Development of PCI-based Pavement Performance Model for Management of Road Infrastructure System

by

Kan Wu

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Graduate Supervisory Committee:

Kamil Kaloush, Chair
Xuesong Zhou
Shane Underwood

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ABSTRACT

The accurate prediction of pavement network condition and performance is important for efficient management of the transportation infrastructure system. By reducing the error of the pavement deterioration prediction, agencies can save budgets significantly through timely intervention and accurate planning. The objective of this research study was to develop a methodology for calculating a pavement condition index (PCI) based on historical distress data collected in the databases from Long-Term Pavement Performance (LTPP) program and Minnesota Road Research (Mn/ROAD) project. Excel™ templates were developed and successfully used to import distress data from both databases and directly calculate PCIs for test sections. Pavement performance master curve construction and verification based on the PCIs were also developed as part of this research effort. The analysis and results of LTPP data for several case studies indicated that the study approach is rational and yielded good to excellent statistical measures of accuracy.

It is believed that the InfoPave™ LTPP and Mn/ROAD database can benefit from the PCI templates developed in this study, by making them available for users to compute PCIs for specific road sections of interest. In addition, the PCI-based performance model development can be also incorporated in future versions of InfoPave™. This study explored and analyzed asphalt pavement sections. However, the process can be also extended to Portland cement concrete test sections. State agencies are encouraged to implement similar analysis and modeling approach for their specific road distress data to validate the findings.

DEDICATION

To my parents and my brother,

who were always there for me

each step of the way.

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TABLE OF CONTENTS

Page

CHAPTER

APPENDIX

APPENDIX Page

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Maintenance and repair of the road pavement network system are major expenses in the budget of local and states department of transportation (DOTs) (Gupta et al. 2012). Timely pavement maintenance and rehabilitation (M&R) can help to keep the network in good condition using limited budget (Madanat, 1993). Therefore, the accurate prediction of pavement network performance is essential for efficient management of the road infrastructure system. In pavement management, much effort has been put to developing an efficient pavement performance prediction model. This study aims on contributing to this effort by developing a sound pavement performance modeling approach for management of pavement networks.

Desirable pavement performance prediction models should relates to various pavement measurements (Gulen et al. 2001), such as pavement condition indicators, pavement age, traffic (truck traffic) and pavement type. The accuracy of pavement performance prediction models is affected by the use of pavement performance indices such as Pavement Condition Index (PCI), International Roughness Index (IRI) and Present Serviceability Index (PSI). Among them, PCI is the only one that provides an objective evaluation and representation of the overall pavement condition.

In addition, the quality of pavement performance prediction models is greatly affected by the available data. Previously developed prediction models are mostly based on limited available data, thus with some limitations. Up to now, increasingly available data of pavement condition has been obtained from various databases such as Long-Term Pavement Performance program (LTPP-Infopave^{TM}) (FHWA, LTPP 2015) and Minnesota Road Research Project (Mn/ROAD) (MnDOT, Mn/ROAD 2015. The LTPP program was established to collect pavement performance data as one of the major research areas of the Strategic Highway Research Program (SHRP). The LTPP database includes performance measures such as the International Roughness Index (IRI) and individual quantities of measured pavement distresses. However, a performance measure based on these distresses, such as the PCI, is not part of the LTPP database and has not been fully developed to date.

1.2 Research Objectives

The objective of this research was to develop a pavement condition index based on the LTPP and Mn/ROAD pavement distress data. The PCI was selected as the performance indicator, being derived from distresses data in either the LTPP or Mn/ROAD databases. The goal was also to develop a programmed Excel™ templates to use imported distress data and directly calculate the PCI for various test sections.

A secondary goal of this research was to use the PCI in unique performance modeling approach. This study documents these developments and their advantages, such as (1) quantification of PCI as a new performance measure used for existing LTPP or Mn/ROAD databases, (2) modeling of pavement condition data using historical data converted to Master PCI curves, (3) demonstration and comparison of models for different pavement networks, and (4) the use of programmed Excel™ templates for PCI-based pavement performance modeling.

In this study, the focus on performance modeling was for the asphalt concrete pavement (ACP) sections. However, the methodology can be also applied and implemented for the Portland Cement Concrete (PCC) pavement sections.

1.3 Thesis Outline

This chapter provided brief introduction on problem statement and research objectives. Chapter 2 contains the literature review, basic definitions of pavement performance and the use of major distresses as an indicator of pavement deterioration. Pavement condition indices as a function of typical pavement condition indicators are also described and compared.

Chapter 3 begins with a detailed description of current PCI methods of quantifying pavement condition. The present PCI calculation method as standardized by ASTM D6433-07 is described and the development of automated PCI calculation template based upon the ASTM method is presented.

Chapter 4 describes the procedures for PCI-based performance modeling and the nonlinear programming model constructed to specify the parameters of the performance curve.

Modeling results are presented in Chapters 5 and 6. These chapters include the results of numerous sets of distress data from two the LTPP and Mn/ROAD databases, which are used to validate the unique modeling approach.

Chapter 6 presents the conclusions of the study along with some recommendations on future follow up work.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

In this chapter, basic definitions of pavement performance and performance indicators are discussed; common pavement condition indices are presented in section 2.2, followed by a summary of general types of pavement performance models in Section 2.3. Section 2.4 reviews the research efforts on two widely-used pavement performance projects: LTPP and Mn/ROAD.

2.1 Background and Basic Definitions

A road pavement continuously deteriorates under the combined actions of traffic loading and the environment (Prozzi, 2001). AASHTO (1993) defines the pavement ***performance*** as the ability of a pavement to satisfactorily serve traffic over time (AASHTO, 1993). The change in the value of these performance indicators over time is referred to as ***pavement deterioration***.

The most general method to show the extent of pavement deterioration or rate the performance of pavement is dependent on collection of types, severity, quantities of common pavement distresses. For instance, rutting, fatigue cracking, longitudinal & transverse cracking are three major ***asphalt concrete pavement*** distresses, which constitute main factors that affect the performance and ride quality of pavements.

Rutting is a surface depression within the wheel path. Rutting results from a permanent deformation in any of the pavement layers or subgrades, usually caused by consolidation or lateral movement of the materials due to traffic loads (Madanat, 2000). Usually, the rutting occurs gradually across the wheel path, reaching a maximum depth in the center of the wheel paths.

Fatigue Cracking, also named alligator cracking, is associated with loads and is usually limited to areas of repeated traffic loading. The cracks surface initially as a series of parallel longitudinal cracks within the wheel path that progresses with time and loads to a more branched pattern that begins to interconnect, is defined as alligator cracking. Eventually the cracks interconnect sufficiently to form many pieces, resembling the pattern of an alligator. Potholes and other occurrences of destroyed or missing pavement are accumulated as high severity alligator may also be noted in the area.

Longitudinal & Transverse Cracking are also two common distresses of asphalt concrete pavements. They are mainly driven by temperature caused shrinkage, and expansion of pavement layer. Traffic loading is also an important factor as it may accelerate the cracking progression. Cracking and rutting are major indicators of pavement performance deterioration.

In addition, there are also some other types of common pavement distresses, their occurrence usually indicates health problems in pavements to some extent. Research studies have been conducted to develop a pavement performance model based on individual distress or several distresses. For example, the rutting model (Kaloush and Witczak, 2000) provides a prediction of rutting progressing process.

In terms of overall pavement performance evaluation, a pavement condition index has been used to better represent the overall pavement condition and it is discussed next.

2.2 Pavement Condition Indices

Studies have focused on models to predict the deterioration and the condition of pavements as a function of cumulative traffic, pavement properties and environmental condition over their service life. Hence, pavement performance is herein defined as the history of the deterioration of pavement condition. The pavement condition can be measured based on the occurrence of surface or structural failures, if any.

The first comprehensive effort to establish an objective indicator of pavement performance was in the late 1950s. Earlier, inadequate attention had been paid to the evaluation of pavement performance: a pavement was considered to be either satisfactory or unsatisfactory. (Haas et al, 1994).

Much effort then has been put to developing a ***pavement condition index*** as an indication to pavement performance. The condition index combines all indicators of pavement distress into a single number. This number can be used at the network-level to define the condition state, to identify when treatments are needed, for ranking or prioritization, and used to forecast pavement condition (FHWA, 2003). There are alternatives types of pavement condition indices, each of which measures pavement performance from different perspectives. These are presented next.

2.2.1 Present Serviceability Index (PSI)

The Present Serviceability Index (PSI) was developed in the early 1960s and constituted the first comprehensive effort to establish performance standards based upon considerations of riding quality (Carey and Irick, 1960). The PSI was based on the values of pavement smoothness, rutting cracking and patching. A panel of highway users from different backgrounds evaluated several flexible pavement sections and rated them on a five-point discrete scale (0 for poor, 5 for excellent).

2.2.2 International Roughness Index (IRI)

Other studies have been carried out to establish alternative indices to measure pavement performance. One of the most well-known concept is the International Roughness Index (IRI) (Gillespie et al, 1980). The IRI is a measure of the surface profile of the road and is computed from the surface elevation. To date, the IRI has seen the broadest application and has been adopted as a standard for the Federal Highway Performance Monitoring System (FHWA, 1987).

2.2.3 Pavement Condition Index (PCI)

The Pavement Condition Index (PCI), developed by the U.S. Army Corps of Engineers, is a very comprehensive condition index (Shahin and Kohn, 1979). The PCI method is based on visual examination of the pavement distress type, extent and severity (ASTM, 2007). The PCI provides a measure of the present condition of the pavement based on the distress observed on the surface of the pavement, which also indicates the structural integrity and surface operational condition (roughness and safety). The PCI provides an objective determination of maintenance and repair needs and priorities. Continuous monitoring of the PCI is used to establish the rate of pavement deterioration, which permits early identification of major rehabilitation needs as is shown in **Table 1**. The PCI also provides feedback on pavement performance for validation or improvement of current pavement design and maintenance procedures.

Table 1. Typical Pavement M&R Strategies based upon PCI Value (*Source: Shahin and Walther, 1990*)

PCI	Rating	Strategy
85 - 100	Good	Routine Maintenance
70 - 85	Satisfactory	Preventive Maintenance
55 - 70	Fair	Minor Rehabilitation
40 - 55	Poor	Minor Rehabilitation
25 - 40	Very Poor	Major Rehabilitation
10 - 25	Serious	Reconstruction
0 - 10	Failed	Reconstruction

Therefore, the PCI is a numerical index between 0 and 100 that is used to indicate the general condition of the surface of a pavement section, with 100 representing the best possible condition and 0 representing the worst possible condition. This PCI rating scale is shown in **Figure 1**. One PCI survey procedure and calculation method has been standardized by ASTM for roads and parking lots pavements (ASTM, 2007).

Figure 1. Standard PCI Rating Scale by ASTM (*Source: ASTM, 2007*)

Usually, a completed pavement distresses survey is required in order to obtain a set of PCIs for the pavement of interest. The PCI has been the most unique index in terms of pavement performance rating. It also received a broad application in network-level pavement management and has been adopted as a basis of the pavement management system - PAVER^{TM} (Shahin and Walther, 1990).

2.3 Pavement Performance Models

A pavement performance prediction model is an equation that relates some extrinsic “time factor” (age, or number of load applications) to a combination of intrinsic factors (structural responses, material properties, drainage, etc.) or performance indicators (Gupta et al. 2012). Depending on the inclusion of attributes and approach followed to develop the performance function, the models can be categorized into two groups: *mechanistic-empirical model* and *pavement performance rating model*. Some of the main characteristics of the two model groups are described in the following sections.

2.3.1 Mechanistic-Empirical Prediction Models

These models mainly include historical data, for example, rut depth, cracking and roughness (IRI), being generated as a result of traffic loading, environmental effects and pavement age. These models predict the deterioration of pavement over time under cumulative traffic loading and/or environment effects manifested in typical sorts of distress. An empirical rutting progression model may use experimental data, axel load equivalences, structural number and thawing index (Archilla and Madanat 2000). Another rutting prediction model developed by Fwa et al estimates the effects of traffic load, loading speed and temperature on rut depth in the asphalt pavement layer (Fwa et al. 2004). Gulen et al modeled IRI as a function of pavement age and AADT (average annual daily traffic) (Gulen et al. 2001).

The main advantage of mechanistic-based models is ability to extrapolate predictions out of the data range and conditions under which they were calibrated, thus, producing deterministic performance predictions (Prozzi, 2001). Their main disadvantage is that it is impossible to assess the reliability of the predictions when these models are used out of the original data range for which they have been calibrated.

2.3.2 Pavement Performance Rating Model

These are some models defining pavement performance using certain arbitrary or weighted values that varies within a certain range. Various indices have been proposed by different researchers; for example, PCI, PSI, and PCR (Pavement Condition Rating). These are based on various characteristics of the pavement as discussed previously, and the formation of a composite index based on those surface and structure characteristics. In these models, the criterion used to select the best specification form among alternatives is to obtain the best possible fit to the data. This is measured by regression analysis (R^2 or root-mean-square error (RMSE)) (Prozzi, 2001).

A PCI-based developed for PAVER^{TM} system using Markov Chain transition probability approach to predict the future performance (Shahin and Walther, 1990). The major limitation of the probabilistic PAVER^{TM} model is that prediction error cannot be assessed using its own approach. Abaza developed a PCI-based pavement performance curve and defined pavement life-cycle performance as the area under the curve generated from actual pavement distress data (Abaza, 2002). Sotil and Kaloush found that a sigmoidal function best represent PCI pavement performance over time (Sotil and Kaloush, 2004);

the study provided a sound modeling approach with the use of master performance curve. However, the modeling approach was limited to the availability of historical PCI data.

2.3.3 Data Shifting Concept-Shift Factor

The data shifting concept and use is most widely known and used in the dynamic modulus (E*) testing of asphalt mixtures and for development of a master curve / mathematical function (Witczak et al. 2002). This data shifting process is illustrated in **Figure 2**. A sigmoidal function is finally developed that will provide E* as a function of either temperature or time of loading. This mathematical function is called the sigmoidal E* master curve (Witczak et al. 2002). In this study, this data shifting concept is used to model pavement performance data; specifically, historical pavement condition index data are shifted to aid in the development of a complete pavement performance master curve.

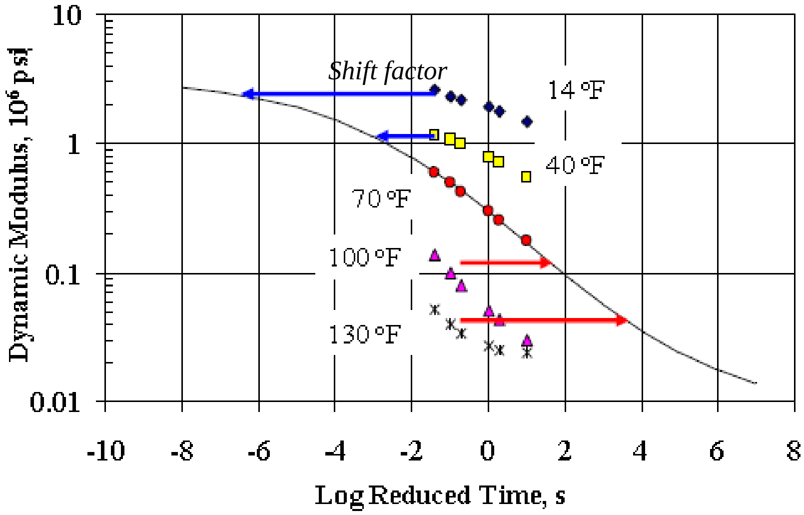


Figure 2. Illustration of Data Shifting Process for Sigmoidal E* Master Curve Construction (*Source: Witczak et al. 2002*)

2.4 Pavement Performance and Data Sources

Due to nature of the pavement deterioration process, data from actual in-service pavement sections subjected to the combined actions of highway traffic and environmental conditions are desirable (Prozzi, 2001). However, the data collection from the actual in-service pavement sections are difficult and costly; programs such as the Long-Term Pavement Performance (LTPP) studies and the Minnesota Road Project (Mn/ROAD) provided very useful data for further analysis on condition and performance.

The Long-Term Pavement Performance (LTPP) program was established to collect pavement performance data as one of the major research areas of the Strategic Highway Research Program (SHRP) (FHWA, LTPP 2015). To date, LTPP is becoming the primary data source of pavement performance research. Park et al developed a transformed linear regression model between PCI and IRI using data from LTPP (Park et al. 2007). In a study by Hall et al based on LTPP data, they focused on determining the relative performance of different maintenance and rehabilitation (M&R) options (Hall et al. 2002).

LTPP data include general inventory and information of test sections, materials experiment, maintenance and rehabilitation (M&R), climate, traffic, deflection (e.g., Falling Weight Deflectometer (FWD)), longitudinal profile (International Roughness Index (IRI)) and pavement distresses. At present, there are a total of 2509 test sections included in the database at more than 900 locations mainly on in-service highways throughout North America. To date, LTPP is becoming the primary data source of pavement performance research. Park et al developed a transformed linear regression model between PCI and IRI using data from LTPP [Park et al. 2007]. In a study by Hall et al based on LTPP data, they focused on determining the relative performance of different maintenance and rehabilitation (M&R) options [Hall et al. 2002].

The distress database in the LTPP program consists of individual distress data of asphalt concrete pavements (ACP), joint plain concrete (JPCP) and continuously reinforcement concrete pavement (CRCP) sections. In this study, we focus on performance modeling of the flexible pavement (ACP) sections. The development of the study’s master database resulted in 1623 section entries, each entry dataset included inventory and general information (State Code, Section/SHRP_ID, width of section, etc..), in addition to distress information and survey dates.

An LTPP test section is generally 3.7m (12ft) ×152.4m (500ft) = 563.88m2 (6000ft2), the distress data included extent, type and severity. Most of the variables within tables extracted from LTPP database are self-explanatory.

