48	18.94	6.95
Rehab threshold	2.5	2.5	2.5
Relative improvement (%)		72.63	



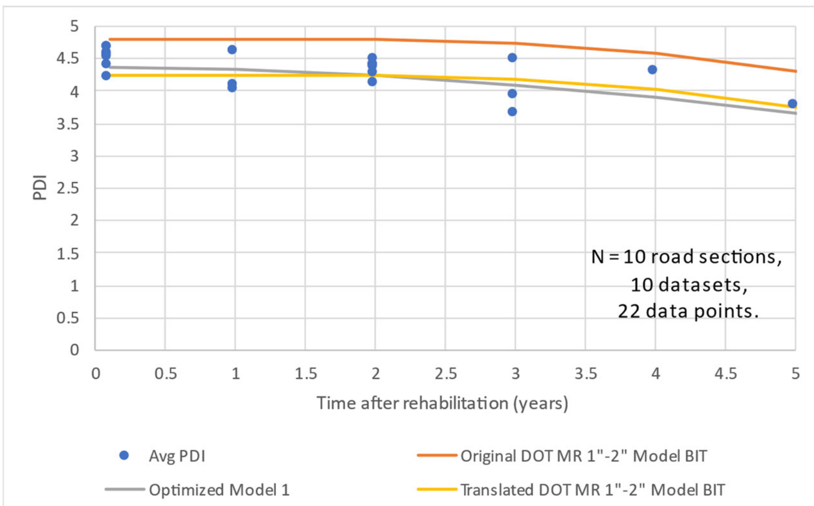
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original DOT MR 1"-2" Model BIT	Optimized Model 1 (recommended)	Translated DOT MR 1"-2" Model BIT
a	2.646	33.59	2.646
b	15.692	37	15.692
c	2.611	1.056	2.611
o	4.8	4.4	4.2
SSE	23.4908	5.8932	6.6189
RMSE	0.6535	0.3273	0.3469
MSE	0.4271	0.1072	0.1203
MAPE (%)	14.33	6.60	6.95
Expected rehab year	9.48	8.36	8.17
Rehab threshold	2.5	2.5	2.5
1st 5 years average slope (%)	-10.11	-15.06	-10.11
2nd 5 years average slope (%)	-41.81	-39.02	-41.81
3rd 5 years average slope (%)	-36.51	-55.50	-32.84
Relative improvement (%)		53.97	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original DOT MR 1"-2" Model BIT	Optimized Model 1 (recommended)	Translated DOT MR 1"-2" Model BIT
a	2.646	33.59	2.646
b	15.692	37	15.692
c	2.611	1.056	2.611
o	4.8	4.4	4.2
SSE	7.2645	4.1959	5.2343
RMSE	0.5746	0.4367	0.4878
MSE	0.3302	0.1907	0.2379
MAPE (%)	11.82	6.46	7.45
Expected rehab year	9.48	8.36	8.17
Rehab threshold	2.5	2.5	2.5
Relative improvement (%)		45.34	

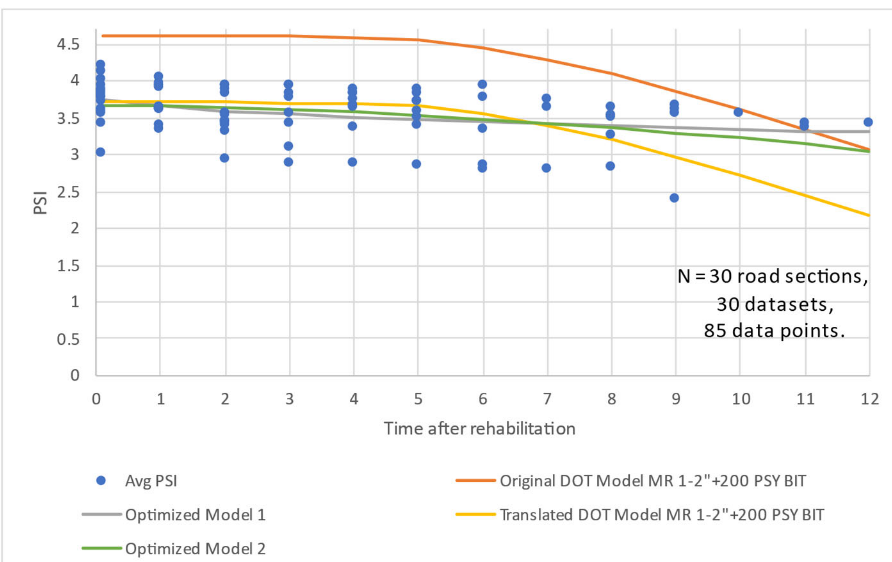


APPENDIX I (MR 1-2" + 200 PSY BIT)

[Mill and Replace 1 to 2 inches + OL 200 PSY for asphalt pavement]

