Pavement Management Performance Modeling: Evaluating the Existing PCI Equations

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December 2014

RIMOS
roadway infrastructure management operations systems program

Iowa State University
Institute for Transportation

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16. Abstract

The work described in this report documents the activities performed for the evaluation, development, and enhancement of the Iowa Department of Transportation (DOT) pavement condition information as part of their pavement management system operation. The study covers all of the Iowa DOT's interstate and primary National Highway System (NHS) and non-NHS system.

A new pavement condition rating system that provides a consistent, unified approach in rating pavements in Iowa is being proposed. The proposed 100-scale system is based on five individual indices derived from specific distress data and pavement properties, and an overall pavement condition index, PCI-2, that combines individual indices using weighting factors.

The different indices cover cracking, ride, rutting, faulting, and friction. The Cracking Index is formed by combining cracking data (transverse, longitudinal, wheel-path, and alligator cracking indices). Ride, rutting, and faulting indices utilize the International Roughness Index (IRI), rut depth, and fault height, respectively.

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PAVEMENT MANAGEMENT PERFORMANCE MODELING: EVALUATING THE EXISTING PCI EQUATIONS

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EXECUTIVE SUMMARY

The work described in this report documents the activities performed for the evaluation, development, and enhancement of the Iowa Department of Transportation (DOT) pavement condition information as part of their pavement management system operation. The study covers all of the Iowa DOT's interstate and primary National Highway System (NHS) and non-NHS system. Personnel from the Iowa DOT Pavement Management Committee (from the offices of Design, Maintenance, Materials, Program Management, and Systems Planning) provided guidance and support throughout the project.

The current Iowa DOT pavement condition index (PCI) is calculated using PCI equations that are based on statistical regression analysis. Different attributes are used for different pavement families. A new pavement condition rating system that provides a consistent, unified approach in rating pavements in Iowa has been proposed.

The proposed 100-scale system is based on five individual indices derived from specific distress data and pavement properties, and an overall pavement condition index, PCI-2, that combines individual indices using weighting factors.

The different indices cover cracking, ride, rutting, faulting, and friction. The Cracking Index is formed by combining cracking data (transverse, longitudinal, wheel-path, and alligator cracking indices). Ride, rutting, and faulting indices utilize the International Roughness Index (IRI), rut depth, and fault height, respectively. The overall pavement condition index, PCI-2, is calculated as follows for Portland cement concrete (PCC) and asphalt concrete (AC) surfaces:

$$\text{PCI-2}_{PCC} = 0.40 \times (\text{Cracking Index}) + 0.40 \times (\text{Riding Index}) + 0.20 \times (\text{Faulting Index})$$

$$\text{PCI-2}_{AC} = 0.40 \times (\text{Cracking Index}) + 0.40 \times (\text{Riding Index}) + 0.20 \times (\text{Rutting Index})$$

1. INTRODUCTION

The work described in this report documents the activities performed for the evaluation, development, and enhancement of the Iowa Department of Transportation (DOT) pavement condition information as part of their pavement management system operation. The study covers all of the Iowa DOT's interstate and primary National Highway System (NHS) and non-NHS systems.

Personnel from the Iowa DOT Pavement Management Committee, including personnel from the offices of Design, Maintenance, Materials, Program Management, and Systems Planning, provided guidance and support throughout the project.

1.1 Background

An index, or pavement condition index, provides a numerical rating for the condition of road segments within the road network. Researchers and highway agencies around the country have developed a host of pavement indices to measure or evaluate the pavement condition.

For instance, a surface distress index may aggregate several distress types (e.g., cracking, rutting, bleeding for asphalt pavement; and cracking, faulting, spalling for concrete pavement). The selected distress types included in the index depend on agency needs. Alternatively, each distress type may be expressed as an individual index. Similarly, other pavement characteristics that are perceived to be important to road users, such as roughness or ride quality, are often utilized as an index. These different pavement measures can be combined in an overall index.

Traditionally, pavement indices have been used by engineers to describe the current and future quality of pavement networks, provide a warning system for early identification of maintenance and rehabilitation requirements, and estimate future funding needs (McNeil et al.1992). The asset management paradigm, along with the increasing demand for accountability in infrastructure management, have promoted strategic decision making approaches for the preservation, operation, expansion, and improvement of transportation infrastructure systems (AASHTO 2011, PB Consult Inc. et al. 2004).