The Minnesota Road Research Project (Mn/ROAD) is an accelerated pavement test facility owned and operated by the Minnesota Department of Transportation (MnDOT). (Worel and Deusen, 2015). To date, the Mn/ROAD database has served for more than 20 years (1994 to 2014). The historical data was being sources for multiple pavement researches, especially for pavement performance analysis (Worel and Deusen, 2015). In late 2006, an NCHRP report was published details the significant of Mn/ROAD data has gone into the mechanistic-empirical design procedure that is commonly known as the 2002 Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP, 2004). After that, several studies has been done on Mn/ROAD test sections to calibrate the MEPDG's rutting model and thermal cracking model of asphalt concrete pavements.

Previous studies completed using both of the Mn/ROAD and the LTPP databases included performance measures such as the International Roughness Index (IRI) and individual quantities of measured pavement distresses. However, no index representing the distress condition of the pavement section (e.g. PCI) was part of these analysis.

2.5 Summary

The Pavement Condition Index, PCI, provides a realistic and reliable measure of pavement condition; it account for most of the distresses and can provide useful information on the surface and structural integrity of the pavement. Despite some performance models have been developed, most of them are of limited applicability and data sources.

The data shifting and master curve construction method is of interest for continued use in PCI performance modeling approach. The LTPP and Mn/ROAD databases contain valuable data and information that are useful to develop pavement condition indices and their application in performance modeling. This PCI-based modeling approach is presented in the following chapters.

CHAPTER 3

PAVEMENT CONDITION INDEX CALCULATION BASED ON ASTM METHOD

This chapter describes the automation of Pavement Condition Index (PCI) calculation based on the American Standard of Testing Materials (ASTM) method (ASTM, 2007). The chapter begins with an introduction of the pavement condition survey process and present PCI calculation method as standardized by ASTM. Afterwards, a discussion is presented on efforts conducted for developing automated Excel^{TM} template to calculate PCI for a specific road section based on the distress data available. The template follows the ASTM procedure, and hundreds of pavement distress data can be quantified in few seconds.

3.1 Background

As discussed earlier, PCI is a numerical index between 0 and 100 that is used to indicate the general condition of the surface of a pavement section, with 100 representing the best possible condition and 0 representing the worst possible condition. The PCI survey procedure and calculation method has been standardized by ASTM for roads and parking lots pavements (ASTM, 2007). More details in PCI quantification and application will be described in Section 3.2. The terminologies defined by ASTM standard are also used in development of automated PCI calculation templates. The next paragraphs provide some basic definitions for PCI calculation used in the ASTM procedure.

Pavement Section - A contiguous pavement area having uniform construction, maintenance, usage history, and condition. A section should have similar traffic volume, structure and geometric characteristics.

Pavement Distress - External indicators of pavement condition deterioration caused by loading, environmental factors, or a combination thereof. Typical distresses are cracks, rutting, and weathering of the pavement surface. Each distress, based upon its effect on pavement performance and riding quality, are classified into three severity levels: Low (L), Moderate (M), and High (H). A completed distress identification manual was provided by Federal Highway Administration (FHWA) in 2003 (FHWA, 2009). Depending on the distress type, the extent of distress within a pavement section are quantified either in square meters (square feet), linear meter (feet), or number of occurrences. For instance, fatigue and block cracking are measured in square feet or square meter, while for longitudinal and transverse cracking, are measured in linear feet.

Distress Density - Percentage to indicate the ratio of distress within an area. It is obtained by dividing total quantity of each distress type at each severity level by the total area of a pavement section.

Deduct Value (DV) **-** Statistical weight number of distresses to determine a combined condition index for pavement sections. According to ASTM 6433-07, for each distress type and severity level, there is a distress ***deduct value curves*** for deduct value determination (ASTM, 2007).

Corrected Deduct Value (CDV) - Adjustment of the cumulative deduct value or the total deduct value (TDV). The CDV adjusts the TDV to fit for a range of 0-100 by using a set of CDV-TDV adjustment curves. The maximum of CDV (maxCDV) is used to calculate PCI (PCI=100-maxCDV). If there is only one deduct value, then the TDV is used in place of the maxCDV in determining the PCI (ASTM, 2007).

3.2 ASTM PCI Calculation Method

3.2.1 Calculation of Deduct Values (DVs)

Because the combined impact of multiple distresses is not cumulative, ASTM D6433-07 procedure provides a family of curves to adjust for multiple distresses (ASTM, 2007). An example of deduct value curves for alligator cracking (fatigue cracking) is shown in **Figure 3**. Basically, the determination of deduct values for a specific pavement distress involves the following steps:

1) Add up the total *quantity of the distress* at each severity level, and record them separately;
2) Divide the total quantity of each distress type at each severity level by the total area of the pavement section and multiply by 100 to obtain the percent *density of each distress* type and severity;
3) Determine the DV for each distress type and severity combination from the distress deduct value curves.

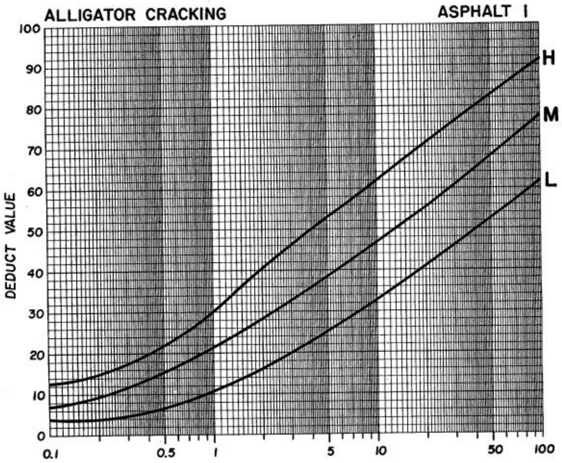


Figure 3. Deduct Value Curves for Fatigue (Alligator) Cracking by ASTM

(*Source: ASTM, 2007*)

The steps for determination of DVs is straightforward and are usually included in the process of field inspection; however, it may take a lot of time when inspecting a large amount of pavement sections.

3.2.2 Calculation of PCI for Asphalt Concrete Pavement

The PCI is then determined by applying the deduct value for each distress type along with any required correction factors (Corrected Deduct Values, CDVs) to account for multiple distress types. The PCI is equal to 100 minus the maximum CDV. According to ASTM (ASTM, 2007), the following steps are used to determine the maximum CDV:

1) If none or only one individual deduct value is greater than two, the total value is used in place of the maximum CDV in determining the PCI; otherwise, maximum CDV is determined using following procedures;
2) List the individual DVs in descending order and determine the allowable number of DVs, m, using the **Equation 1**,

$$m = 1 + \left(\frac{9}{98}\right)(100 - HDV) \le 10 \tag{1}$$

Where, HDV = highest individual DV. The number of individual deduct values then is reduced to the m largest DVs, including the fractional part. If less than m DVs are available, all of the DVs are used;

3) Determine the maximum CDV using iterations as below,
    a. Determine total deduct value (TDV) by summing individual DVs;
    b. Determine *q* as the number of DVs with a value greater than 2.0;
    c. Determine the CDV from TDV and *q* by looking up the appropriate correction curve as shown in **Figure 4**;
    d. Reduce the smallest individual DV greater than 2.0 to 2.0 repeat *a, b, c* until *q*=1;
    e. Determine the maxCDV, which is the largest value of the CDVs. And PCI is then calculated; PCI = 100 – maxCDV.

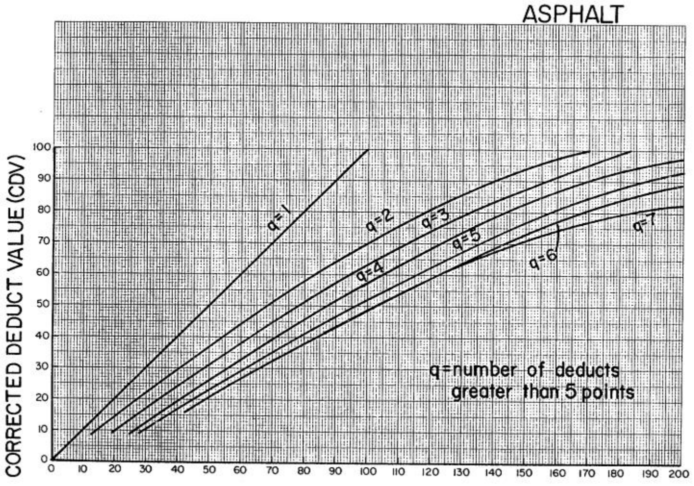


Figure 4. Corrected Deduct Value Curves for Asphalt-Surfaced Pavements.

(*Source: ASTM, 2007*)

3.3 Automation of ASTM's PCI Calculations

The existing ASTM PCI method provides an objective evaluation of pavement condition; however, it can be labor-intensive for a large road network. This is because there are a lot of calculations needed to be completed, even for a small road pavement network. It is therefore beneficial to develop a tool for automating the PCI calculation of road sections.

The following sections describes the development of mathematical formulas based upon the available DV curves found in the ASTM 6433-07 procedure; this is followed by describing how these equations are used in an automated PCI calculation Excel^{TM} template.

3.3.1 DV Curves Nonlinear Math Functions

The family of DV curves as was shown in **Figures 3** and **4** provides a reference for manually determining the deduct values. However, there were no mathematical equations known for the DV curves. In this study, data points for each curve were logged, and nonlinear regression analysis were conducted to arrive at the appropriate DV mathematical functions for each DV curve. A total of 24 nonlinear (multinomial) functions and plots were developed to be used for the determination of DVs. The same approach was used to determine the CDVs (A family of curves for DVs' determination is listed in APPENDIX A). **Figure 5** shows an example of the DV-density curve for fatigue cracking (low severity). The regression analysis shows the polynomial function between DV and logarithm of density with high degree of accuracy. The plots, regression analysis and nonlinear equations for all of the distresses can be found in Appendix A.

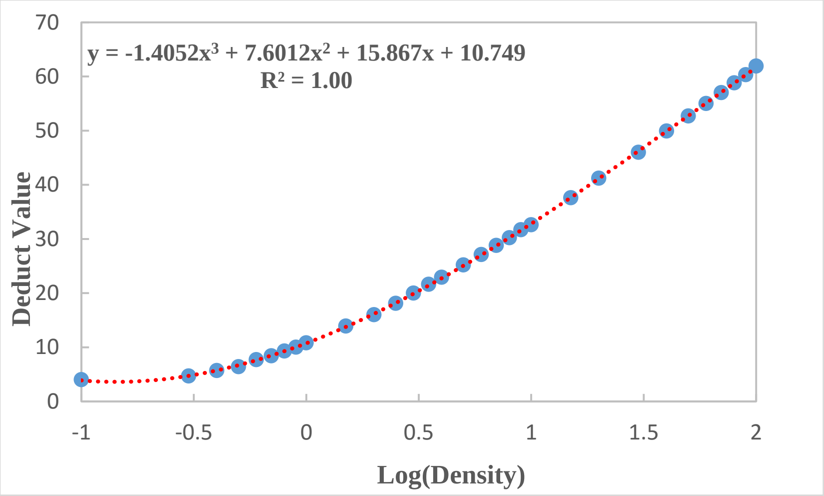


Figure 5. DV-log (Density) Curve for Fatigue Cracking (Low Severity)

In general, the nonlinear (multinomial) math functions derived from those DV curves can be mathematically represented as follows (**Equations 2** and **3**),

$$DV = \sum_{i=0}^{N} A_i \cdot (\log(D))^i \tag{2}$$

$$CDV = \sum_{n=0}^{N} B_i \cdot TDV^i \tag{3}$$

Where,

D = Density (%) of a specific distress of low, moderate and high severities

N = Highest-degree of polynomial function

i = index of polynomial

A_i, B_i= Coefficients of polynomial, determined by polynomial simulation

3.3.2 Excel^{TM} Template for PCI Calculation

According to ASTM, the procedure used to determine PCI for a pavement section can be divided into following four steps:

(1) Convert raw data to distress density (%) using area of surveyed section as denominator;

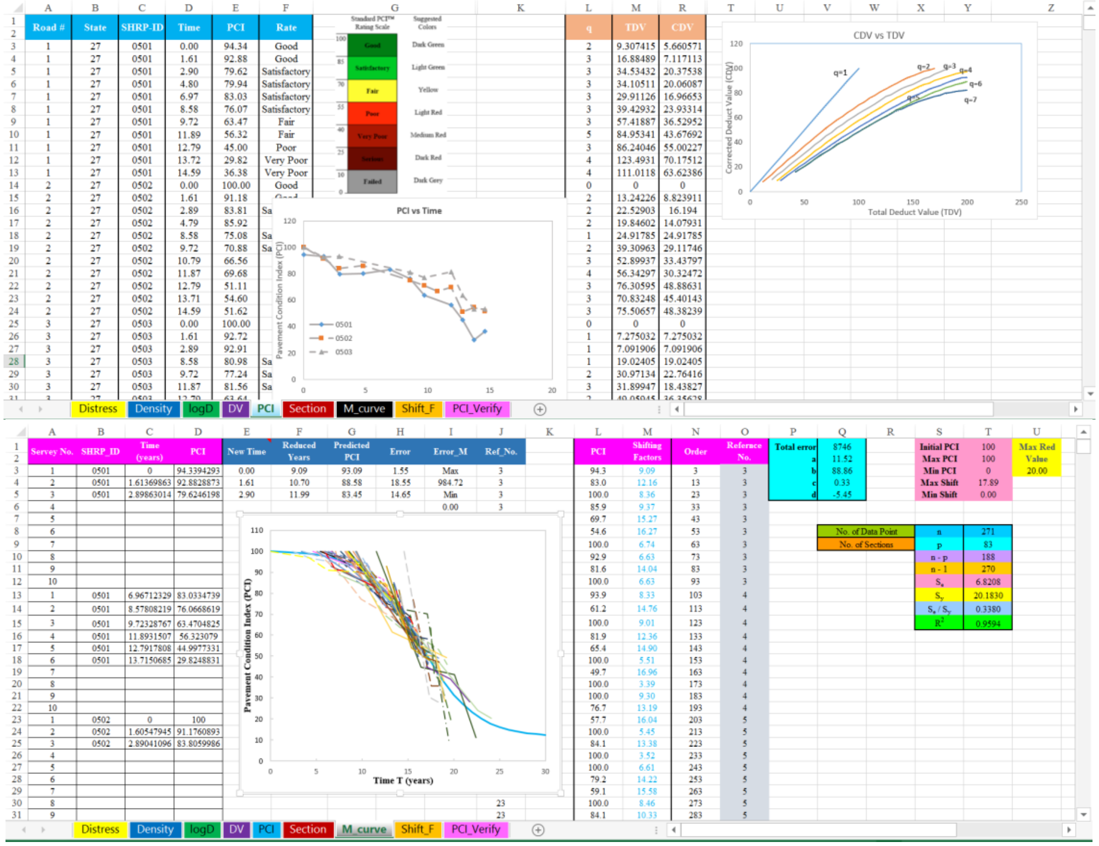
(2) Find deduct value (DV) using DV-Density graph;

(3) Sum the largest 7 DVs resulting in total deduct value (TDV);

(4) Find corrected deduct value (CDV) using CDV-TDV graph and PCI equal to 100-CDV.

The next phase is to implement all of the mathematical functions and algorithms into an Excel^{TM} template. The nonlinear (multinomial) functions for DV curves are derived directly from ASTM. The algorithm to determine maximum CDV and PCI followed the procedures in Section 3.2.

The template provides user-friendly transformation of distresses to PCI values for each road section data (for example, LTPP or Mn/ROAD). The format developed was made compatible with the dataset available from the LTPP database. A screenshot of the template is shown in **Figure 6.** The first Excel^{TM} sheet (labeled as “Distress”) of the template includes the type, quantity, severity level of each distress, section ID, survey date, and other basic inventory data. The second sheet (labeled as “Density”) function as distress-density transformation, and along with the “logD” and “DV” sheets are used for determination of DVs. The final PCIs are shown in the “PCI” sheet. In addition, the sheets labeled as “Section”, “M_curve”, “Shift_F” and “PCI_Verify” constitute the PCI-based pavement performance modeling template, which will be explained in the next Chapters.