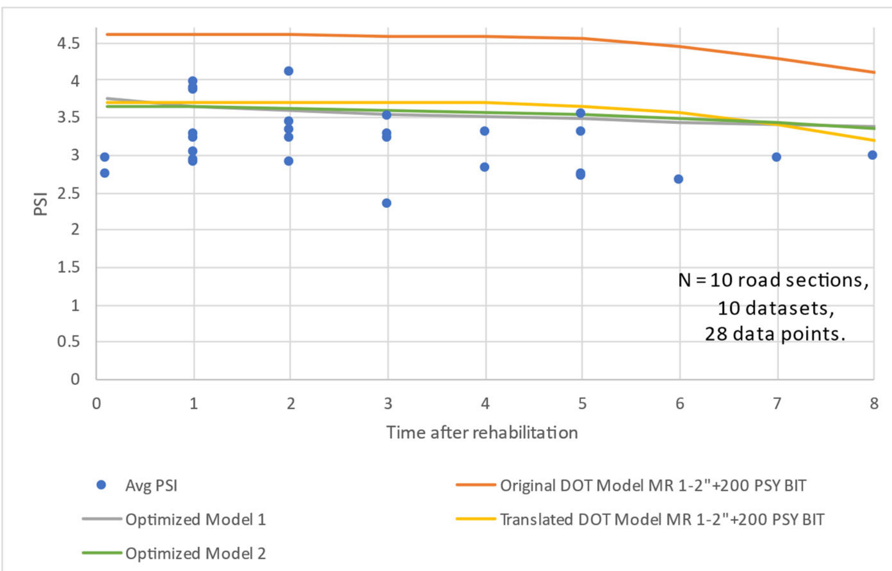
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original DOT Model MR 1-2"+200 PSY BIT	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model MR 1-2"+200 PSY BIT
a	1.994	22.09	58.32	1.994
b	40.91	24.16	63.419	40.91
c	3.711	1.023	1.031	3.711
o	4.6	3.8	3.7	3.7
SSE	79.5738	7.7171	8.0370	8.5196
RMSE	1.0166	0.3166	0.3231	0.3326
MSE	1.0334	0.1002	0.1044	0.1106
MAPE (%)	28.06	7.51	7.63	7.83
Expected rehab year	14.28	84.21	17.28	10.80
Rehab threshold	2.5	2.5	2.5	2.5
1st 5 years average slope (%)	-1.05	-5.43	-2.55	-1.05
2nd 5 years average slope (%)	-21.20	-2.54	-6.60	-21.20
3rd 5 years average slope (%)	-25.27	-1.98	-9.56	-25.27
Relative improvement (%)			72.79	



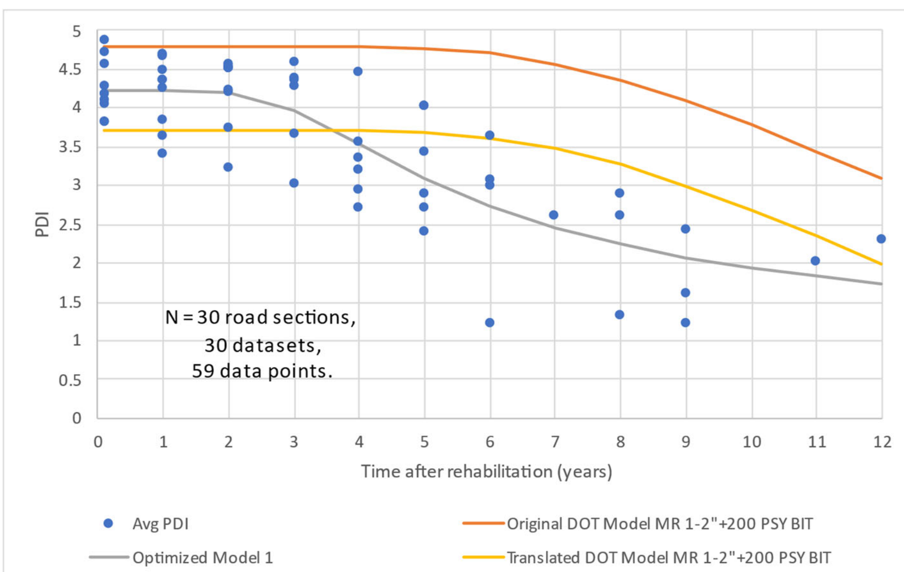
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original DOT Model MR 1-2"+200 PSY BIT	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model MR 1-2"+200 PSY BIT
a	1.994	22.09	58.32	1.994
b	40.91	24.16	63.419	40.91
c	3.711	1.023	1.031	3.711
o	4.6	3.8	3.7	3.7
SSE	58.0129	9.5812	10.5454	11.3315
RMSE	1.4394	0.5850	0.6137	0.6362
MSE	2.0719	0.3422	0.3766	0.4047
MAPE (%)	45.85	17.19	18.27	18.98
Expected rehab year	14.28	84.21	17.28	10.80
Rehab threshold	2.5	2.5	2.5	2.5
Relative improvement (%)			60.15	