This evolution and need for change have motivated researchers, practitioners, and public officials to use existing pavement condition indices for strategic decision making, such as setting statewide goals for infrastructure conditions, and to compare the performance of highway systems among the states.

2. EVALUATION OF PAVEMENT CONDITION BY OTHER STATES IN THE US

Pavement condition is often a function of exhibited distress types, the severity of these distress types, and the extent of these distress types (extent of occurrence in surveyed pavement area) (PB Consult Inc. et al. 2004, Carey and Irick 1962). The primary challenge is how to combine these characteristics into a single distress index if needed.

The development of an overall condition index is even more challenging because other pavement characteristics such as surface roughness are also considered, adding an extra dimension to the index. Existing pavement performance indices combine these characteristics through various methods as follows:

- Direct panel rating
- Utility functions
- Deduct values and weighting factors

2.1. Indices Determined Based on Direct Panel Ratings

Early efforts in developing pavement condition indices used direct panel ratings. This approach involves a panel that drives the surveyed pavement (normally at posted speed) and subjectively rates the pavement sections either using a numeric scale or verbal descriptions such as good, fair, poor, etc., based on observed distress types and ride quality.

Subjective panel ratings date back to the American Association of State Highway and Transportation Officials (AASTHO) road tests in the 1950s (Carey and Irick 1962). A panel rated sections of differing pavement types in Ottawa, Illinois on a 0 to 5 scale known as the Present Serviceability Rating (PSR). Because PSR depends on passenger perception of ride quality, it generally has stronger correlation with road roughness measurements than with distress measurements.

Two of the state DOTs that the researchers found to currently use distress indices derived from direct subjective panel ratings are Oregon and Michigan as follows:

- *Oregon's Good-Fair-Poor (GFP) Rating Method:* The Oregon DOT (ODOT) uses this rating method primarily for non-NHS highways. Occasionally, the GFP rating method is used for a few NHS highways in high-density urban areas for safety and practicality (ODOT 2012). The GFP method involves two-person panels who drive the surveyed pavement at 50 mph or the posted speed (whichever is lower) and rate pavement sections as very good, good, fair, poor, or very poor based on observed distress types and ride quality.

- *Michigan's Sufficiency Rating (SR):* This is a subjective "windshield survey" that rates pavement distress condition and ride quality on a 1 to 5 scale, with one being the best. Ratings are based on the observed amount and severity of pavement cracking, faulting, wheel tracking, and patching. The Michigan DOT (MDOT) uses additional pavement performance indicators to complement the SR, including a detailed distress index, a ride quality index, and an estimation of remaining service life.

While panel ratings have the advantages of being simple and representative of the perception of roadway users, they are inherently subjective and do not provide sufficient engineering data that can be used to identify effective repair alternatives.

2.2. Indices Computed Based on Utility Values

The utility values method was developed by the Texas DOT (TxDOT) in the late 1980s and resulted in two primary pavement performance indices:

- *Distress Score (DS):* 1 to 100 index with 100 representing no or minimal distress. DS considers various sets of distress types for various pavement types.

- *Condition Score (CS):* 1 to 100 index with 100 representing no or minimal distress and roughness. CS considers the pavement DS and roughness (measured using International Roughness Index/IRI).

Both DS and CS are implemented in the TxDOT Pavement Management Information System (PMIS) and are computed in Equations 1 and 2 as follows:

$$DS = 100 \times \prod_{i=1}^{n} U_i \tag{1}$$

$$CS = URide \times DS \tag{2}$$

where U_i is a utility value for distress type i and is computed in Equation 3 as follows:

$$U_i = \begin{cases} 1.0 & when\ L_i = 0 \\ 1 - \alpha e^{-\left(\frac{\rho}{L_i}\right)^{\beta}} & when\ L_i > 0 \end{cases} \tag{3}$$

L_i represents the density of the distress in the pavement section (quantity of distress per mile, quantity of distress per section area, quantity of distress per 100 ft, etc.). α (Maximum Loss factor), β (Slope factor), and ρ (Prolongation factor) control the location of the utility curve's inflection point and the slope of the curve at that point, as illustrated in Figure 1.

U_i ranges between zero and 1.0 and represents the quality of a pavement in terms of overall usefulness (e.g., a U_i of 1.0 indicates that distress type *i* is not present and thus is most useful).