	Road #	State	SHRP-ID	Time	PCI	Rate	q	TDV	CDV
3	1	27	0501	0.00	94.34	Good	2	9.307415	5.660571
4	1	27	0501	1.61	92.88	Good	3	16.88489	7.117113
5	1	27	0501	2.90	79.62	Satisfactory	3	34.53432	20.37538
6	1	27	0501	4.80	79.94	Satisfactory	3	34.10511	20.06087
7	1	27	0501	6.97	83.03	Satisfactory	3	29.91126	16.96653
8	1	27	0501	8.58	76.07	Satisfactory	3	39.42932	23.93314
9	1	27	0501	9.72	63.47	Fair	3	57.41887	36.52952
10	1	27	0501	11.89	56.32	Fair	5	84.95341	43.67692
11	1	27	0501	12.79	45.00	Poor	3	86.24046	55.00227
12	1	27	0501	13.72	29.82	Very Poor	4	123.4931	70.17512
13	1	27	0501	14.59	36.38	Very Poor	4	111.0118	63.62386
14	2	27	0502	0.00	100.00	Good	0	0	0
15	2	27	0502	1.61	91.18		2	13.24226	8.823911
16	2	27	0502	2.89	83.81	Sa	2	22.52903	16.194
17	2	27	0502	4.79	85.92		2	19.84602	14.07931
18	2	27	0502	8.58	75.08	Sa	1	24.91785	24.91785
19	2	27	0502	9.72	70.88	Sa	2	39.30963	29.11746
20	2	27	0502	10.79	66.56		3	52.89937	33.43797
21	2	27	0502	11.87	69.68		4	56.34297	30.32472
22	2	27	0502	12.79	51.11		3	76.30595	48.88631
23	2	27	0502	13.71	54.60		3	70.83248	45.40143
24	2	27	0502	14.59	51.62		3	75.50657	48.38239
25	3	27	0503	0.00	100.00		0	0	0
26	3	27	0503	1.61	92.72		1	7.275032	7.275032
27	3	27	0503	2.89	92.91		1	7.091906	7.091906
28	3	27	0503	8.58	80.98	Sa	1	19.02405	19.02405
29	3	27	0503	9.72	77.24	Sa	2	30.97134	22.76416
30	3	27	0503	11.87	81.56	Sa	3	31.89947	18.43827

Standard PCI™ Rating Scale		Suggested Colors
100–85	Good	Dark Green
85–70	Satisfactory	Light Green
70–55	Fair	Yellow
55–40	Poor	Light Red
40–25	Very Poor	Medium Red
25–10	Serious	Dark Red
10–0	Failed	Dark Grey

	Servey No.	SHRP_ID	Time (years)	PCI	New Time	Reduced Years	Predicted PCI	Error	Error_M	Ref_No.	PCI	Shifting Factors	Order	Refernce No.
3	1	0501	0	94.3394293	0.00	9.09	93.09	1.55	Max	3	94.3	9.09	3	3
4	2	0501	1.61369863	92.8828873	1.61	10.70	88.58	18.55	984.72	3	83.0	12.16	13	3
5	3	0501	2.89863014	79.6246198	2.90	11.99	83.45	14.65	Min	3	100.0	8.36	23	3
6	4								0.00	3	85.9	9.37	33	3
7	5										69.7	15.27	43	3
8	6										54.6	16.27	53	3
9	7										100.0	6.74	63	3
10	8										92.9	6.63	73	3
11	9										81.6	14.04	83	3
12	10										100.0	6.63	93	3
13	1	0501	6.96712329	83.0334739							93.9	8.33	103	4
14	2	0501	8.57808219	76.0668619							61.2	14.76	113	4
15	3	0501	9.72328767	63.4704825							100.0	9.01	123	4
16	4	0501	11.8931507	56.323079							81.9	12.36	133	4
17	5	0501	12.7917808	44.9977331							65.4	14.90	143	4
18	6	0501	13.7150685	29.8248831							100.0	5.51	153	4
19	7										49.7	16.96	163	4
20	8										100.0	3.39	173	4
21	9										100.0	9.30	183	4
22	10										76.7	13.19	193	4
23	1	0502	0	100							57.7	16.04	203	5
24	2	0502	1.60547945	91.1760893							100.0	5.45	213	5
25	3	0502	2.89041096	83.8059986							84.1	13.38	223	5
26	4										100.0	3.52	233	5
27	5										100.0	6.61	243	5
28	6										79.2	14.22	253	5
29	7										59.1	15.58	263	5
30	8									23	100.0	8.46	273	5
31	9									23	84.1	10.33	283	5

Total error	8746
a	11.52
b	88.86
c	0.33
d	-5.45

Initial PCI	100
Max PCI	100
Min PCI	0
Max Shift	17.89
Min Shift	0.00

Max Red Value
20.00

No. of Data Point	n	271
No. of Sections	p	83
	n - p	188
	n - 1	270
	S_e	6.8208
	S_y	20.1830
	S_e / S_y	0.3380
	R^2	0.9594

Figure 6. Screenshot of Templates for PCI Calculations and Performance Modeling

3.4 Summary

The manual use of the existing PCI method provided by ASTM to a large number of road sections (such as the LTPP database) is time-consuming, costly and labor-intensive. Due to the need for large scale data analysis in this research study, it was necessary to develop an automated version of the ASTM PCI calculation procedure. The algorithm and mathematical functions used in the automated Excel^{TM} template are the same as those provided by ASTM. The template, will serve as an efficient PCI calculation tool for the rest of the analysis in this study. In addition, the automated PCI calculation template can be utilized with any pavement performance database that is driven by pavement distresses data.

CHAPTER 4

METHODOLOGY FOR PCI-BASED PAVEMENT PERFORMANCE MODELING

The second objective of this study was the development of PCI-based performance model approach. In this chapter, the basic principles behind the modeling approach are described. The concept of a master performance curve is discussed and mathematically represented by a sigmoidal function as described in Section 4.2. The nonlinear programming developed for the master performance curve construction is shown in Section 4.3. Section 4.4 describes the error terms using root-mean-square-error method.

4.1 Mathematical Background of Master Performance Curve

Pavement performance prediction models are based on analysis of historical PCI. For a set of road sections of similar characteristics (such as traffic level, geometry, structure, road classification), the model is an equation that relates PCI to time (pavement age) for this group of road sections. Ideally, a pavement continuously deteriorates under the combined influence of traffic loading and environmental condition, which consists of three stages (without any maintenance or rehabilitation intervention) as shown in **Figure 7.**

1) Within stage 1, newly constructed and reconstructed/rehabilitated pavements hold high resistance to traffic and environmental effects. Therefore, a relatively slow deterioration rate would be observed for the first stage.

2) For stage 2, accelerated damage caused by increasingly cumulative traffic loading leads to more and more severe distresses. The decrease in PCI would be more and more significant during this stage.
3) At the end of service life, the pavement is typically in such a poor condition, and the PCI value tends to approach or stabilize to a minimum within stage 3.

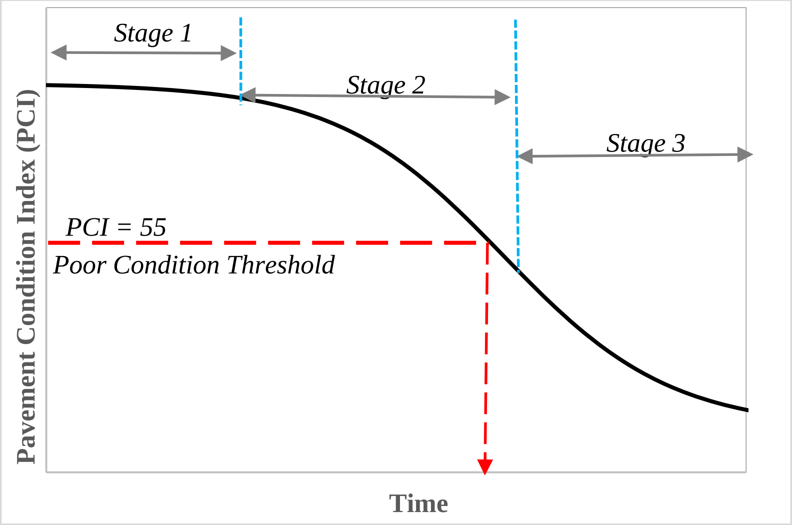


Figure 7. Schematic of PCI-based Pavement Performance Model

Note that no road section in the LTPP database or in reality would have complete performance data as shown in **Figure 7**. This is because there will be some sort of maintenance applied during the pavement service life. However, if such performance data exists, or can be assembled as will be shown in the next section, a ***master curve*** of performance can be mathematically constructed and best derived using a ***sigmoidal function***. A fundamental approach to develop the PCI-based performance model was presented in (Sotil and Kaloush 2004). The basic approach used in the analysis was to shift segments of the PCI performance data available for the road sections on the time scale to represent their position on the curve shown in **Figure 8**. The shifting is dependent on the PCI values recorded as will be explained next. The relationship between PCI and time is mathematically represented by **Equations 4** and **5**:

$$PCI = a + \frac{b}{1 + \exp(c \cdot T + d)} \tag{4}$$

$$T = t + f(PCI) \tag{5}$$

where,

t = Time since latest major M&R activity or first available date

f (PCI) = Shift factor for each specific PCI determined by nonlinear programming

T = Reduced time (basically the adjusted time within the projected service life)

a, b, c, d = Parameters describing the shape of the master curve

The use of the sigmoidal function form in **Equation 4** implies that PCI decreases as reduced time/T increases.

4.2 Analysis of Road Subsections

It is necessary to run historical data analysis of PCI versus time before modeling. **Figure 8** shows a sample output of PCI calculation based on LTPP sections in Florida (more details on LTPP sections are explained in Chapter 5). The dashed line (i.e. from point 5 to 6 in **Figure 8**) indicates a possible M&R on section-0103 because of increasing PCI. However, “0103A”, “0103B” and “0103C” are good candidates for further use as they are.

When M&R is identified for a section, one option is to divide the performance history of the test section into subsections depending on the M&R frequency, if any. These subsection will now have no M&R activity applied to the pavement. In this process, new datasets of subsections will be generated after dividing and regrouping of pavement sections data. By doing so, a pavement test section is seen as a “new segment” or “subsection” once a major maintenance activity was applied. Theoretically and expectedly, successive reduction or sustained PCI should be observed within each subsection over the years because of cumulative effects of traffic and environmental factors.

Another benefit of using “subsection” would be reduce or remove the errors during distress survey or PCI calculation. From engineering judgement, if without any M&R, a pavement section condition must keep deteriorating (or at least, staying the same for a while), hence, PCI keep decreasing. Therefore, any suddenly increased PCI should be discarded, the use of “subsection” could remove those error PCIs, at least reduce the occurrence of them.

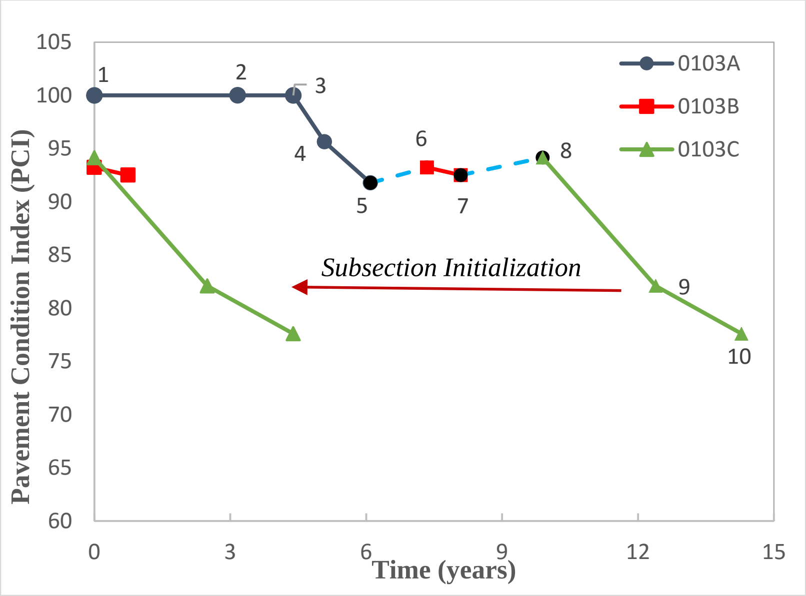


Figure 8. Illustration of Subsections Developed for LTPP Section-0103 in Florida

To automate this process, an Excel^{TM} template named "Section" was developed. Generally speaking, it is difficult to extract subsections and remove "dashed-line segments" through one single step. Therefore, the algorithms incorporated in the template cover two main steps:

Step 1: Subsection start-row labeling

The template starts with an algorithm to find out the starting row of possible subsections when PCI is non-decreasing within a pavement section dataset. **Table 2** shows a sample output for pavement sections in Florida. The number in "Start_Row" column represents row numbers of possible start rows of subsections. For example, subsection 0103A start with row-23 and end at row-28 where the PCI increased. Subsection 0103B includes two entries before the PCI increased again and necessitated the creation of subsection 0103C.

Table 2. Analysis of Subsections, Example of Pavement Sections in Florida

SHRP_ID	Time (yrs)	PCI	Start_Row	Description	Subsection
0103	0	100	23	*First available data*	0103A
0103	3.16	100		*same PCI*	0103A
0103	4.39	100		*same PCI*	0103A
0103	5.08	95.63		*Decreasing PCI*	0103A
0103	6.10	91.77		*Decreasing PCI*	0103A
0103	7.34	93.23	28	*Nondecreasing PCI*	0103B
0103	8.09	92.50		*Decreasing PCI*	0103B
0103	9.90	94.15	30	*Nondecreasing PCI*	0103C
0103	12.39	82.10		*Decreasing PCI*	0103C
0103	14.28	77.60		*Decreasing PCI*	0103C
3995	0	89.1	345	*First available data*	N/A
3996	0	92.89	346	*First available data*	3996A
3996	4.35	89.47		*Decreasing PCI*	3996A

Step2: Subsections preparation for modeling

Those sections with only one data entry (i.e. section-3995 in **Table 2**) are not used. After regrouping those raw data, standardized subsections dataset would consists of rows with data and blanks (total number of rows is 10), and the start time of each subsection will be initialized to be 0 as shown in **Figure 8**.

4.3 PCI Data Shifting and Master Performance Curve

Figure 9 shows the schematic of performance master curve construction. Basically, the whole process can be summarized as follows: (1) it is considered that the master curve is mathematically modeled by a sigmoidal function with parameters to be determined; (2) the *shift factors-f(PCI)* for subsections (e.g., 0501A) are dependent variables, which are used to match observed PCIs converted from distress data; graphically, subsections plots are shifted to master curve; (3) a master curve approximation method was applied to best (statistically) represent the historical pavement performance data.

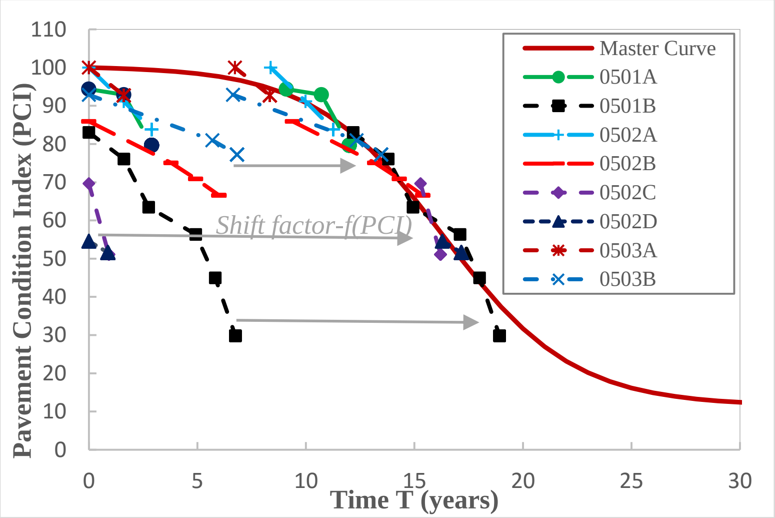


Figure 9. Illustration of PCI Shifting and Master Curve Construction

The accuracy of performance model is dependent upon the approximation error. The approximation error can be larger under unmatched/unsatisfied sigmoidal function and/or shift factors. In this study, an optimization problem is developed to minimize the approximation error by changing parameters and shift factors.

4.3.1 Nonlinear Programming Model

The optimization problem for pavement performance modeling includes (1) measured/recorded PCIs, which are calculated based on distresses data and related survey time for subsections, $mPCI_k^i$ and t_k^i, and (2) minimum and maximum values of PCI. The proposed nonlinear programming model aims to minimize the total error between predicted PCIs and observed PCIs by determining shift factors of subsections and parameters of the sigmoidal function. As the observed PCIs for each subsection is deterministic (input), the total error is basically determined by the value of PCI predicted from the sigmoidal function.

It is also assumed that the predicted $pPCI_k^i$ = 100 when time T_k^i = 0, as warranted using Equation 10. This assumption is to ensure the master curve has an initial PCI of 100. The development of mathematical model for the optimization problem resulted in a nonlinear objective function with linear constraints, these are described in more detail below.

1) *Reduced Time, Predicted PCI and Error*

   As noted previously in Equation 4, reduced time for entries in subsection-i can be calculated as follows:

$$T_k^i = t_k^i + fPCI^i \tag{6}$$

   The predicted PCIs can be determined by the exponential equation:

$$pPCI_k^i = a + \frac{b}{\exp\left(c \cdot T_k^i + d\right)} \tag{7}$$

   In order to calculate the difference between predicted PCIs and observed PCIs, a quadratic equation is used:

$$Er_k^i = (mPCI_k^i - pPCI_k^i)^2 \tag{8}$$

2) *Objective Function*

   The objective function is to minimize the total-error (E) of predicted PCIs versus observed PCIs by changing shift factors and parameters of the sigmoidal function, as shown below:

$$\min \mathrm{E} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \sum_{\mathrm{k}=1}^{\mathrm{K}} \mathrm{Er}_{\mathrm{k}}^{\mathrm{i}} \tag{9}$$

3) *Constraints*

As noted previously, PCI is a numerical index between 0 and 100, which constrains the value of predicted PCIs as represented in Equations 9 and 10. Basically, all shift factors should be non-negative as shown in Equation 11, and the pre-specified maximum shift factor ($fPCI_{max}$) may generally vary between 15 and 25, which depends on the characteristics of pavement sections within each network.

$$a, c \geq 0 \tag{10}$$

$$a + \frac{b}{\exp(d)} = 100 \tag{11}$$

$$0 \leq fPCI^{i} \leq fPCI_{max}, \forall i \tag{12}$$

Table 3. Definition of Notations in Nonlinear Programming Model

i	index of subsections, $i \in [1, N]$, N is total number of subsections;
k	index of data entry, $k \in [1, K]$, K is number of entries of a given subsection;
Input parameters	
$mPCI_k^i$	measured PCI in kth data-point of subsection-i;
t_k^i	time-entries of subsection-i, $t_1^i = 0$;
PCI_{min}	pre-specified minimum PCI, it is 0;
PCI_{max}	pre-specified maximum PCI, it is 100;
$fPCI_{max}$	pre-specified maximum shift factor;
Variables	
a	parameter of sigmoidal function;
b	parameter of sigmoidal function;
c	parameter of sigmoidal function;
d	parameter of sigmoidal function;
$pPCI_k^i$	predicted or calculated PCI in kth data entry of subsection-i;
$fPCI^i$	shift factor of subsection-i;
T_k^i	reduced time entries of subsection-i;
Er_k^i	error between predicted PCI and measured PCI.

The above formulated model leads to a nonlinear programming with a quadratic objective function and linear constraints. The Generalized Reduced Gradient (GRG) nonlinear algorithm in Excel™ Solver was used to solve the optimization problem. The datasheet named “M_curve” was developed to implement the optimization model. However, because the limitation of Excel™ Solver, the template developed can deal with a total of 100 variables at one time, that is, 4 parameters (master curve function) and 96 shift factors corresponding to 96 subsections.