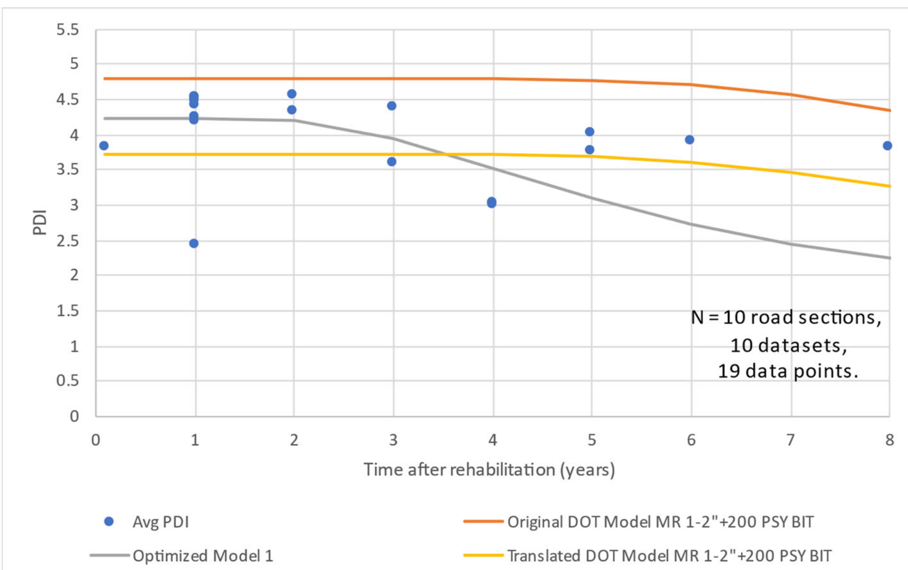
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original DOT Model MR 1-2"+200 PSY BIT	Optimized Model 1 (recommended)	Translated DOT Model MR 1-2"+200 PSY BIT
a	2.47	1.133	2.47
b	50.166	16.18	50.166
c	3.711	5.649	3.711
o	4.8	4.2	3.7
SSE	87.7148	15.7145	32.2649
RMSE	1.2745	0.5395	0.7730
MSE	1.6243	0.2910	0.5975
MAPE (%)	37.18	14.60	21.72
Expected rehab year	13.60	6.82	10.57
Rehab threshold	2.5	2.5	2.5
1st 5 years average slope (%)	-0.55	-23.38	-0.55
2nd 5 years average slope (%)	-23.05	-19.98	-23.05
3rd 5 years average slope (%)	-36.04	-6.71	-36.04
Relative improvement (%)		60.73	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original DOT Model MR 1-2"+200 PSY BIT	Optimized Model 1 (recommended)	Translated DOT Model MR 1-2"+200 PSY BIT
a	2.47	1.133	2.47
b	50.166	16.18	50.166
c	3.711	5.649	3.711
o	4.8	4.2	3.7
SSE	18.1610	11.5180	8.4005
RMSE	0.9777	0.7786	0.6649
MSE	0.9558	0.6062	0.4421
MAPE (%)	23.05	16.65	15.97
Expected rehab year	13.60	6.82	10.57
Rehab threshold	2.5	2.5	2.5
Relative improvement (%)		27.76	

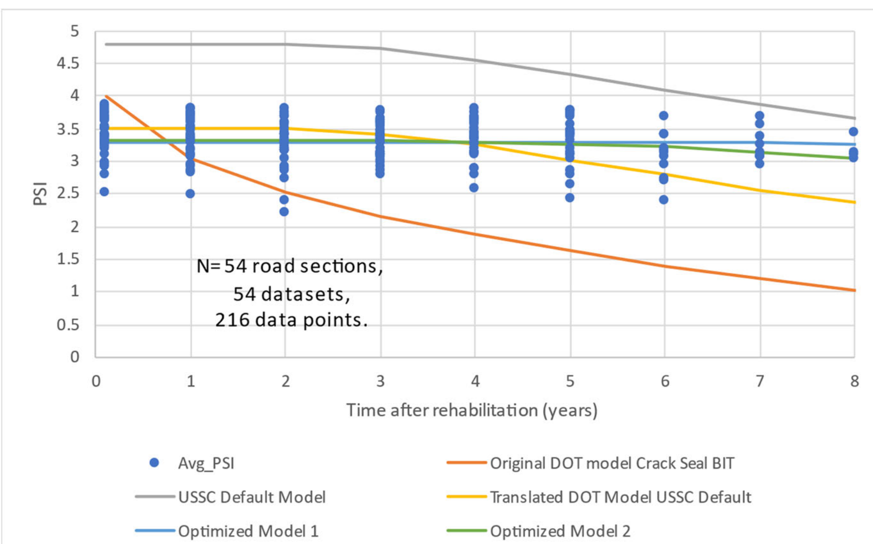


APPENDIX J (CRACK SEAL BIT)

[Crack seal for asphalt pavement]