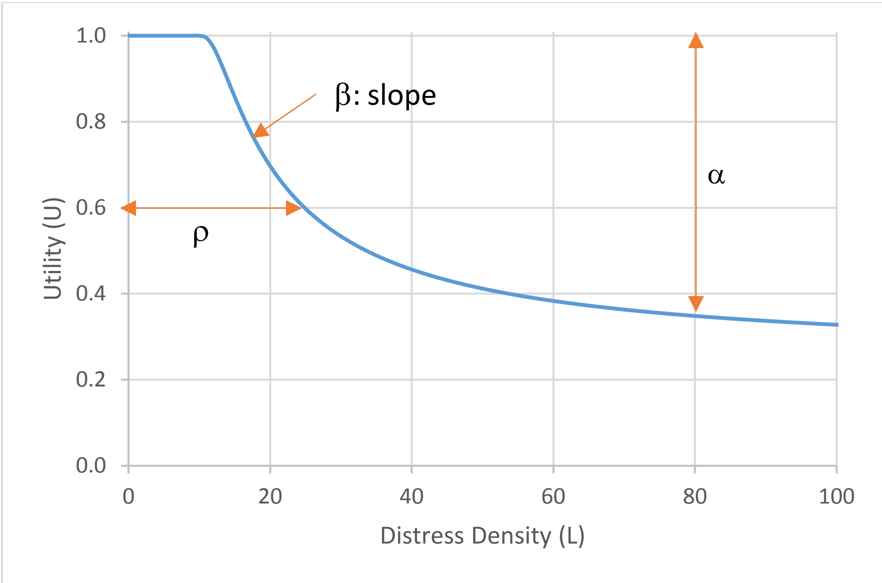


Figure 1. General shape of utility curves used for computing TxDOT pavement performance indices

2.3. Indices Computed Based on Deduct Values

The deduct values method captures the effect of distress type, severity, and extent, and ride quality, on the total score through deduct values. The general expression for computing a distress index using deduct values as follows in Equation 4:

$$CI = C - (a_1 d_1 + a_2 d_2 + a_3 d_3 + \ldots + a_n d_n + a_r d_r) \quad \mathbf{(4)}$$

where *CI* is the condition index, *C* is the maximum value of the distress/condition index (perfect score), $a_{1,2,\,,,,n}$ are the adjustment factors for distress types 1 through n, d_i is the deduct values for distress types 1 through n, a_r is the adjustment factor for roughness, and d_r is the deduct value for roughness.

A widely used distress index that is derived from deduct values is the Pavement Condition Index (PCI), developed in the late 1970s by the U.S. Army Corp of Engineers (Shahin et al. 1980). The PCI scale ranges from 0 to 100, with 100 representing the perfect score (a pavement in excellent condition).

In 2000, the American Society for Testing of Materials (ASTM) adopted the PCI method as a standard practice for pavement condition index surveys of roads and parking lots (ASTM D 6433). The general expression for computing PCI is as follows in Equation 5 (Shahin et al. 1978, Shahin et al. 1980).

$$PCI = C - \sum_{i=1}^{P}\sum_{j=1}^{m_i} a(T_i, S_j, D_{ij})F(t,q) \quad \textbf{(5)}$$

where C is the maximum value of the condition index (perfect score); *a (T, S, D)* is the deduct value function that varies with distress type (T), severity (S), and density (D); *F(t,q)* is an adjustment function that varies with total deduct value (t) and number of deducts (q); i and j are counters for distress types and severity levels, respectively; p is the total number of observed distress types; and m_i is the number of severity levels for the i th distress type.

Typically, three levels of severity are used (low, medium, and high). Most state DOTs use distress indices that are derived from deduct values.

2.4. Pavement Condition Indices in the US

2.4.1. Iowa DOT

The Iowa DOT PMIS database contains information of homogeneous pavement segments (i.e., pavement management sections). The data for each pavement section include the following shown in Table 1.