4.4 Measurement of Performance Model Prediction Error

The Excel^{TM} template also measures the R^2 of the performance master curve using root-mean-square-error (RMSE) analysis. The equations used for RMSE determination is shown below,

$$R^2 = \sqrt{[1 - (\frac{n-p}{n-1})(\frac{S_e}{S_y})^2]} \tag{13}$$

$$S_e = \sqrt{E/_{(n-p)}}\ , S_y = STDEV(mPCI) \tag{14}$$

where,

n = number of total data points;

p = number of “subsections”;

E = minimum total error, see Eq. (8);

mPCI = measured PCI (calculated directly from distress data);

STDEV() = standard deviation.

Besides, the comparison of measured PCI and predicted PCI provided in the sheet of “PCI_Verify” in the template is also an alternative way for performance model verification.

4.5 Summary

This chapter described how the programmed PCI calculation template is extended for further application in PCI-based pavement performance modelling. Some basic ideas behind the modeling approach are summarized as follows:

1) Historical PCI data of a specific road section is analyzed, reduced or removed, depending on the occurrence of maintenance; the occurrence of maintenance is detected by increasing PCI values using the method of “subsection” construction process described.
2) The sigmoidal function proposed was based on continuous analysis of historical PCI data for several road sections. The sigmoidal function was found to fit well the pavement deterioration observed.
3) The nonlinear programming approach provided means of minimizing the difference between predicted and measured PCI. The parameters of the sigmoidal function, together with shift factors, were determined, and the performance master curve was obtained.

The basic procedures for PCI-based performance modeling using the automated Excel^{TM} template is described in *APPENDIX D*.

CHAPTER 5

MODELING OF STATE-LEVEL PAVEMENT NETWORK PERFORMANCE USING LTPP DATA SETS

This chapter illustrates the application of the pavement performance model analysis for data obtained from the LTPP database. A description of the database is provided in Section 5.1. Section 5.2 describes the PCI analysis of a pavement sections in Minnesota pavement network using data from LTPP. The details on development of PCI-based state-level models are described in Section 5.3. At the end of this chapter, the application of the PCI-based model on pavement network life-span expectancy is also validated using the LTPP data.

5.1 The Long-Term Pavement Performance (LTPP) Database

LTPP data include general inventory and information of test sections, materials experiment, maintenance and rehabilitation (M&R), climate, traffic, deflection (e.g., Falling Weight Deflectometer (FWD)), longitudinal profile (International Roughness Index (IRI)) and pavement distresses. At present, there are a total of 2509 test sections included in the database at more than 900 locations mainly on in-service highways throughout North America.

The distress database in the LTPP program consists of individual distress data of asphalt concrete pavements (ACP), joint plain concrete (JPCP) and continuously reinforcement concrete pavement (CRCP) sections. In this study, the focus on performance modeling of the flexible pavement (ACP) sections. A total of 11 common distresses are considered for flexible pavements in LTPP. The measurement of these distresses are shown in **Table 4**.

Table 4. Common Flexible Pavement Distresses Considered in LTPP

Measure Type (Unit)		
Length (m or ft)	**Area (m^2 or ft^2)**	**Number of Occurrences**
Longitudinal Cracking Transverse Cracking Edge Cracking	Fatigue Cracking Block Cracking Rutting, Patching Bleeding, Shoving, Pumping Raveling, Polished Aggregate	Potholes

The development of the study's master database resulted in 1623 road section entries, each entry dataset included inventory and general information (State Code, Section/SHRP_ID, width of section, etc..), in addition to distress information and survey dates. A testing section is generally 3.7m (12ft) ×152.4m (500ft) = 563.88m^2 (6000ft^2), the distress data included extent, type and severity. Most of the variables within tables extracted from LTPP database are very straightforward and self-explanatory.

5.2 PCI Calculation using LTPP Data

Table 5 shows an example PCI calculation result of an LTPP road section. The pavement distress data was measured in a pavement condition survey conducted on Aug. 18th, 2001. Based on the distress data table, it can be observed the pavement section is seriously cracked with some other distresses. It is reasonable to find the PCI of this section being 18.5, indicating very poor condition.

Table 5. PCI Calculation Outputs of LTPP Section-0507 in Minnesota (08/18/2001)

(Data Source: FHWA, LTPP 2015)

Distress Type	Patching (H*, m^2)	L&T* Crack (L*, m)	L&T* Crack (H*, m)
Distress Quantity	4.2	2.9	356.2
DVs	8.3	0	79.5
Maximum CDV	81.5		
PCI	18.5		
H, L: High, Low severity distress; L&T*: Longitudinal and Transverse Cracking.*			

The maintenance and rehabilitation (M&R) history is shown in **Table 6**, the data is extracted from the M&R historical data set of the LTPP database. According to the table, there were a total of five asphalt concrete (AC) overlays being done to repair and preserve this specific section from 1990 to 2004, other routine maintenance include patching and crack sealing.

Table 6. Maintenance and Rehabilitation History of LTPP Section-0507 in Minnesota

M&R Activity	**Complete Date**
AC Overlay	9/15/1990
AC Overlay	6/15/1991
AC Overlay	6/1/1999
AC Overlay	8/1/2001
AC Overlay	9/1/2004
Patching	8/1/2001
Crack Seal	6//15/1991

Figure 10 shows the historical PCI data of Section-0507. It shows the whole pavement condition deterioration trend for the section from 1990 to 2005 in terms of PCI. The maintenance and rehabilitation information, along with the high severity longitudinal and transverse cracking data, is also shown in **Figure 10** for PCI data checking. As shown in the figure, there was generally an increase in PCI associated with a decrease in linear

cracking (longitudinal and transverse cracking) quantity when M&R (AC overlay) was completed for Section-0507. This is attributed to the specific pavement treatment, a better pavement condition of the road section will be observed (i.e., an increase in PCI).

Basically, the PCI curve can be divided into several phases dependent on the maintenance and rehabilitation activities (M&R), if any. Even though, the slight increase may have been due to condition survey measuring error. Basically, the algorithm developed will not tolerate any increase in the PCI value and would remove this part of the PCI curve from the analysis. Fortunately, there were only few cases that were found in this category. The other phases showed a decrease in PCI values as expected, and hence these parts of the PCI curve were used to predict future trend in pavement performance of section-0507.

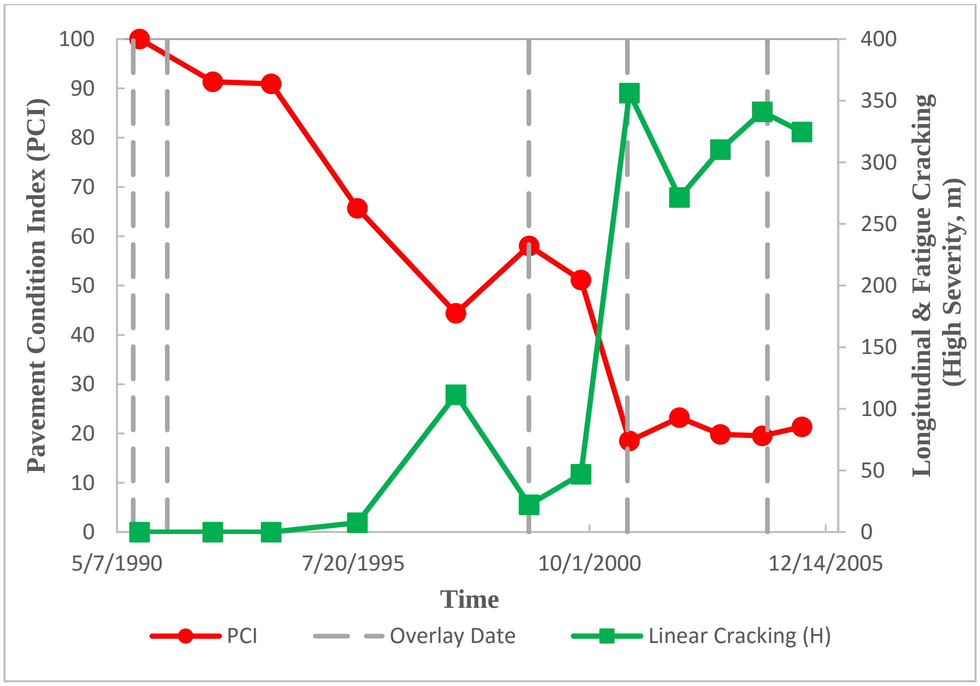


Figure 10. Historical PCI and Data Checking of LTPP Section-0507 in Minnesota

5.3 Performance Modeling for State-level Pavement Networks

The next few sections illustrate the application of predictive pavement performance model for data obtained from the LTPP database. The accuracy of predictive network-level pavement performance models depends on homogeneity of test sections included. That is, an ideal model for a pavement network would be developed for road sections with similar traffic and environmental (climate, subgrade, etc.) conditions, and share common materials and structural characteristics. Therefore, given sufficient historical data, models for smaller networks are generally more accurate than larger ones.

5.3.1 Model Development for State-level Network

In this effort, a Minnesota pavement network consisting of 54 pavement sections (or 83 subsections), is used first. The state of Minnesota is in a wet freeze climatic region, and all the test sections were constructed on arterial or interstates roads. The traffic data collected in LTPP database shows that there are 42 sections with an average daily truck traffic less than 5000 according to estimated data from 1990 to 2005. Therefore, the Minnesota pavement network consists of nearly homogeneous test sections in terms of traffic and climate condition. The model developed relating pavement condition to time (reduced time) is given by:

$$PCI = 11.52 + \frac{88.86}{1 + exp(0.33T - 5.45)} \tag{15}$$

Figure 11 shows the schematic of pavement performance master curve and subsections. In this case, a PCI value of 55 is considered as poor condition threshold according to ASTM standards. An application of the performance model developed for Minnesota would be network-level pavement life expectancy. For a specific pavement segment within this Minnesota pavement network, and given distress data, the remaining life can be predicted on the basis of the master curve. As shown in **Figure 11,** the predicted pavement life span is 16.4 years before major rehabilitation or reconstruction is warranted.

To verify the accuracy of model, a comparison of predicted PCI to observed PCI for each data entry is shown in **Figure 12**. The relationship is a linear with very good measures of accuracy (R^2=0.9926) of the fitted performance master curve. It is evident that the model developed can be used to predict state-level pavement network performance.

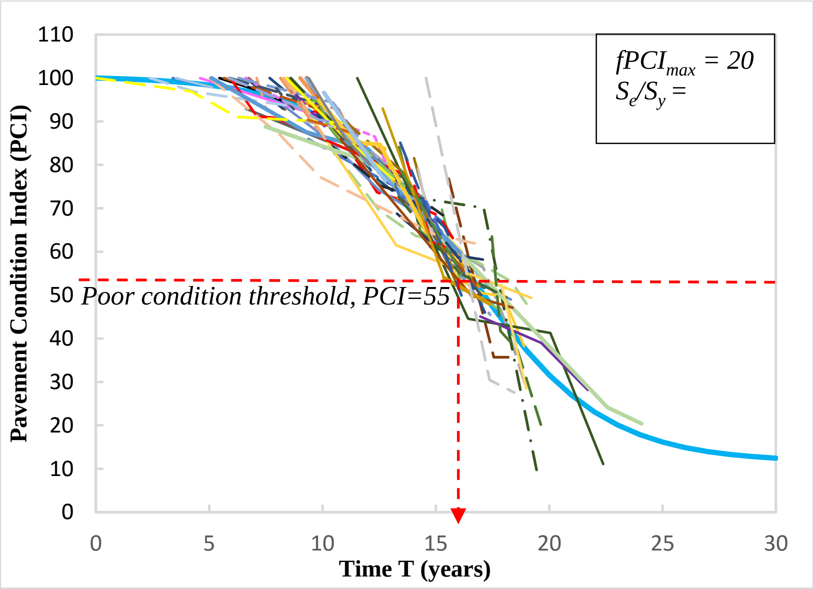


Figure 11. Pavement Performance Master Curve for Minnesota Pavement Network

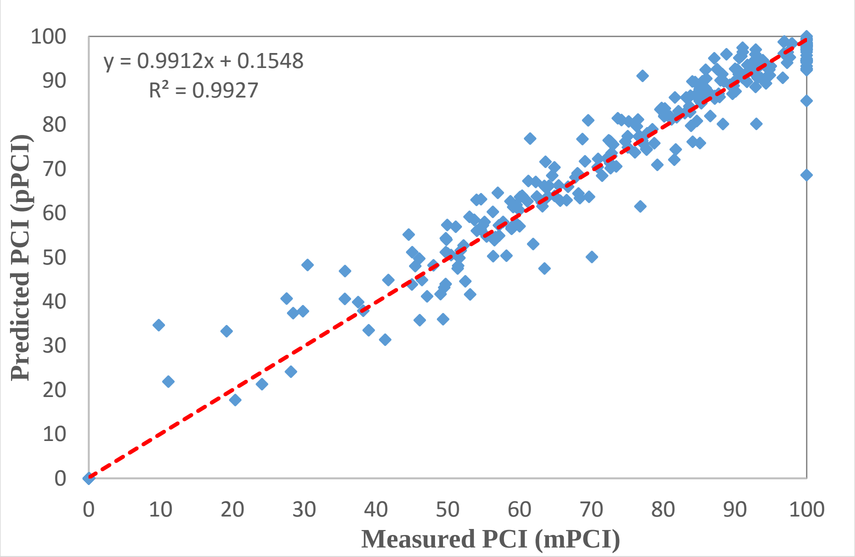


Figure 12. Comparison of Predicted PCI to Measured PCI

The shift factor of each subsection is associated with the initial condition (or first available data) of the pavement section. Usually, a subsection derived from a perfect condition pavement section (PCI = 100) is inherent a “0” shift factor. The relationship between shift factor and initial PCI of Minnesota subsections is shown in **Figure 13**.

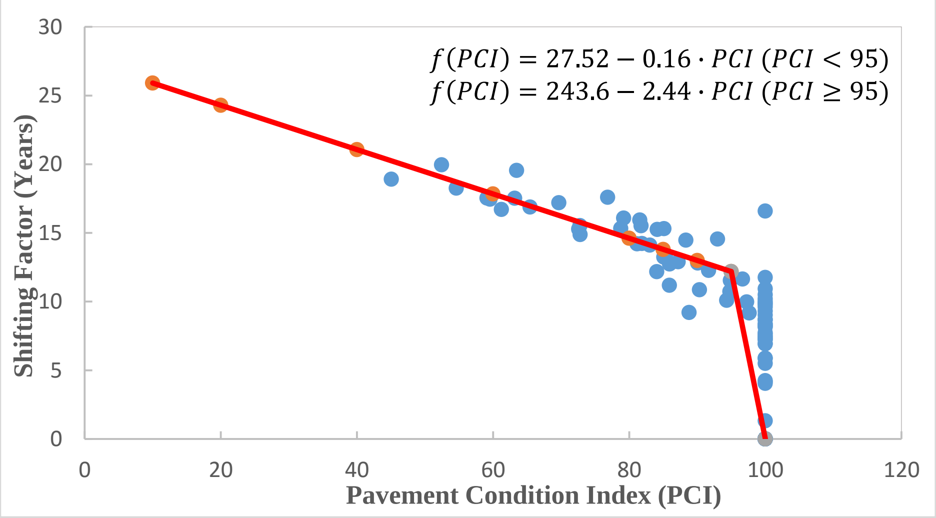


Figure 13. Shift Factors as a Function of PCI

5.3.2 Validation of the Modeling Approach using Additional Datasets

This process was repeated for a set of master curves for the States of: Arizona, Florida and Utah pavement networks and the results are shown in **Figure 14**. Some characteristics of the pavement network and models coefficients are summarized in **Table 7**. The applicability and accuracy of models developed are demonstrated by the regression coefficients presented in **Table 7**. Additional and complete set of plots of predicted versus measured PCI for the three States (Arizona, Florida and Utah road networks) are shown in *APPENDIX B* and *APPENDIX C*.

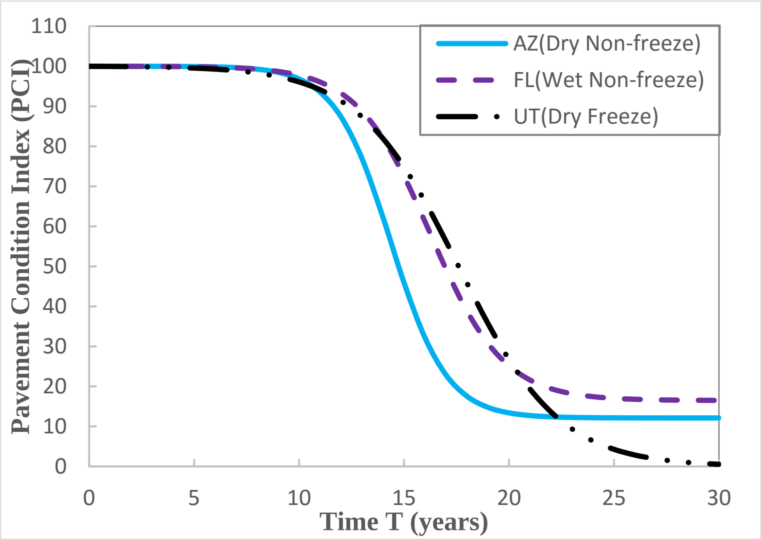


Figure 14. Sample Master Curves of Arizona, Florida and Utah Pavement Network

Note that **Figure 14** is not intended to compare road networks across states at this point. There are variables that need to be considered for such analysis. For example, the master curves in **Figure 14** shows that pavement performance of the Arizona network is poorer than Florida, which one may think unreasonable because pavement deterioration generally should be worse under wetter condition. However, the traffic analysis showed that the truck traffic of LTPP sections in Arizona pavement network is higher than that in Florida. Specifically, 8 out of the 71 sections in Florida had an Average Annual Daily Truck Traffic (AADTT) greater than or equal to 2000, while for Arizona 48 out of the 62 road sections exceeded this level of AADTT. Other heterogeneities of pavement networks can be subgrade conditions and temperature fluctuation as discussed earlier.