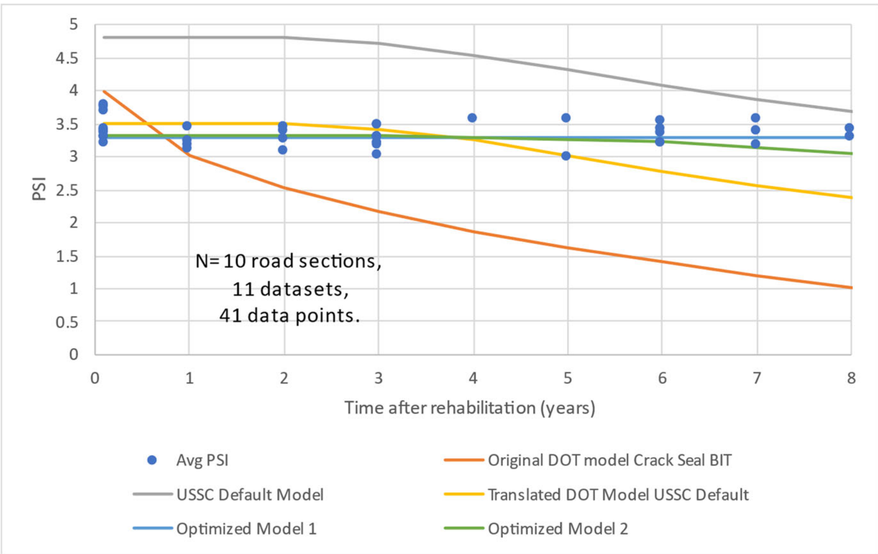
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original DOT Model Crack Seal BIT	USSC Default Model	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model USSC Default
a	20.887	1.133	12.47	58.317	1.133
b	20.437	15.468	38.1	66.770	15.468
c	1.02	3.711	1.33	1.057	3.711
o	4.6	4.8	3.3	3.3	3.5
SSE	315.0073	398.97	22.0246	21.5498	33.2785
RMSE	1.2076	1.3591	0.3193	0.3159	0.3925
MSE	1.4584	1.8471	0.1020	0.1031	0.1541
MAPE (%)	32.13	40.70	8.01	7.84	9.76
Expected rehab year	2.07	20.22	47.23	11.00	7.34
Rehab threshold	2.5	2.5	2.5	2.5	2.5
1st 5 years average slope (%)	-48.43	-9.72	0.00	-1.26	-9.72
2nd 5 years average slope (%)	-17.56	-18.73	-0.02	-12.46	-18.73
3rd 5 years average slope (%)	-12.82	-9.94	-0.12	-35.38	-9.94
Relative improvement (%)				75.61	



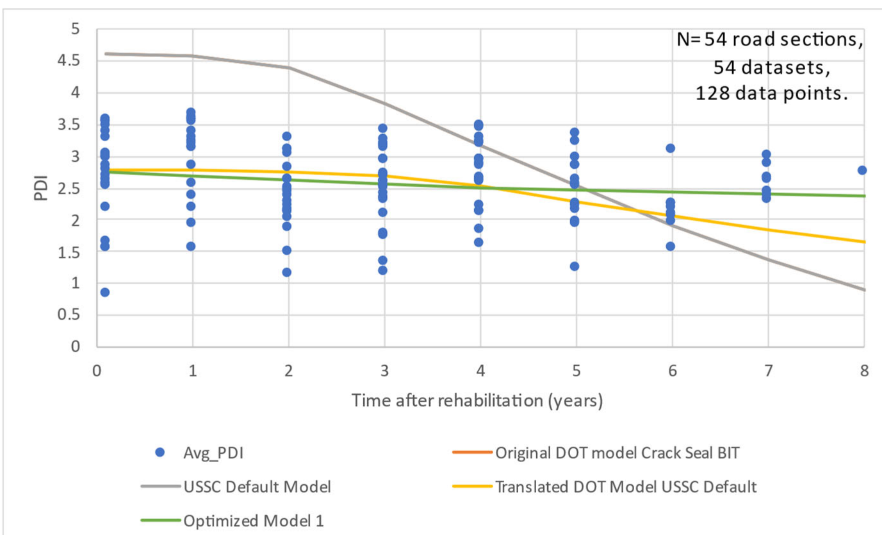
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original DOT Model Crack Seal BIT	USSC Default Model	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model USSC Default
a	20.887	1.133	12.47	58.3	1.133
b	20.437	15.468	38.1	66.77	15.468
c	1.02	3.711	1.33	1.06	3.711
o	4.6	4.8	3.3	3.3	3.5
SSE	88.3554	61.1533	1.4091	4.9525	12.4403
RMSE	1.4680	1.2213	0.1854	0.3476	0.5508
MSE	2.1550	1.4915	0.0344	0.1208	0.3034
MAPE (%)	37.29	33.84	4.40	7.32	12.49
Expected rehab year	2.07	20.22	47.23	11.00	7.34
Rehab threshold	2.5	2.5	2.5	2.5	2.5
Relative improvement (%)				80.37	