Table 1. Iowa DOT PMIS data for each pavement section

Category	Field Examples
Section control information	year of data entry, identification no, highway system, route, beginning and ending mileposts, pavement type, county no, DOT district, construction year, resurfacing year, segment length, city no, urban area code
Condition data	IRI, friction, fault height, rut depth, pavement condition index
Distress data	test year, transverse cracking, longitudinal cracking, wheel-path cracking, alligator cracking, joint spalling, durability cracking, patching
Structural data	test date, structural no, 80% structural rating, average K-rating, falling weight deflectometer
Traffic data	average daily traffic, average daily truck traffic, predicted 18-kip ESALs, annual 18-kip ESALs, accumulated traffic, percent life used based on traffic
Miscellaneous	maintenance region and garage, speed limit, surface type, pavement depth and width, surface treatment, aggregate durability class, drainage, shoulder information

IRI=International Roughness Index
ESALs=equivalent single axle loads

The PCI for the PMIS sections is calculated using equations that were obtained using statistical regression analysis. The variables used in the regression equations vary based on the following:

- Pavement type
- Highway system (e.g., interstate or primary roads that are US and Iowa highways)
- Source of distress data collection (e.g., in-house or contractor)

In the mid-1990s, the Iowa DOT started contracting out pavement data collection. The shift resulted in not only a change in the collection method (e.g., more automation) but also the variety of the information. Furthermore, default equations where PCI is deteriorated based on age are also used when there is no distress data available. The basis for PCIs used by the Iowa DOT are summarized in Table 2.

Table 2. PCI matrix used by the Iowa DOT

Pavement Type	Highway System	Main PCI Equation Variables
Type 1 (Portland cement concrete)	Interstate	Age; percent life used based on ESALs; longitudinal cracking
	Primary	IRI; age; durability cracking; structural rating at joints
Type 2A (Continuously reinforced concrete with asphalt treated base)	Interstate	Age; aggregate durability class; IRI; pavement thickness
Type 2B (Continuously reinforced concrete with cement treated base)	Interstate	Aggregate durability class; friction; pavement thickness; combined cracking and patching
Type 3 (Composite)	Primary	IRI; age; transverse cracking; longitudinal wheel-path cracking; percent life used based on ESALs
Type 3A (Composite built on old jointed Portland cement concrete pavement)	Interstate	Age rating; friction; annual ESALs; patching; surface layer thickness; total asphalt depth
Type 3B (Composite built on continuously reinforced Portland cement concrete pavement)	Interstate	Aggregate durability class; IRI; percent life used based on ESALs; relative structural ratio; total asphalt depth
Type 4 (Full-depth asphalt)	Interstate	Age; base thickness; IRI
	Primary	IRI; age; alligator cracking; patching

ESALs=equivalent single axle loads
IRI=International Roughness Index

2.4.2. State Practices in the US

Table 3 presents pavement condition performance measures used by highway agencies in the US. It includes the use of pavement scores by the states, including the distresses that are used for generating the scores, the score scales, and descriptions. The data is compiled from sources listed in the References for Table 3 at the end of this report and may not reflect the most current practice for each state.

Table 3. Pavement condition rating practices in the US

State	Data Collected	Individual Indices	Overall Index
Alabama	Cracking, patching, roughness, rutting, raveling		Pavement Condition Rating (PCR); scale of 100; regression equation
Alaska	Roughness (IRI), rutting		Pavement Serviceability Rating (PSR); scale of 5
Arizona	Roughness (IRI), cracking, rutting, and patching	Present Serviceability Rating (PSR) 0 to 5; Pavement Distress Index (PDI)	AASHTO Present Serviceability Index (PSI); scale of 100
Arkansas	Roughness (IRI), rutting, faulting, and cracking		Rigid=0.65×Defects + 0.35×Ride, Flexible=$\text{Ride}^{1/2}$
California	Roughness (IRI), Mean Profile Depth (MPD) in the wheel paths, ground penetrating radar (GPR) used as the tool for data collection of continuous layer thicknesses, cracking, rutting, faulting		Pavement Condition Survey (PCS)
Colorado	Roughness (IRI), rutting, cracking (fatigue, transverse, longitudinal, and corner break)	Normalized into individual index values; scale of 100	Remaining Service Life (RSL) in years determined by the minimum index
Connecticut	Roughness/ride (IRI), cracking (transverse, structural, wheel-path), rutting	Roughness (Ride) Index; Transverse Cracking Index; Structural Cracking Index; Wheel-path Index; Rutting Index	Pavement Condition Index (PCI) at network level; scale of 9; roughness, distortion, cracking, disintegration, drainage are combined by Pavement Management System software