Table 7. Characteristics of Models of Minnesota, Florida, Arizona and Utah Pavement Networks

State	**Minnesota(MN)**	**Florida(FL)**	**Arizona(AZ)**	**Utah(UT)**
Climate Region	Wet, Freeze	Wet, Nonfreeze	Dry, Nonfreeze	Dry, Freeze
Number of Sections	54	71	62	34
Subsections	83	84	89	41
Data-points	271	272	288	121
Parameter-a	11.52	16.49	12.13	0.00
Parameter-b	88.86	83.52	87.87	100.06
Parameter-c	0.33	0.57	0.75	0.42
Parameter-d	-5.45	-9.32	-10.79	-7.38
$fPCI_{max}$ (Pre-specified)	20	25	20	20
RMSE/R^2 (Master Curve)	0.9594	0.9504	0.9516	0.9639
Predicted life span (years)	16.4	16.5	14.4	17.1

CHAPTER 6

MODELING OF MN/ROAD PAVEMENT NETWORKS PERFORMANCE

This chapter includes additional effort to validate the application of the PCI-based model presented in Chapter 5. A description of a new data source, Mn/ROAD database, is provided in Section 6.1. In addition, Section 6.2 presents a comparison of the PCI data developed to historical IRI data. This was to further validate and verify the automated PCI calculation templates. Section 6.3 describes the details of the PCI-based model development for this data set.

6.1 Minnesota Road Research Project (Mn/ROAD)

In the Mn/ROAD database, the detailed information collected for each test section include (1) cell / layers information (surface material, construction and M&R, etc.), (2) environment and traffic condition (e.g. temperature, ESALs), (3) ride quality data (roughness, IRI), (4) distress data (surface distresses, rutting, etc.). Some other data found are for specific performance testing, such as HMA material test data and FWD data. The distress and IRI data are collected usually twice a year for each road section (or cell). Compared with the LTPP database, less road sections are included; however, the performance data for each section is more detailed.

6.1.1 Mainline (Flexile Pavement) Sections

The Minnesota Road Research Project facility is located parallel to Interstate 94 (I-94) near Albertville, Minnesota. (MnDOT, Mn/ROAD 2015). It currently consists of two separate roadway segments containing over 50 test cells/sections.

1) 3.5-mile, 2-lane (passing-lane and driving-lane) Interstate mainline (I-94);
2) 2.5-mile 2 lane closed loop Low Volume Road (LVR);

Among them, the cells in the 3.5-mile, 2-lane Interstate mainline are test sections of interest in this chapter / study. There are a total of 28 cells included in the mainline segments, 14 cells are asphalt concrete pavement sections. A schematic of mainline cells are shown in **Figure 15**, the ones highlighted are the flexible sections of interest in this study.

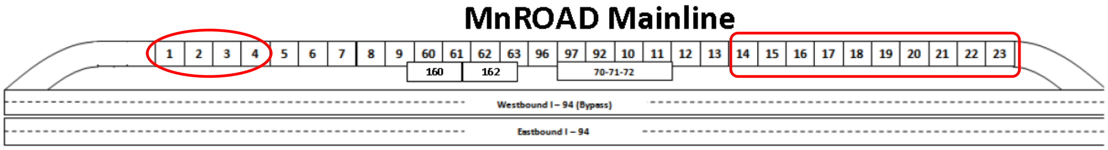


Figure 15. Illustration of Mn/ROAD Mainline Cells (*Source: MnDOT, Mn/ROAD 2015*)

The width and length of each flexible sections are shown in **Table 8**. From the table, we can find that each of cell/section is set uniformly, with similar parameters. According to the Mn/ROAD database, these cells share very similar structural design, traffic and environmental condition. Therefore, they are a good family of pavement sections for further analysis.

Table 8. Parameters of Flexible Pavement Cells in Mainline Segment (*Source: MnDOT, Mn/ROAD 2015*)

Cell	**1**	**2**	**3**	**4**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Width (ft)	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Length (ft)	462	500	454	500	567	500	500	500	500	500	500	500	500	500

6.1.2 Traffic Analysis of the Mainline Sections

The mainline is carrying "live" I-94 traffic, averaging 26500 vehicles per day with 13% truck traffic for the westbound lanes providing approximately 750,000 Equivalent Single Axle Loads (ESALs) (flexible pavement) per year (MnDOT, 2011). According to the latest released report by Mn/ROAD (Mn/ROAD, 2014), the traffic data of passing and driving lanes of the mainline sections (in ESALs) from 2004 to 2013 are shown in **Figure 16**. As is noted previously, the structural design and environmental condition are very similar for the two-lane sections/cells, hence, the traffic condition is the main factor that is associated with the differences in two-lane performance, if any.

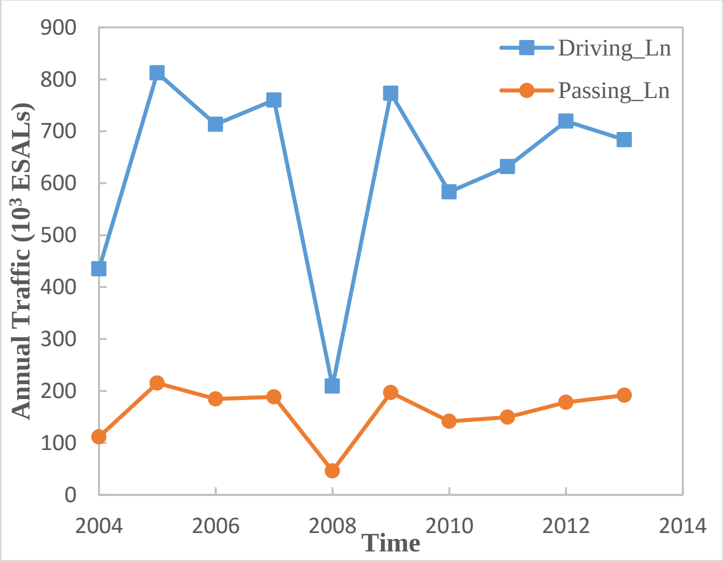


Figure 16. Traffic (ESALs) Difference between Driving-lane and Passing-lane

(*Data Source: Mn/ROAD, 2014*)

6.2 Rationality of PCI Calculation using IRI Mn/ROAD Data

In the Mn/ROAD database, there are detailed distresses and roughness (IRI) data. Theoretically, for a specific section, there should be a relationship (negative correlation) between the IRI and the PCI derived from distresses data within the same analysis period. This is because, from the basic definition, a high PCI or a low IRI usually indicates a good pavement condition. Therefore, the following case study was used to check the rationality of the calculated PCI using the IRI as a benchmark.

The PCI was calculated using historical distress data using the developed automated template. The test section used in this case study was *Cell-1* in the mainline Interstate segment. The IRI data was from the roughness database. The major causes of decreasing PCI was attributed to increasing occurrence of low severity transverse cracking and rutting. This is shown in **Figure 17**, the decreasing value in PCI and increasing value in IRI are correlated with each other; this is rational, and in a way verified that the PCI calculations method in this study is reliable.

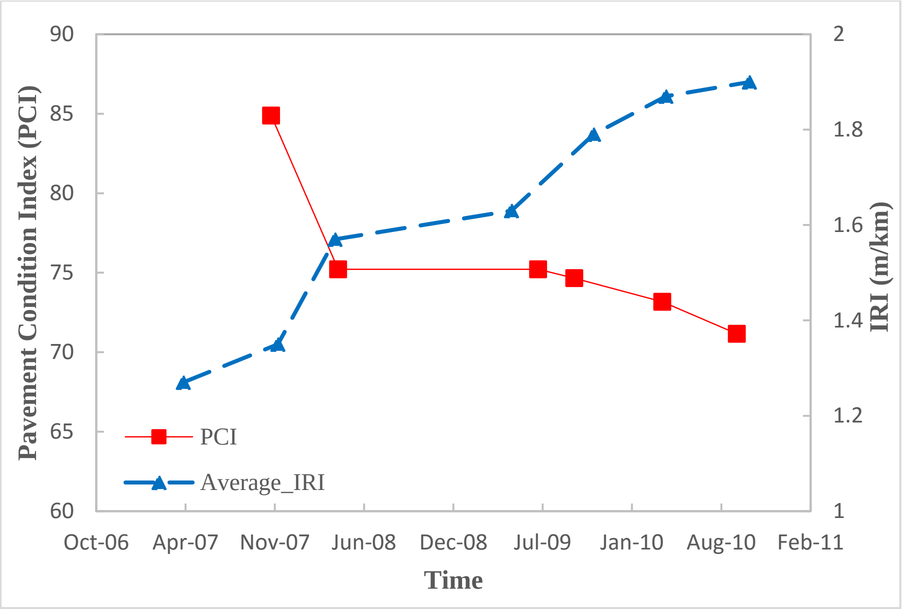


Figure 17. Comparison of IRI and PCI using Cell-1 Data from Mn/ROAD

6.3 Development of Performance Models based on Mn/ROAD Data

A total of 14 flexible pavement test sections (cells) are used for PCI-based performance modelling. Those sections are located in the 2-lane mainline Interstate segment (I-94). The historical data used includes distress data from 2004 to 2013. Previous analysis revealed that there is significant traffic difference between the two lanes, which should be considered in this analysis. Therefore, two separate performance master curve are developed for both lanes. In this case study, it is intentionally designed to investigate the effect of traffic condition on pavement performance.

By following the same procedure as described previously, the performance models of the passing and driving-lanes are shown in **Figure 18**. Characteristics of the models developed for the two lanes are presented in **Table 9.** The models accuracy are represented in the RMSE/R^2 values. The same model verification and validation procedures are repeated for these two master curves and they are shown in *APPENDIX B*. The plots of shift factor versus PCI can be found in *APPENDIX C*.

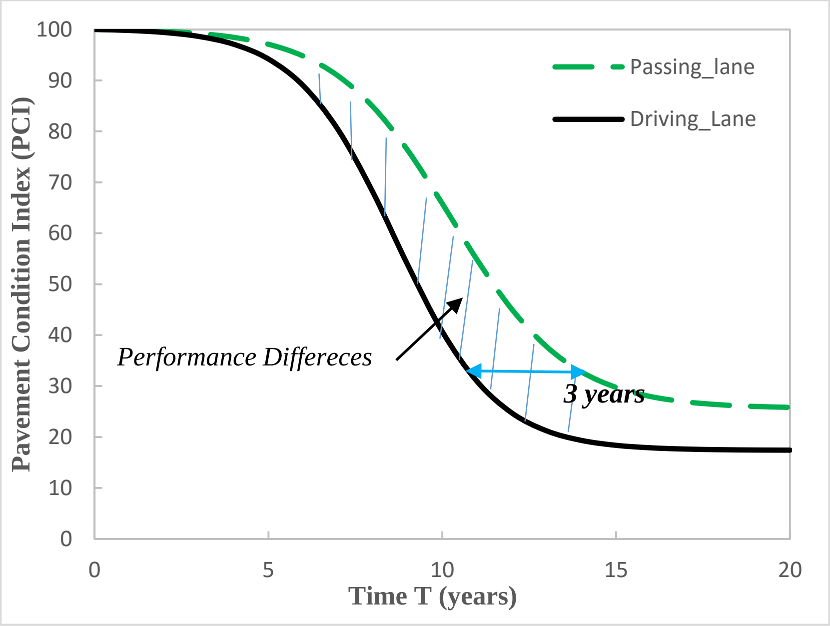


Figure 18. Master Performance Curves of Driving-lane and Passing-lane Pavement Sections

Figure 18 revealed that PCI-decreasing trend are very similar for both lanes. Intuitively, this is reasonable because of the same environmental condition and structural design they shared. It is also clear that the passing lane has a better performance than driving lane, and the maximum life span difference between those two lanes is 3 years at the end of service life. This supported previous analysis that the heavy traffic (especially truck traffic) accelerate pavement deterioration. Basically, the performance difference validates the different contributions of traffic loading (ESALs) to pavement deterioration.

Given more available data, the relationship between traffic loading and performance can be quantified using the method provided in this study. The same study approach can be also utilized to quantify the contribution to pavement deterioration of the other relevant variables such as environment conditions, layer thickness, etc.

Table 9. Characteristics of Performance Models for Two Lanes Pavement Sections

Lane	**Passing**	**Driving**
Number of Sections	14	14
Subsections	52	53
Data-points	234	235
Parameter-a	25.6	17.39
Parameter-b	74.56	82.81
Parameter-c	0.6	0.7
Parameter-d	-6.14	-6.04
$fPCI_{max}$ **(Pre-specified)**	15	15
RMSE/R^2 (Master curve)	0.9743	0.9707
Predicted life span (years)	11	9

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

The objective of this research was to develop a pavement condition index (PCI) based on LTPP pavement distress data. The PCI was selected as the performance indicator and used the ASTM D6433-07 standards for deduct values and calculations. Programmed Excel™ templates were developed and successfully used to import LTPP distress data and directly calculate PCIs for various LTPP and Mn/ROAD test sections. In addition, the PCIs were used in a unique performance modeling approach. A PCI master curve was mathematically modeled using nonlinear optimization techniques to arrive at a sigmoidal function with parameters determined for each group of road sections of common characteristics. The model demonstrated how historical PCI data can be analyzed to arrive at pavement performance master curves. The analysis and results of LTPP data for several States indicated that the study approach is rational, and further study using Mn/ROAD data yielded good to excellent statistical measures of accuracy for smaller road data networks.

The LTPP database itself (InfoPave™), and possibly the Mn/ROAD database, can benefit from the PCI templates developed in this study, and perhaps make them available for users to either download or compute specific PCIs for specific road sections of interest. Furthermore, the PCI-based performance model development can be also incorporated in future versions of InfoPave™. It is recommended that this study's findings be further evaluated and implemented for more road sections from alternative databases. State and local agencies are encouraged to use and apply the analysis procedures and modeling approach for their specific road distress data to validate the findings.

7.2 Limitations and Future Research

Like other performance models, the modeling approach developed in this study is an approximation of the actual deterioration of pavement condition. The prediction error associated with the model is still there, however, it can be estimated to assess the uncertainty in the predictions. Although the newly developed performance models are superior to most existing models, some limitations has been identified and further research should be recommended.

The two databases were not fully utilized in this research study. For example, data representing other States, or further filtering of road sections and PCI data sets to represent more specific climatic, traffic, pavement structural properties and design characteristics should be further evaluated.

In addition, this study efforts focused on PCI calculations and performance modeling for the asphalt pavement sections. However, the methodology can be also applied and implemented for the Portland Cement Concrete (PCC) pavement sections. By applying the similar approach to PCC sections, an overall evaluation of all sections can be addressed, thus, provides a comparison of performance of those two basic types of pavements within the same network.

Enhanced prediction accuracy and/or wider applicability could also improve future prediction process of pavement deterioration. For instance, the modeling approach assumes that, for a pavement network, the model parameters are constant. An alternative approach would allow the variation, by updating, of those parameters along with newly collected data. That is, the developed model will exemplifies the best possible representation of network performance, and thus, provide a sound prediction of future performance.

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APPENDIX A

DENSITY-DEDUCT VALUE CURVES FOR FLEXIBLE PAVEMENT

This appendix lists density (log (density)) deduct curves developed for automated PCI calculation in Chapter 3, Section 3.3. A total of 11 figures are listed to explain the efforts on determination of DV-density nonlinear (multinomial) functions, the parameters of the multinomial functions for all distresses (except for Polished Aggregate) are shown in **Table (1)**. The **FIG. 12** shows the relationship between CDV and TDV, the parameters of quantified multinomial function is shown in **Table (2).**