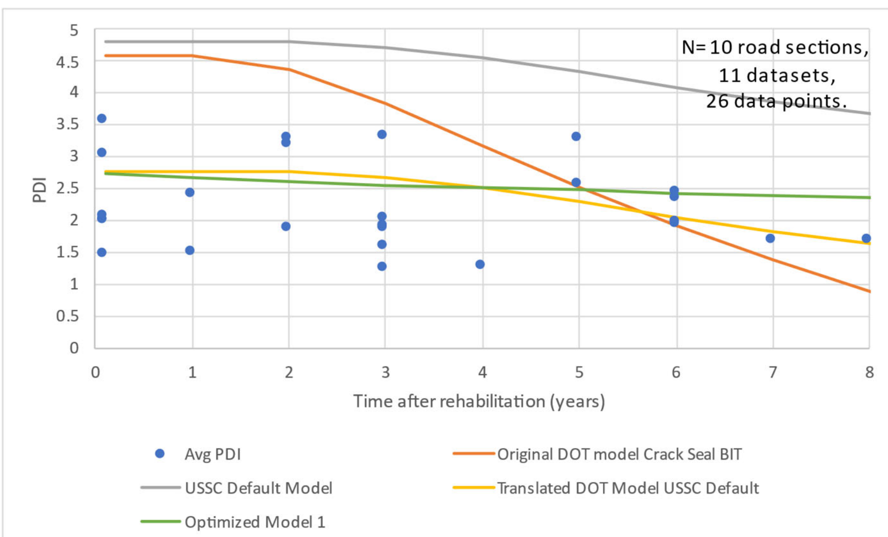
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original DOT Model Crack Seal BIT	USSC Default Model	Optimized Model 1 (recommended)	Translated DOT Model USSC Default
a	2.318	1.133	1.133	1.133
b	7.431	15.468	3.90	15.468
c	2.611	3.711	1.333	3.711
o	4.6	4.8	2.7	2.8
SSE	302.9042	570.9933	46.2780	52.8468
RMSE	1.5383	2.1121	0.6013	0.6426
MSE	2.3664	4.4609	0.3616	0.4129
MAPE (%)	60.50	91.49	22.77	24.46
Expected rehab year	5.03	20.22	4.41	4.10
Rehab threshold	2.5	2.5	2.5	2.5
1st 5 years average slope (%)	-42.45	-9.72	-5.40	-9.72
2nd 5 years average slope (%)	-45.28	-18.73	-2.83	-18.73
3rd 5 years average slope (%)	Not applicable	-9.94	-1.99	-9.94
Relative improvement (%)			62.37	



[PDI model evaluation using validation data]

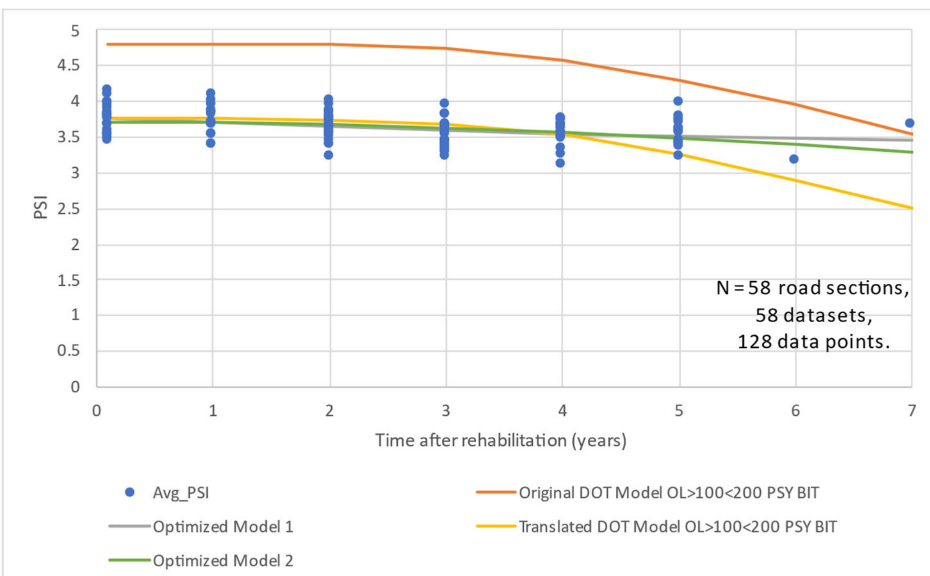
PDI Coef. (Validation model)	Original DOT Model Crack Seal BIT	USSC Default Model	Optimized Model 1 (recommended)	Translated DOT Model USSC Default
a	2.318	1.133	1.133	1.133
b	7.431	15.468	3.90	15.468
c	2.611	3.711	1.333	3.711
o	4.6	4.8	2.7	2.8
SSE	84.1912	153.7864	14.7123	15.6607
RMSE	1.7995	2.4320	0.7522	0.7761
MSE	3.2381	5.9149	0.5659	0.6023
MAPE (%)	80.93	123.09	35.99	35.54
Expected rehab year	5.03	20.22	4.41	4.10
Rehab threshold	2.5	2.5	2.5	2.5
Relative improvement (%)			55.53	



APPENDIX K (OL 100-200 PSY BIT)
[OL 100 – 200 PSY for asphalt pavement]