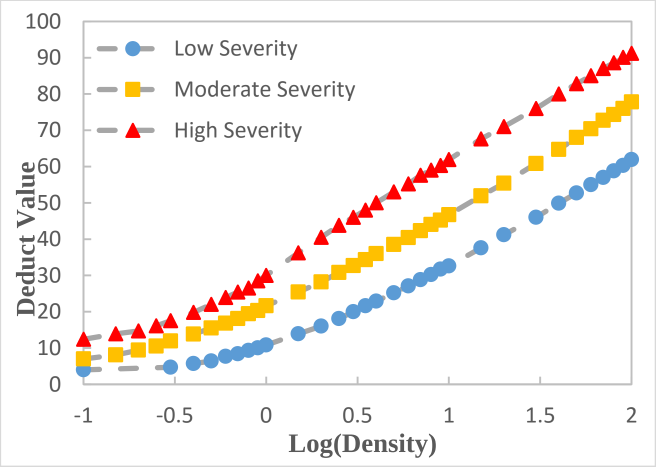


FIG. 1. Alligator/Fatigue Cracking

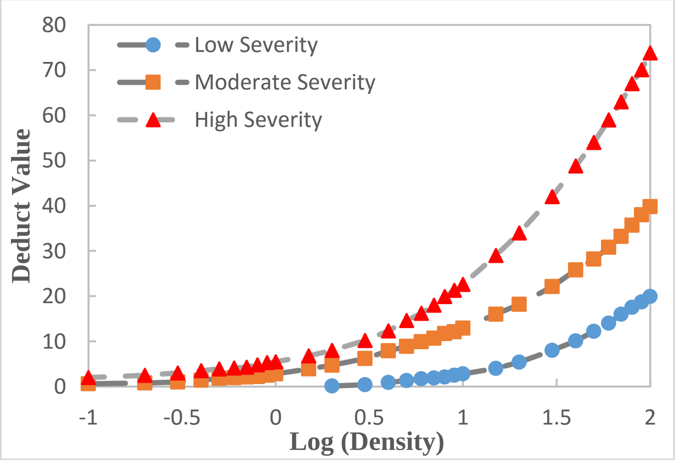


FIG. 2. Bleeding

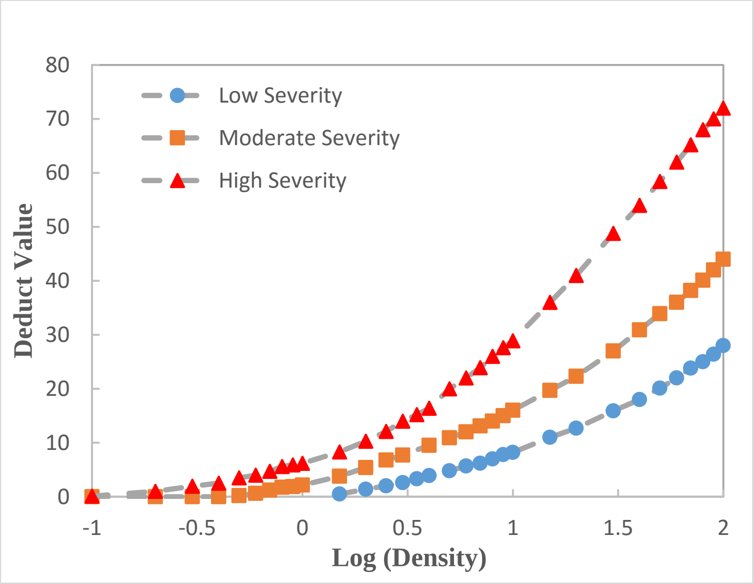


FIG. 3. Block Cracking

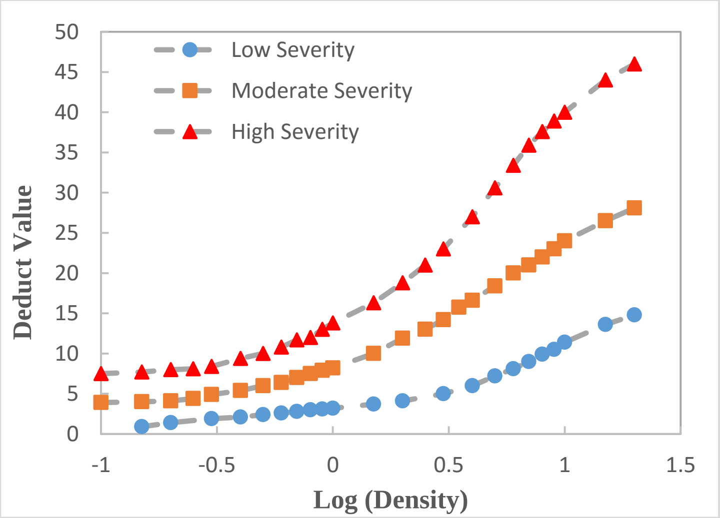


FIG. 4. Edge Cracking

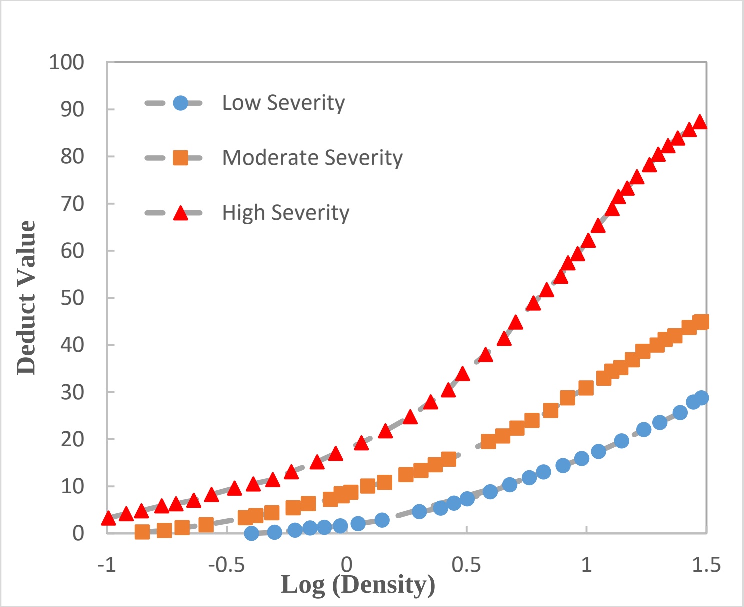


FIG. 5. Longitudinal & Transverse Cracking (L&T)

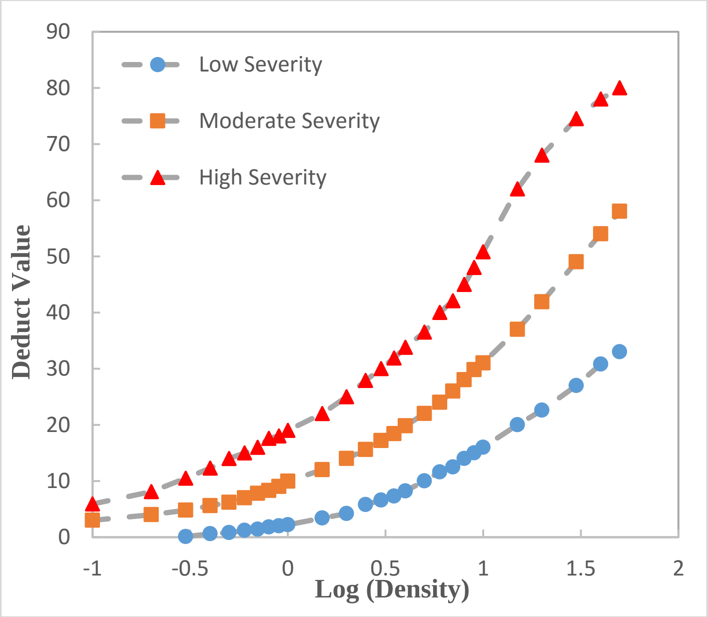


FIG. 6. Patching

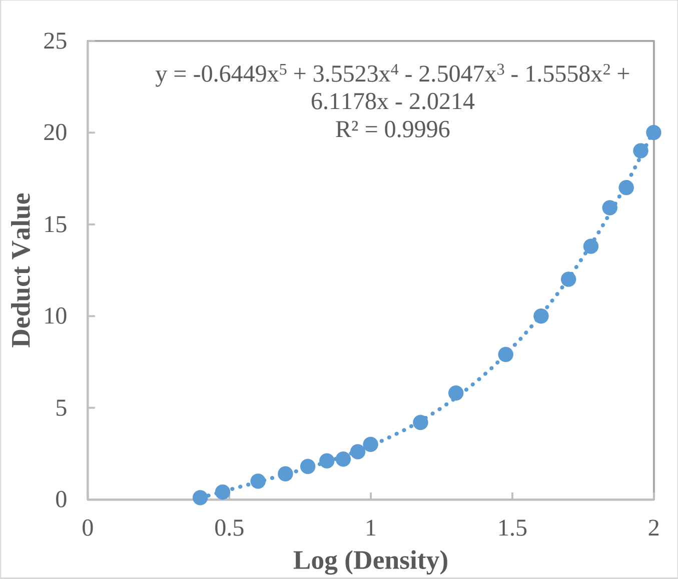


FIG. 7. Polished Aggregate

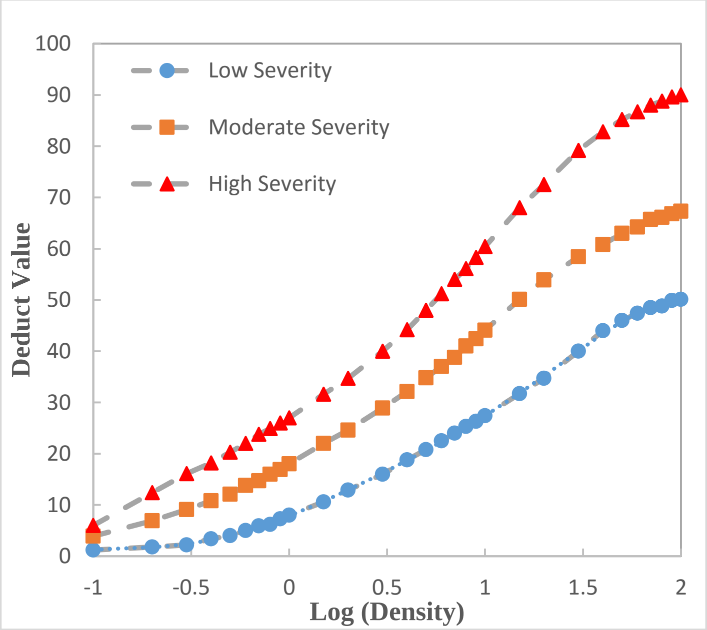


FIG. 8. Rutting

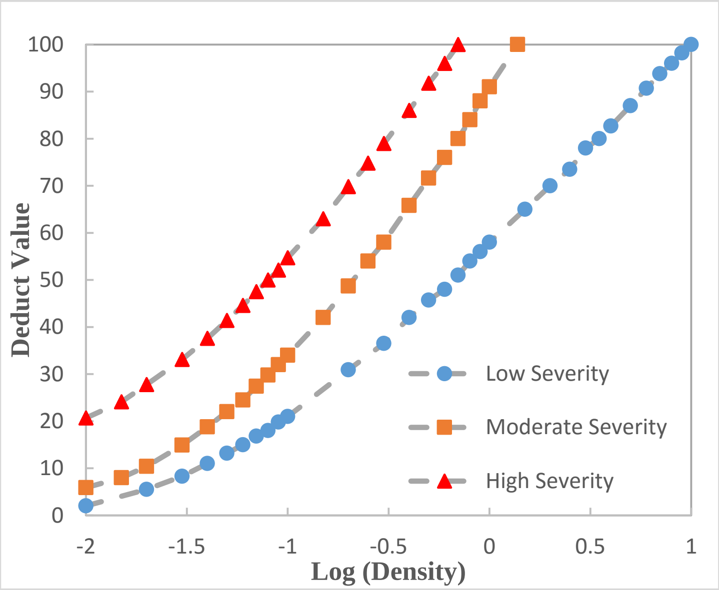


FIG. 9. Potholes

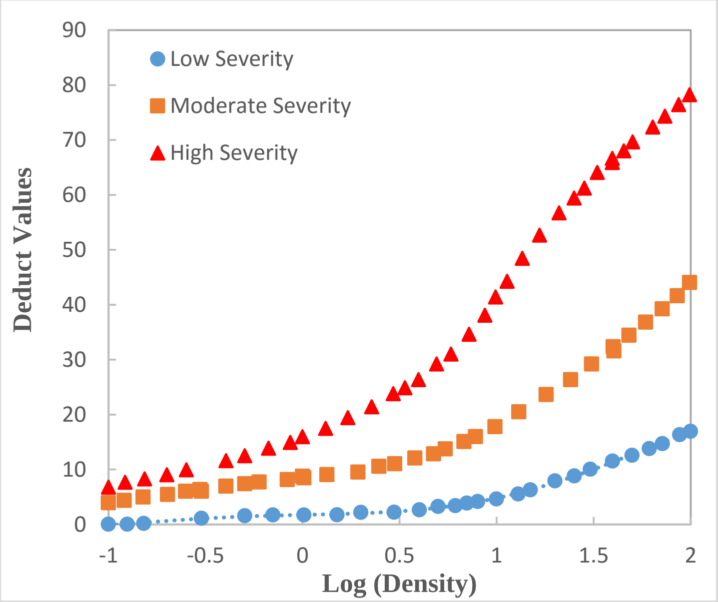


FIG. 10. Raveling

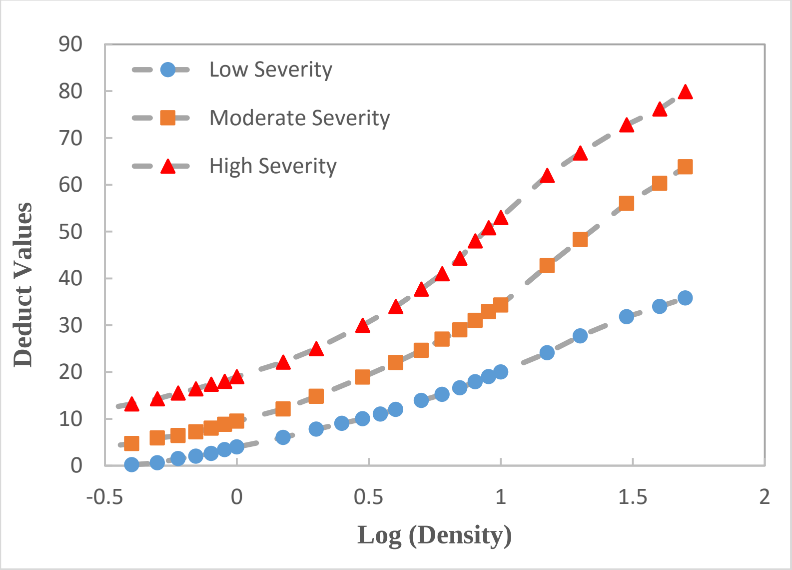


FIG. 11. Shoving

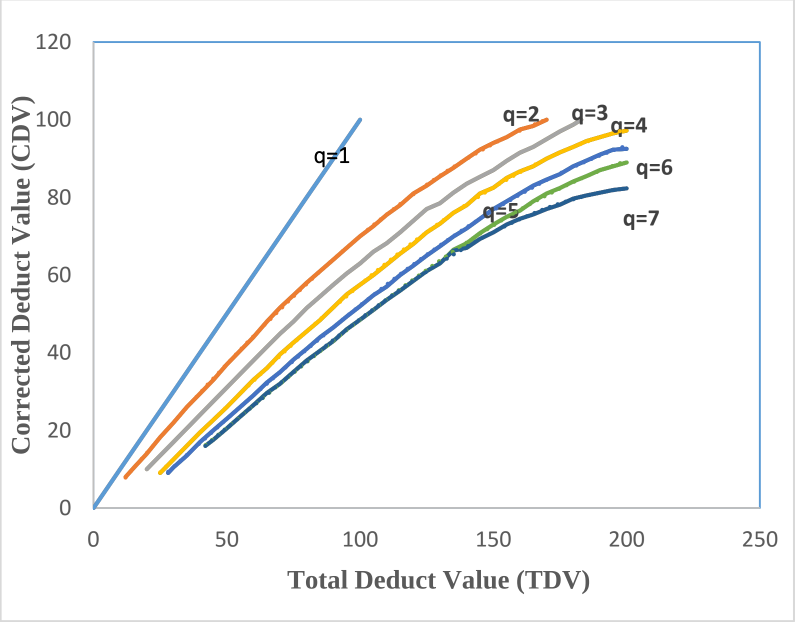


FIG. 12. CDV as a Function of TDV

The following two tables provide detailed parameters of the polynomial functions. The variables used in these tables were explained in **Equation 2** and **Equation 3**. For example, the function of low severity fatigue cracking:

$$y\ (DV) = -1.4052x^3 + 7.6012x^2 + 15.867x + 10.749$$

($x = log\ (Density)$) can be represented as an array: A[4] = {A_0, A_1, A_2, A_3}, where,

$A_0 = 10.749$; $A_1 = 15.867$; $A_2 = 7.6012$; $A_3 = -1.4052$.

Table (1). Parameters of Developed Deduct Value Curve Nonlinear Functions

Distress (Severity)	**A_0**	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**	**R^2**
Fatigue cracking (L)	10.749	15.867	7.6012	-1.4052	0	0	0	1
Fatigue cracking (M)	21.39	21.483	5.0615	-1.5665	0.355	0	0	1
Fatigue cracking (H)	30.188	31.353	7.9737	-10.227	0.2232	3.7003	-1.1542	0.9999
Bleeding (L)	1.8295	-14.933	42.465	-47.127	25.107	-4.5804	0	0.9999
Bleeding (M)	2.7872	5.3875	4.6612	0.3091	-0.6957	0.5096	0	0.9999
Bleeding (H)	5.2119	6.414	7.4293	4.0615	-0.4107	0	0	0.9999
Block cracking (L)	-0.1016	2.3786	8.6496	-3.7548	1.164	0	0	0.9998
Block cracking (M)	2.315	8.9552	5.602	-3.4737	3.32	-0.7577	0	0.9999
Block cracking (H)	6.0091	11.269	10.017	3.4588	-1.5089	0	0	0.9999
Edge cracking (L)	3.1444	2.0074	1.1778	6.222	2.0139	-3.3278	0	0.9995
Edge cracking (M)	8.2677	8.533	6.5905	1.8119	-0.9679	-1.349	0	0.9998
Edge cracking (H)	13.367	13.955	12.973	6.5226	-2.3835	-4.1062	0	0.9996
L&T cracking (L)	1.7349	6.0577	8.563	7.0654	-11.37	4.3642	0	0.9998
L&T cracking (M)	8.4355	14.045	5.2439	3.3775	2.1445	-2.4006	0	0.9999
L&T cracking (H)	17.67	22.303	15.702	11.802	-0.432	-4.7342	0	0.9999
Patching (L)	2.1419	5.324	6.6383	5.2832	-4.5093	1.0189	0	0.9997
Patching (M)	9.5535	12.007	6.5043	2.8351	0.9623	-0.8932	0	0.9999
Patching (H)	19.016	16.806	3.9878	11.342	5.4961	-5.7158	0	0.9992
Rutting (L)	8.0082	14.038	5.0636	-0.0406	1.4484	-0.9035	0	0.9996
Rutting (M)	17.663	19.717	7.8427	0.5225	-1.5932	0	0	0.9998
Rutting (H)	26.761	23.525	9.4589	3.7395	-3.2432	0	0	0.9999
Potholes (L)	57.481	41.042	3.0305	-1.5721	0.1291	0	0	0.9999
Potholes (M)	90.65	66.661	7.8051	-2.1575	0	0	0	0.9999
Potholes (H)	109.11	58.957	1.3903	-2.9872	0	0	0	1
Raveling (L)	1.7828	0.5165	-0.6228	3.191	0.9732	-1.2907	0.2628	0.9993
Raveling (M)	8.4392	3.406	1.3728	5.739	0.667	-2.1711	0.5652	0.9998
Raveling (H)	15.741	9.3802	7.0157	15.47	-0.3931	-7.6863	2.2487	0.9994
Shoving (L)	3.8756	10.363	2.7931	5.7746	-2.6249	0	0	0.9995
Shoving (M)	9.4749	13.999	7.2303	4.1283	2.415	-2.1604	0	0.9997
Shoving (H)	18.608	16.77	12.338	8.1407	-1.3562	-2.3024	0	0.9993

Table (2). Parameters of CDV as a Function of TDV

q	B_0	B_1	B_2	B_3	R^2
0	0	0	0	0	1
1	0	1	0	0	1
2	-1.907	0.819	-0.0006	-0.000004	0.9999
3	-6.1516	0.8016	-0.0009	-0.000002	0.9999
4	-7.9770	0.6844	0.0002	-0.000005	0.9999
5	-7.8998	0.6105	0.0003	-0.000004	0.9999
6	-6.6359	0.5140	0.0009	-0.000005	0.9999
7	-7.2983	0.5192	0.0012	-0.000008	0.9999

APPENDIX B

PCI VERIFICATION PLOTS

In this appendix, a family of plots of predicted PCI versus measured (calculated) PCI is presented as a complement of Chapter 5 and Chapter 6.