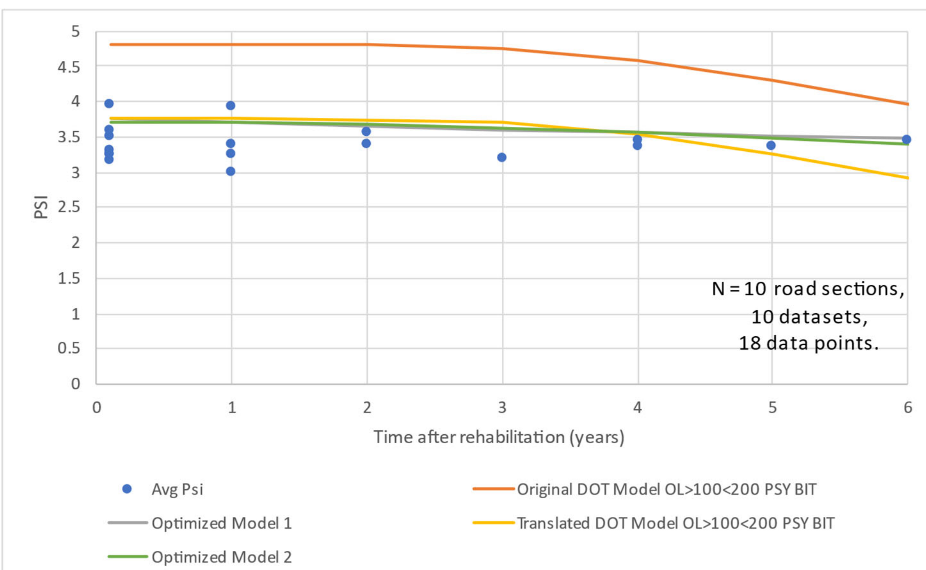
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original DOT Model BIT OL>100<200 PSY	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model BIT OL>100<200 PSY
a	2.646	1.133	58.3	2.646
b	15.692	4.059	62.799	15.692
c	2.611	1.328	1.031	2.611
o	4.8	3.753	3.7	3.8
SSE	148.4231	4.5766	4.7152	6.6906
RMSE	1.0811	0.1898	0.1927	0.2295
MSE	1.1687	0.0360	0.0371	0.0527
MAPE (%)	29.39	4.29	4.34	5.12
Expected rehab year	9.48	196.54	12.48	7.01
Rehab threshold	2.5	2.5	2.5	2.5
1st 5 years average slope (%)	-10.11	-4.82	-4.76	-10.11
2nd 5 years average slope (%)	-41.81	-2.64	-12.31	-41.81
3rd 5 years average slope (%)	-36.51	-1.88	-17.83	Not applicable
Relative improvement (%)			85.25	



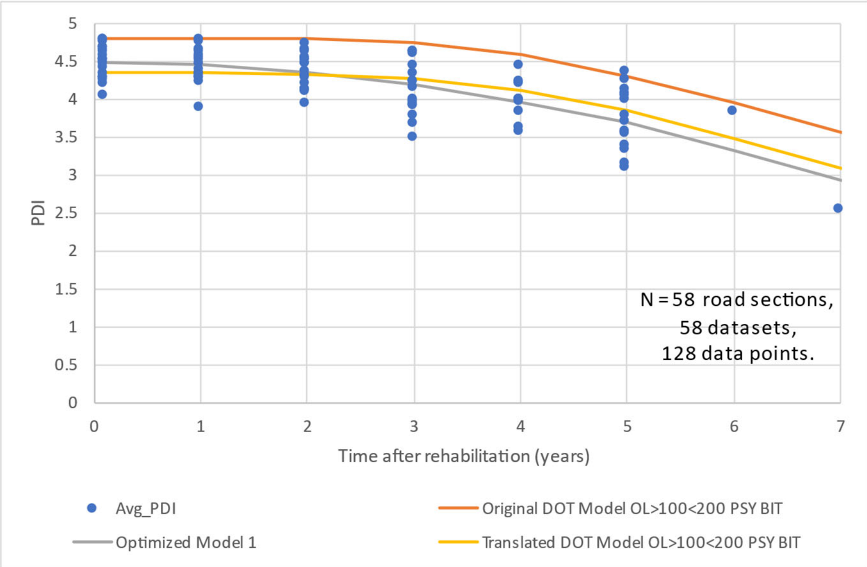
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original DOT Model BIT OL>100<200 PSY	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Model BIT OL>100<200 PSY
a	2.646	1.133	58.3	2.646
b	15.692	4.059	62.799	15.692
c	2.611	1.328	1.031	2.611
o	4.8	3.8	3.7	3.8
SSE	32.1650	2.4124	2.3195	3.0163
RMSE	1.3368	0.3661	0.3590	0.4094
MSE	1.7869	0.1340	0.1289	0.1676
MAPE (%)	38.80	9.64	9.53	11.00
Expected rehab year	9.48	196.54	12.48	7.01
Rehab threshold	2.5	2.5	2.5	2.5
Relative improvement (%)			75.44	



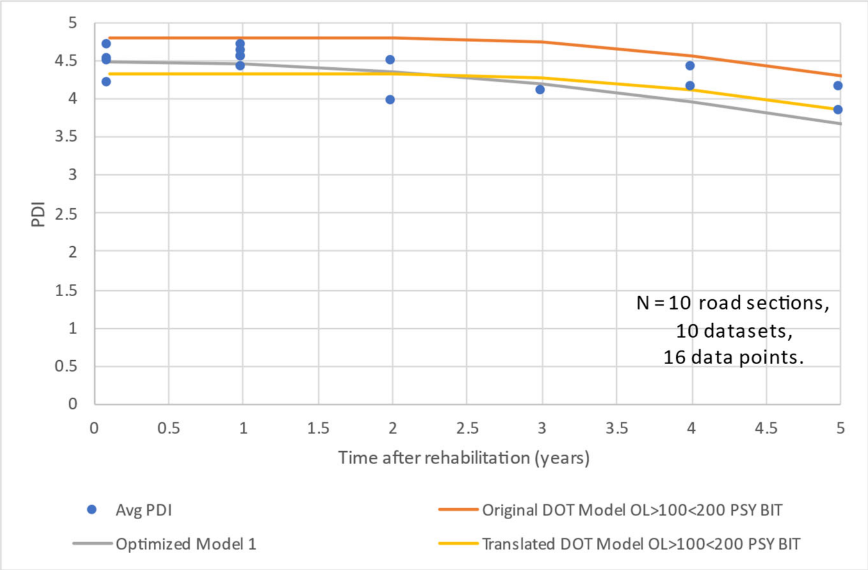
[PDI model evaluation using training data]

PDI Coef. (Training model)	Original DOT Model BIT OL>100<200 PSY	Optimized Model 1 (recommended)	Translated DOT Model BIT OL>100<200 PSY
a	2.646	49.1	2.646
b	15.692	52.62	15.692
c	2.611	1.041	2.611
o	4.8	4.5	4.3
SSE	27.1741	7.1201	8.3166
RMSE	0.5465	0.2797	0.3023
MSE	0.2986	0.0782	0.0914
MAPE (%)	11.51	5.56	6.11
Expected rehab year	9.48	7.94	8.40
Rehab threshold	2.5	2.5	2.5
1st 5 years average slope (%)	-10.11	-16.30	-10.11
2nd 5 years average slope (%)	-41.81	-48.78	-41.81
3rd 5 years average slope (%)	-36.51	Not applicable	Not applicable
Relative improvement (%)		51.69	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original DOT Model BIT OL>100<200 PSY	Optimized Model 1 (recommended)	Translated DOT Model BIT OL>100<200 PSY
a	2.646	49.1	2.646
b	15.692	52.62	15.692
c	2.611	1.041	2.611
o	4.8	4.5	4.3
SSE	2.4546	0.8834	0.8684
RMSE	0.3917	0.2350	0.2330
MSE	0.1534	0.0552	0.0543
MAPE (%)	7.95	4.45	4.63
Expected rehab year	9.48	7.94	8.40
Rehab threshold	2.5	2.5	2.5
Relative improvement (%)		44.02	

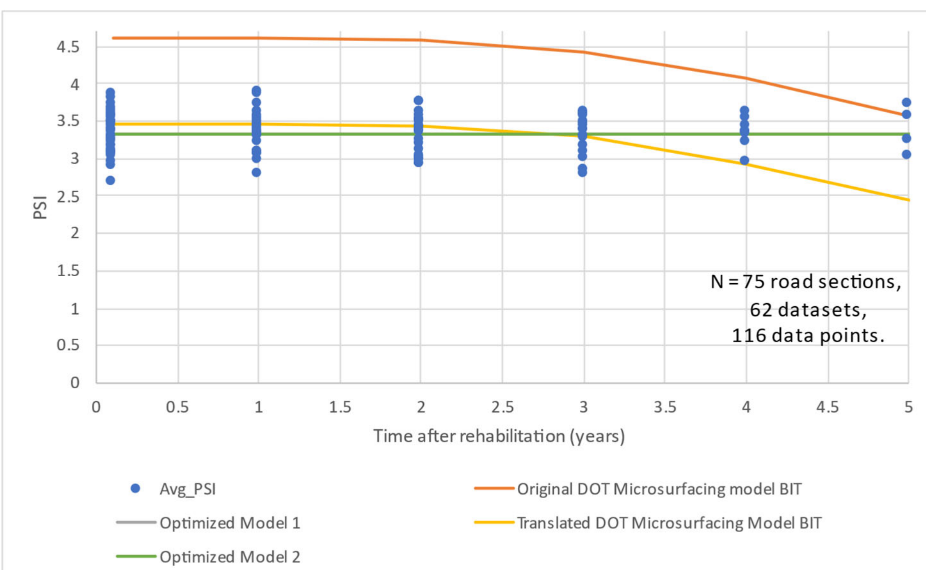


APPENDIX L (MICRO-SURFACING BIT)

[Micro-surfacing for asphalt pavement]

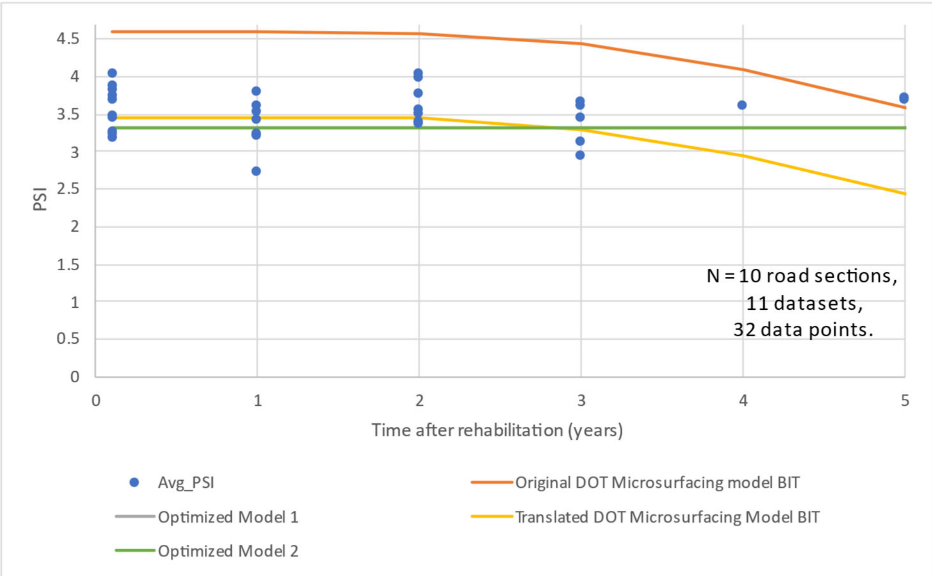
[PSI model evaluation using training data]