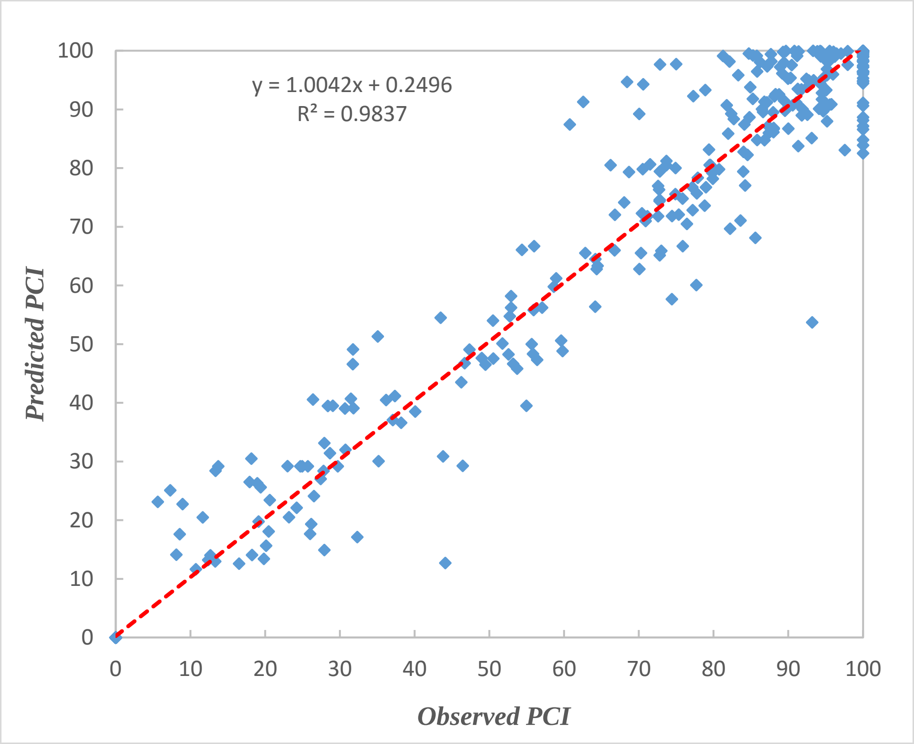


FIG. 1. PCI Verification for Arizona Network

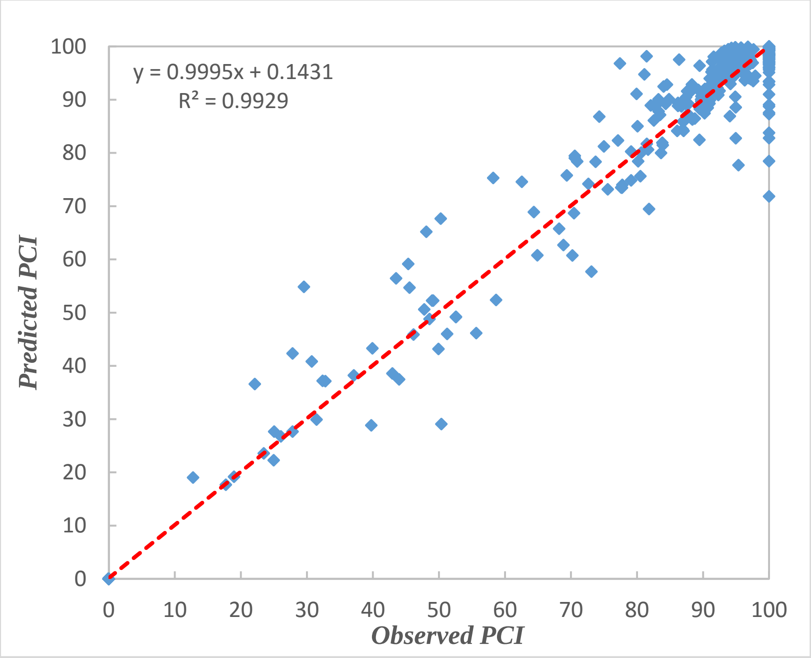


FIG. 2. PCI Verification for Florida Network

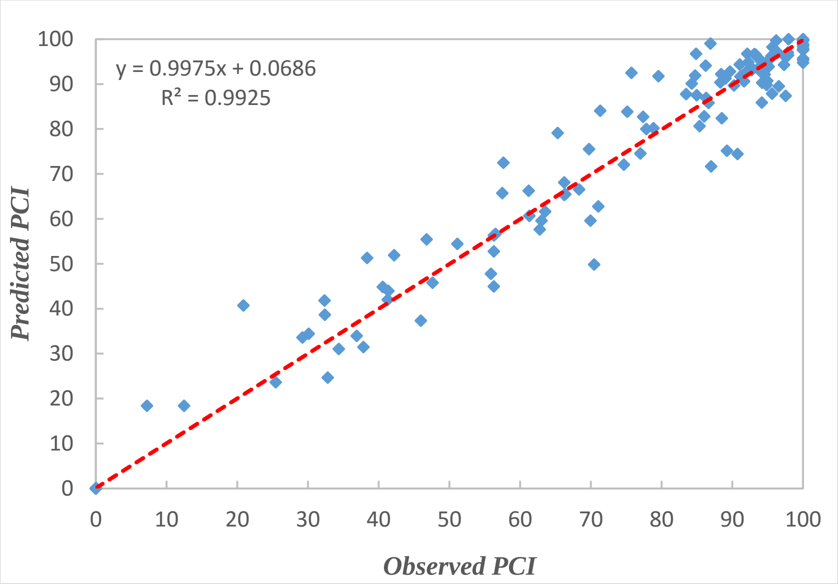


FIG. 3. PCI Verification for Florida Network

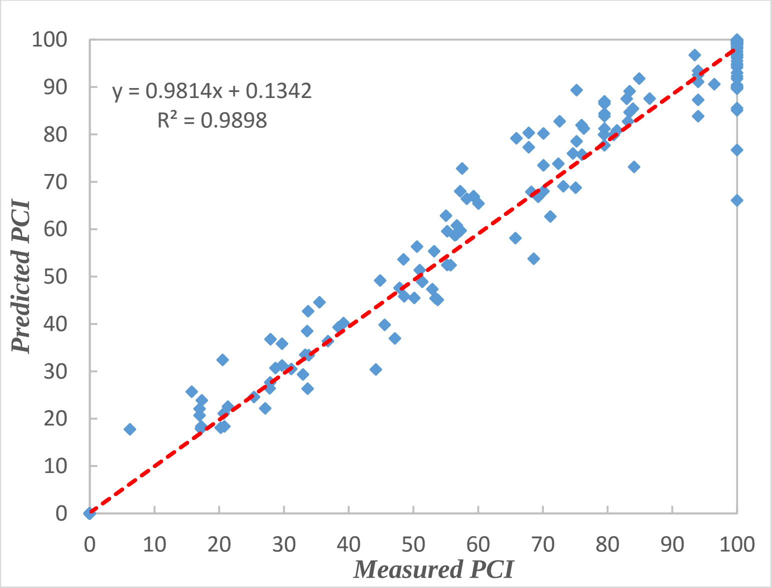


FIG. 4. PCI Verification for Mn/ROAD Mainline Driving-lane Network

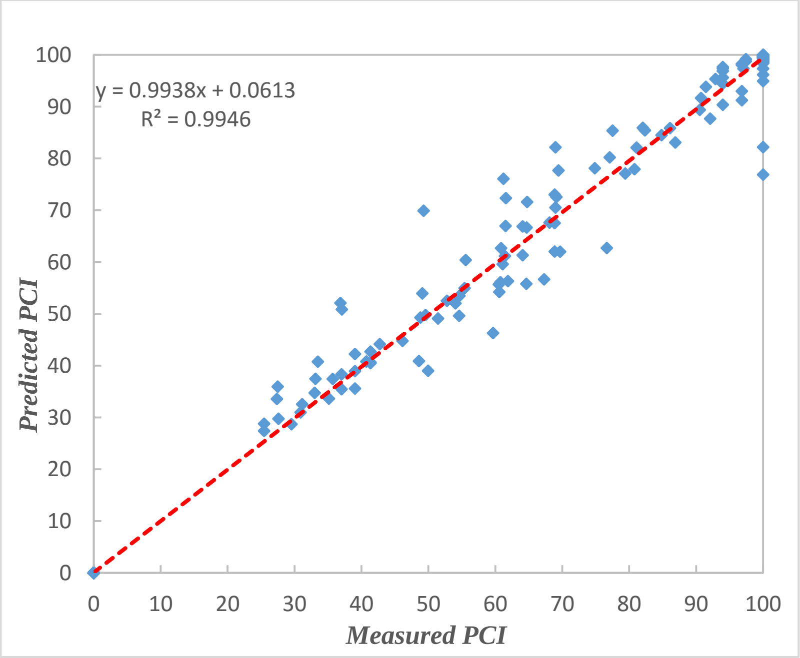


FIG. 5. PCI Verification for Mn/ROAD Mainline Passing-lane Network

APPENDIX C

PLOTS OF SHIFT FACTOR VERSUS PCI

The relationship between shift factor - *f(PCI)* and initial PCI of a subsection can be mathematically represented as follows,

$$f(PCI) = p_1 \times PCI + q_1 \; (PCI < 95)$$

$$f(PCI) = p_2 \times PCI + q_2 \; (PCI \geq 95)$$

Where, p_1, p_2, q_1, q_2 are parameters determined by linear programming method

This appendix exhibits 5 plots of shift factor versus PCI, three of them are for LTPP networks, and the other two are for Mn/ROAD networks.

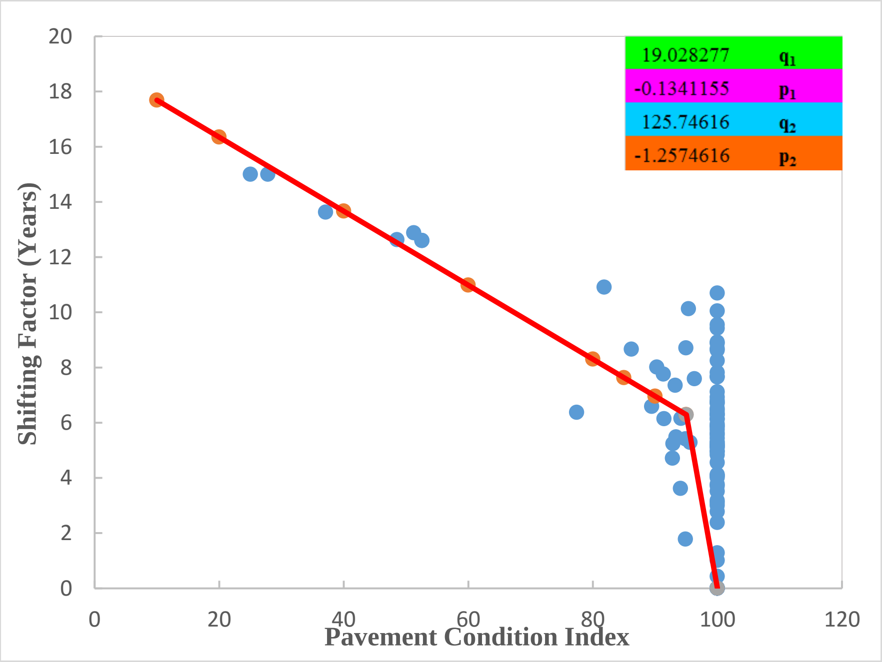


FIG. 1. Shift Factor as a Function of PCI (Florida Network)

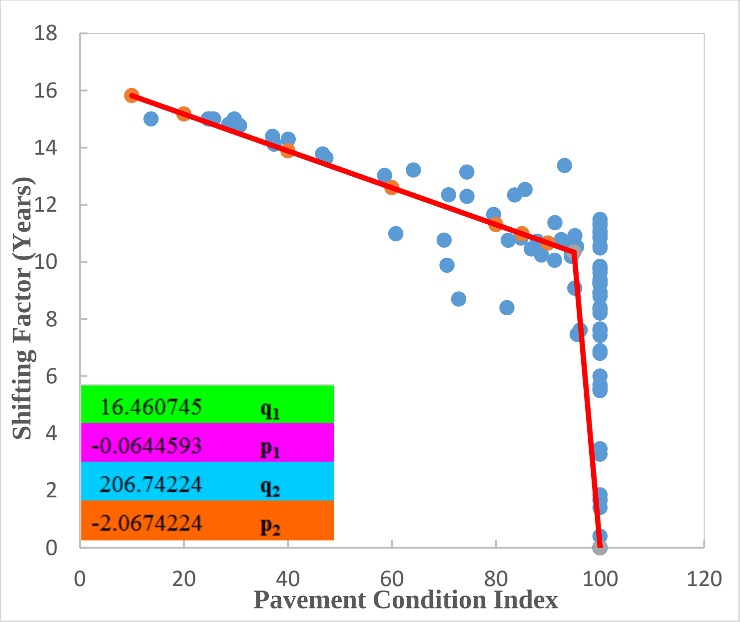


FIG. 2. Shift Factor as a Function of PCI (Arizona Network)

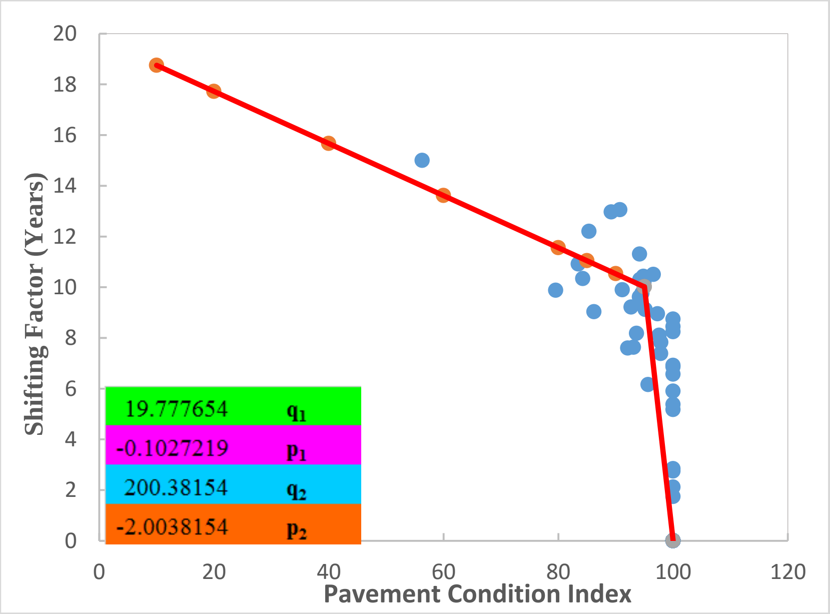


FIG. 3. Shift Factor as a Function of PCI (Utah Network)

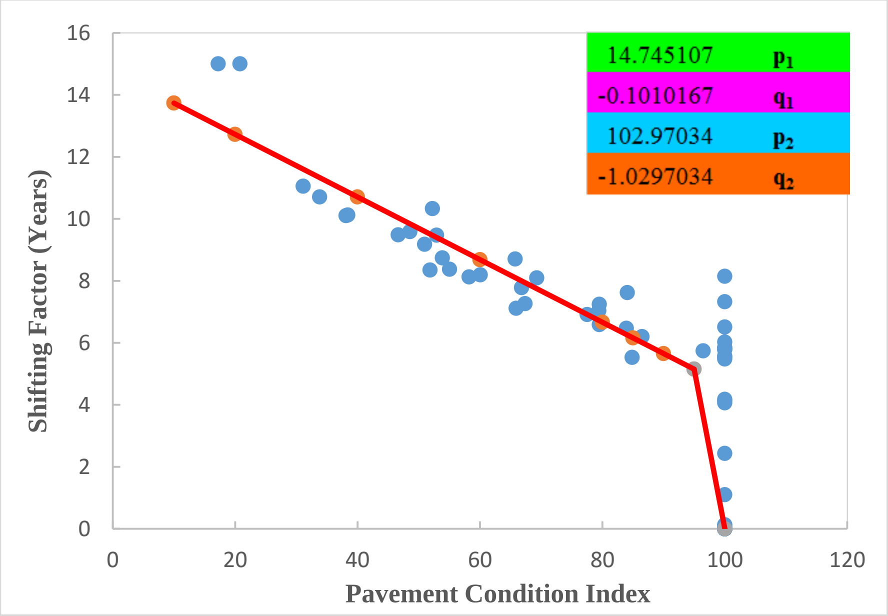


FIG. 4. Shift Factor as a Function of PCI (Mn/ROAD Mainline Driving-lane Network)