PSI Coef. (Training model)	Original DOT Microsurfacing Model BIT	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Microsurfacing Model BIT
a	2.861	1.591	25.9	2.861
b	13.313	82.32	79.019	13.313
c	2.611	1.797	1.618	2.611
o	4.6	3.3	3.3	3.5
SSE	174.2292	7.6188	7.6195	21.0231
RMSE	1.2256	0.2541	0.2541	0.4221
MSE	1.5020	0.0660	0.0660	0.1219
MAPE (%)	36.29	6.33	6.34	8.84
Expected rehab year	6.79	693.39	10.00	4.88
Rehab threshold	2.5	2.5	2.5	2.5
1st 5 years average slope (%)	-20.82	0.00	0.00	-20.82
2nd 5 years average slope (%)	-61.17	0.00	-20.70	Undefined
3rd 5 years average slope (%)	Not applicable	0.00	Not applicable	Not applicable
Relative improvement (%)			82.54	



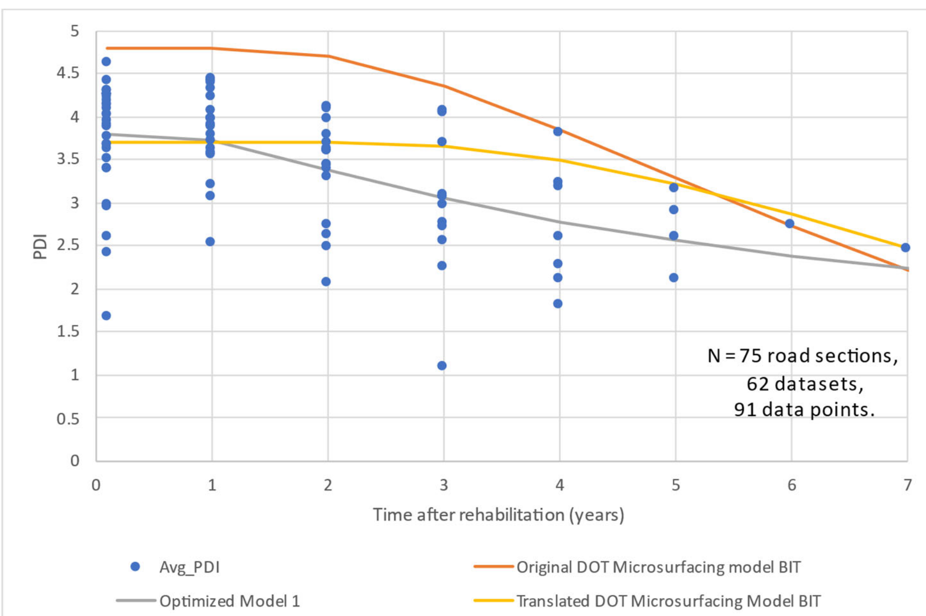
[PSI model evaluation using validation data]

PSI Coef. (Validation model)	Original DOT Microsurfacing model BIT	Optimized Model 1	Optimized Model 2 (recommended)	Translated DOT Microsurfacing Model BIT
a	2.861	1.591	25.9	2.861
b	13.313	82.32	79.019	13.313
c	2.611	1.797	1.618	2.611
o	4.6	3.3	3.3	3.5
SSE	36.1870	4.3299	4.3299	7.8725
RMSE	1.0634	0.3678	0.3679	0.4884
MSE	1.1308	0.1353	0.1353	0.1891
MAPE (%)	29.31	8.58	8.58	9.77
Expected rehab year	6.79	693.39	10.00	4.88
Rehab threshold	2.5	2.5	2.5	2.5
Relative improvement (%)			70.73	



[PDI model evaluation using training data]

PDI Coef. (Training model)	Original DOT Microsurfacing model BIT	Optimized Model 1 (recommended)	Translated DOT Microsurfacing Model BIT
a	2.348	1.133	2.646
b	9.06	3.603	15.692
c	2.611	2.343	2.611
o	4.8	3.8	3.7
SSE	148.3110	34.2185	39.9667
RMSE	1.2766	0.6132	0.6627
MSE	1.6298	0.3760	0.4393
MAPE (%)	38.92	16.76	18.57
Expected rehab year	6.45	5.32	6.91
Rehab threshold	2.5	2.5	2.5
1st 5 years average slope (%)	-30.90	-25.37	-10.11
2nd 5 years average slope (%)	-45.20	-11.29	-41.81
3rd 5 years average slope (%)	Not applicable	-5.58	Not applicable
Relative improvement (%)		56.95	



[PDI model evaluation using validation data]

PDI Coef. (Validation model)	Original DOT Microsurfacing model BIT	Optimized Model 1 (recommended)	Translated DOT Microsurfacing Model BIT
a	2.348	1.133	2.646
b	9.06	3.603	15.692
c	2.611	2.343	2.611
o	4.8	3.8	3.7
SSE	30.3106	8.7226	10.4076
RMSE	1.2014	0.6445	0.7040
MSE	1.4434	0.4154	0.4956
MAPE (%)	32.93	16.24	16.80
Expected rehab year	6.45	5.32	6.91
Rehab threshold	2.5	2.5	2.5
Relative improvement (%)		50.68