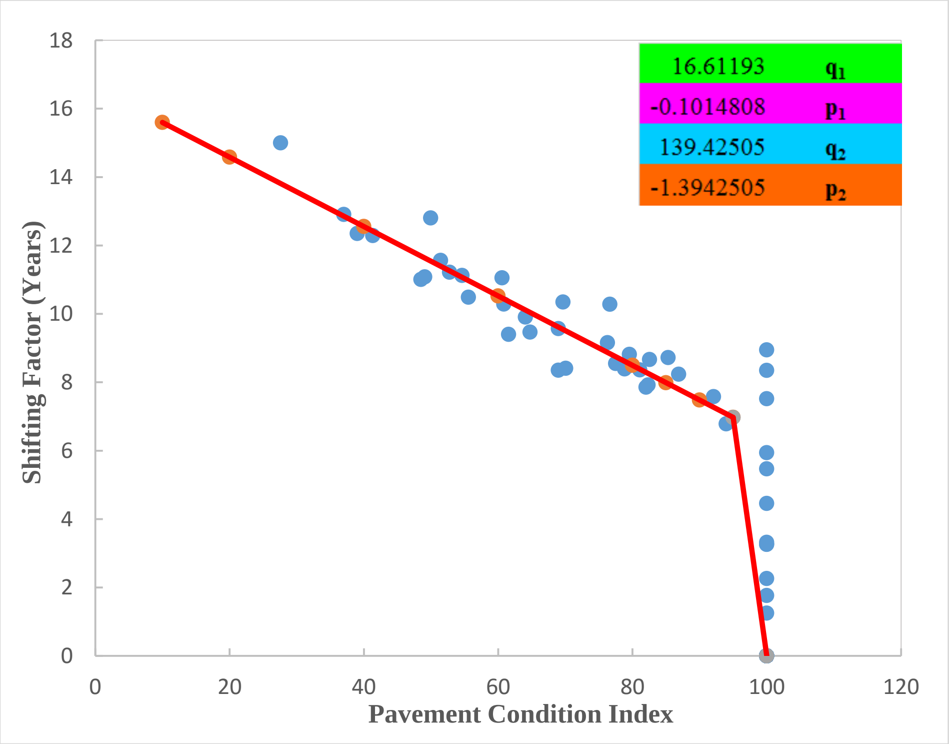


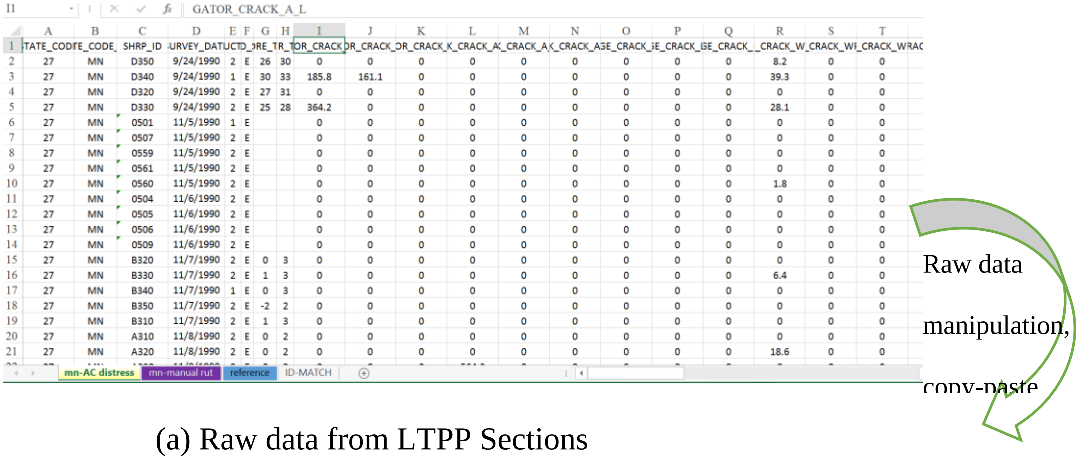
FIG. 5. Shift Factor as a Function of PCI (Mn/ROAD Mainline Passing-lane Network

APPENDIX D

PCI-BASED PERFORMANCE MODELING PROCEDURES USING THE DEVELOPED EXCEL^{TM} TEMPLATES

The basic procedures for PCI-based performance modeling can be summarized as follows,

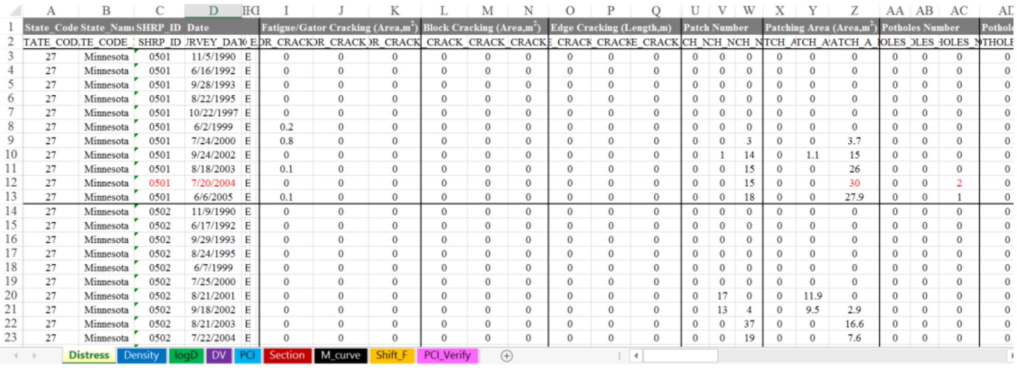
1) Check and manipulate distress raw data from the database to obtain a set of well-organized data;
2) Match the distress data with the Excel™ template column by column, and copy-paste to the sheet named "Distress";



I1 fx GATOR_CRACK_A_L

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	TATE_COD	TE_CODE_	SHRP_ID	URVEY_DAT	UCTD_	RE_	TR_	T	OR_CRACK	OR_CRACK_	OR_CRACK_	K_CRACK_A	_CRACK_A	K_CRACK_A	GE_CRACK_	E_CRACK_	GE_CRACK_	_CRACK_W	CRACK_WI	CRACK_WRAC
2	27	MN	D350	9/24/1990	2	E	26	30	0	0	0	0	0	0	0	0	0	8.2	0	0
3	27	MN	D340	9/24/1990	1	E	30	33	185.8	161.1	0	0	0	0	0	0	0	39.3	0	0
4	27	MN	D320	9/24/1990	2	E	27	31	0	0	0	0	0	0	0	0	0	0	0	0
5	27	MN	D330	9/24/1990	2	E	25	28	364.2	0	0	0	0	0	0	0	0	28.1	0	0
6	27	MN	0501	11/5/1990	1	E			0	0	0	0	0	0	0	0	0	0	0	0
7	27	MN	0507	11/5/1990	2	E			0	0	0	0	0	0	0	0	0	0	0	0
8	27	MN	0559	11/5/1990	2	E			0	0	0	0	0	0	0	0	0	0	0	0
9	27	MN	0561	11/5/1990	2	E			0	0	0	0	0	0	0	0	0	0	0	0
10	27	MN	0560	11/5/1990	2	E			0	0	0	0	0	0	0	0	0	1.8	0	0
11	27	MN	0504	11/6/1990	2	E			0	0	0	0	0	0	0	0	0	0	0	0
12	27	MN	0505	11/6/1990	2	E			0	0	0	0	0	0	0	0	0	0	0	0
13	27	MN	0506	11/6/1990	2	E			0	0	0	0	0	0	0	0	0	0	0	0
14	27	MN	0509	11/6/1990	2	E			0	0	0	0	0	0	0	0	0	0	0	0
15	27	MN	B320	11/7/1990	2	E	0	3	0	0	0	0	0	0	0	0	0	0	0	0
16	27	MN	B330	11/7/1990	2	E	1	3	0	0	0	0	0	0	0	0	0	6.4	0	0
17	27	MN	B340	11/7/1990	1	E	0	3	0	0	0	0	0	0	0	0	0	0	0	0
18	27	MN	B350	11/7/1990	2	E	-2	2	0	0	0	0	0	0	0	0	0	0	0	0
19	27	MN	B310	11/7/1990	2	E	1	3	0	0	0	0	0	0	0	0	0	0	0	0
20	27	MN	A310	11/8/1990	2	E	0	2	0	0	0	0	0	0	0	0	0	0	0	0
21	27	MN	A320	11/8/1990	2	E	0	2	0	0	0	0	0	0	0	0	0	18.6	0	0

(a) Raw data from LTPP Sections



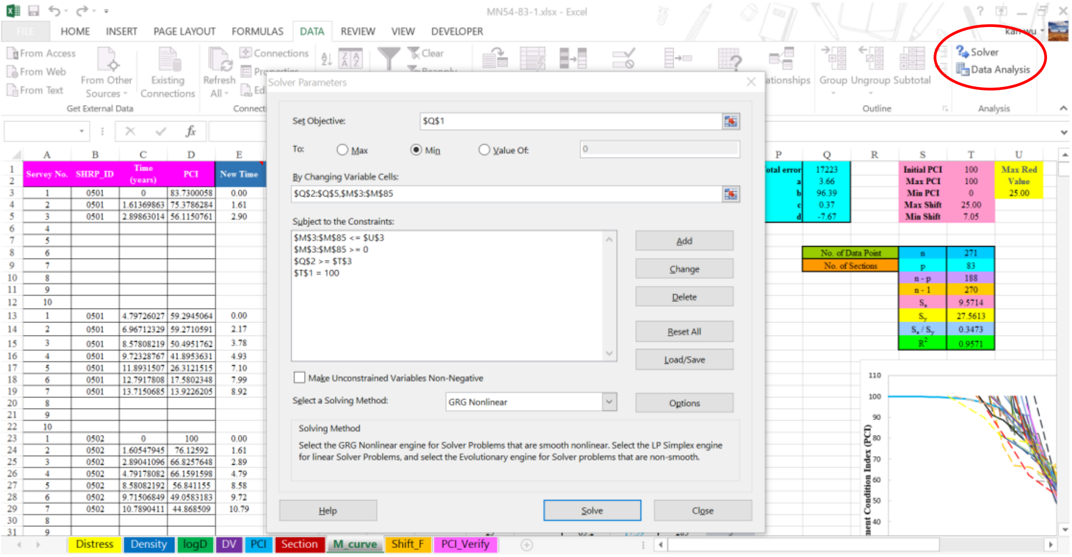
	A	B	C	D	E	I	J	K	L	M	N	O	P	Q	U	V	W	X	Y	Z	AA	AB	AC	AD
1	State_Code	State_Nam	SHRP_ID	Date		Fatigue/Gator Cracking (Area,m^2)			Block Cracking (Area,m^2)			Edge Cracking (Length,m)			Patch Number			Patching Area (Area,m^2)			Potholes Number			Pothole
2	TATE_COD	TE_CODE_	SHRP_ID	RVEY_DAT	E	OR_CRACK	OR_CRACK	OR_CRACK	_CRACK	CRACK_	CRACK	_CRACK	CRACK	E_CRACK	CH_N	CH_N	CH_N	TCH_A	TCH_A	ATCH_A	OLES	LES	OLES	THOLE
3	27	Minnesota	0501	11/5/1990	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	27	Minnesota	0501	6/16/1992	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	27	Minnesota	0501	9/28/1993	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	27	Minnesota	0501	8/22/1995	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	27	Minnesota	0501	10/22/1997	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	27	Minnesota	0501	6/2/1999	E	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	27	Minnesota	0501	7/24/2000	E	0.8	0	0	0	0	0	0	0	0	0	0	3	0	0	3.7	0	0	0	0
10	27	Minnesota	0501	9/24/2002	E	0	0	0	0	0	0	0	0	0	0	1	14	0	1.1	15	0	0	0	0
11	27	Minnesota	0501	8/18/2003	E	0.1	0	0	0	0	0	0	0	0	0	0	15	0	0	26	0	0	0	0
12	27	Minnesota	0501	7/20/2004	E	0	0	0	0	0	0	0	0	0	0	0	15	0	0	30	0	0	2	0
13	27	Minnesota	0501	6/6/2005	E	0.1	0	0	0	0	0	0	0	0	0	0	18	0	0	27.9	0	0	1	0
14	27	Minnesota	0502	11/9/1990	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	27	Minnesota	0502	6/17/1992	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	27	Minnesota	0502	9/29/1993	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	27	Minnesota	0502	8/24/1995	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	27	Minnesota	0502	6/7/1999	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	27	Minnesota	0502	7/25/2000	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	27	Minnesota	0502	8/21/2001	E	0	0	0	0	0	0	0	0	0	0	17	0	0	11.9	0	0	0	0	0
21	27	Minnesota	0502	9/18/2002	E	0	0	0	0	0	0	0	0	0	0	13	4	0	9.5	2.9	0	0	0	0
22	27	Minnesota	0502	8/21/2003	E	0	0	0	0	0	0	0	0	0	0	0	37	0	0	16.6	0	0	0	0
23	27	Minnesota	0502	7/22/2004	E	0	0	0	0	0	0	0	0	0	0	0	19	0	0	7.6	0	0	0	0

(b) Well-organized distress data set in "Distress" Excel™ sheet

FIG. 1. Raw Data Manipulation and Distress Data Sheet Implementation

3) Check all the input data and PCI calculation outputs, the automated PCI calculation is accomplished by the Excel™ templates.

4) Setup the Excel^{TM} "Solver" in the sheet of "M_Curve" to finally obtain the parameters of PCI-based performance model and shift factors. Demos of Solver setup are shown below.



Solver Parameters

Set Objective: $Q$1

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells: $Q$2:$Q$5,$M$3:$M$85

Subject to the Constraints:

$M$3:$M$85 <= $U$3
$M$3:$M$85 >= 0
$Q$2 >= $T$3
$T$1 = 100

☐ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

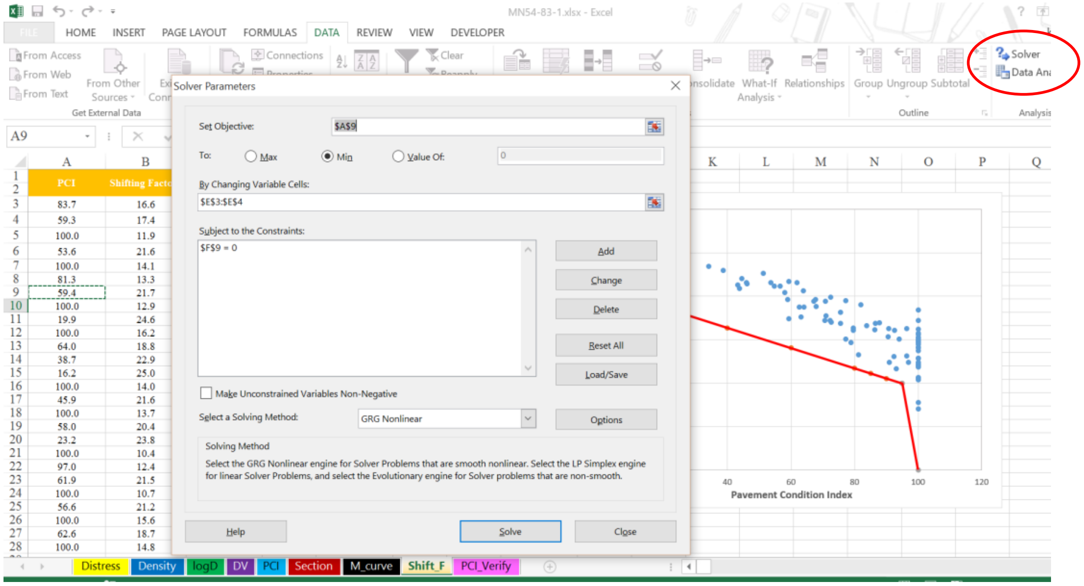
	A	B	C	D	E
1–2	Servey No.	SHRP_ID	Time (years)	PCI	New Time
3	1	0501	0	83.7300058	0.00
4	2	0501	1.61369863	75.3786284	1.61
5	3	0501	2.89863014	56.1150761	2.90
6	4				
7	5				
8	6				
9	7				
10	8				
11	9				
12	10				
13	1	0501	4.79726027	59.2945064	0.00
14	2	0501	6.96712329	59.2710591	2.17
15	3	0501	8.57808219	50.4951762	3.78
16	4	0501	9.72328767	41.8953631	4.93
17	5	0501	11.8931507	26.3121515	7.10
18	6	0501	12.7917808	17.5802348	7.99
19	7	0501	13.7150685	13.9226205	8.92
20	8				
21	9				
22	10				
23	1	0502	0	100	0.00
24	2	0502	1.60547945	76.12592	1.61
25	3	0502	2.89041096	66.8257648	2.89
26	4	0502	4.79178082	66.1591598	4.79
27	5	0502	8.58082192	56.841155	8.58
28	6	0502	9.71506849	49.0583183	9.72
29	7	0502	10.7890411	44.868509	10.79
30	8				
31	9				

P	Q
otal error	17223
a	3.66
b	96.39
c	0.37
d	-7.67

S	T	U
Initial PCI	100	Max Red Value
Max PCI	100	25.00
Min PCI	0	
Max Shift	25.00	
Min Shift	7.05	

No. of Data Point	n	271
No. of Sections	p	83
	n - p	188
	n - 1	270
	S_e	9.5714
	S_y	27.5613
	S_e / S_y	0.3473
	R^2	0.9571

FIG. 2. Demo of Excel^{TM} Solver Setup for Development of Performance Curve



Solver Parameters

Set Objective: $A$9

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells: $E$3:$E$4

Subject to the Constraints:

$F$9 = 0

☐ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

A9

	A	B
1–2	PCI	Shifting Facto
3	83.7	16.6
4	59.3	17.4
5	100.0	11.9
6	53.6	21.6
7	100.0	14.1
8	81.3	13.3
9	59.4	21.7
10	100.0	12.9
11	19.9	24.6
12	100.0	16.2
13	64.0	18.8
14	38.7	22.9
15	16.2	25.0
16	100.0	14.0
17	45.9	21.6
18	100.0	13.7
19	58.0	20.4
20	23.2	23.8
21	100.0	10.4
22	97.0	12.4
23	61.9	21.5
24	100.0	10.7
25	56.6	21.2
26	100.0	15.6
27	62.6	18.7
28	100.0	14.8

FIG. 3. Demo of Excel^{TM} Solver Setup to Determine Relationship between PCI and Shift Factor