State	Data Collected	Individual Indices	Overall Index
Delaware	Roughness (IRI), fatigue, joint reflection, block cracking, patching, transverse cracking, slab cracking, alkali silica reactivity (ASR), joint deterioration, joint seals, bleeding, and edge cracking		Overall Pavement Condition (OPC); Deducts from distresses; OPC = (Threshold Value) + [(Remaining Service Life)*(Reduction Rate)]
Florida	Roughness (IRI), cracking, raveling, patching, rut depth	Ride Rating (from a calculated Ride Number based on IRI); Defect Rating (based on distress deducts) for rigid pavements Crack Rating (based on predominant crack); Rut Rating (based on rut depth); Ride Rating (from a calculated Ride Number based on IRI) for flexible pavements	Pavement Condition Rating (PCR); lowest of two/three represents the overall pavement condition/score
Georgia	Roughness (IRI), cracking (composite reflection, transverse, longitudinal, asphalt alligator/fatigue, punch-out), faulting		Present Serviceability Rating (PSR); if IRI is reported, PSR is not reported.
Hawaii	Roughness (IRI), cracking (transverse, longitudinal, alligator/fatigue, punch-out), faulting		Pavement Condition Index (PCI); scale of 100 deducts based on ASTM/AASHTO

State	Data Collected	Individual Indices	Overall Index
Idaho	Roughness (IRI), rutting, cracking (alligator, block, edge, transverse, longitudinal), patching, and potholes for asphalt; transverse slab cracking, spalling, scaling, corner cracking and faulting for concrete	Cracking Index (CI) Roughness Index (RI); scale of 5 Rutting Index; 0 to 1.50 in.	Good, fair, poor, very poor; Independent deficiency thresholds (e.g., poor and very poor) for each index
Illinois	Ride quality (IRI)	Condition Rating Survey (CRS) for distress; scale of 9	
Indiana	Roughness (IRI), surface distress, rutting, skid resistance, deflection (falling weight deflectometer/FWD), and layers thickness		Pavement Condition Rating (PCR); deducts; scale of 100
Kansas	Roughness (IRI), transverse cracking and rutting for flexible pavements, joint distress and faulting for rigid pavements		Performance Level (PL): three-digit number stating the levels of pavement condition; pavement condition parameter 1, 2, 3 from best to worst
Kentucky	Roughness (IRI), distress, rut depth, skid resistance	Rideability Index (RI)	Condition Index; demerit points (i.e., higher value poor condition); adjusted to traffic

State	Data Collected	Individual Indices	Overall Index
Louisiana	Roughness (IRI), rutting, cracking (fatigue/alligator, longitudinal in the wheel path, transverse), surface friction, joint faulting, joint spalling, punch-out, patching, raveling	Distress indices depending on the pavement type (hot mix asphalt/HMA, jointed plain concrete pavement/JPCP, continuously reinforced concrete pavement/CRCP, Composite); scale of 100. Present Serviceability Rating (PSR) from IRI	Present Serviceability Index (PSI): a subjective rating of the pavement condition made by a group of individuals riding over the pavement; may also be determined based on condition survey information
Maine	Roughness/ride quality (IRI), transverse, longitudinal, alligator cracking, rut		Pavement Condition Rating (PCR); scale of 0 to 5 Combined equally weighted IRI, rutting, structural and functional cracking
Maryland	Rut, cracking, friction, IRI		
Massachusetts	Distress, rut, IRI	Condition/distress Index Rut Index Ride Index (IRI)	Pavement Serviceability Index (PSI); scale of 5
Michigan	Distress, rutting, IRI	Sufficiency Rating (SR); scale of 5 Distress Index (DI) Pavement Surface Evaluation and Rating (PASER); scale of 10 Ride Quality Index (RQI)	Remaining Service Life (RSL)

State	Data Collected	Individual Indices	Overall Index
Minnesota	Surface distress, IRI	Surface Rating (SR); scale of 4.0 Ride Quality Index (RQI) correlated to IRI via input from road users; scale of 5	Pavement Quality Index (PQI); scale of 4.5 (Combine RQI and SR) PQI=$\sqrt{RQI \times SR}$
Mississippi	Roughness (IRI), cracking, potholes, patching, punch-out, rutting, and faulting	Roughness Rating: IRI Distress Rating: (cracking, potholes, patching , punch-out, rutting, and faulting)	Pavement Condition Rating (PCR); deducts from 100; very poor to very good scale
Missouri	Distress, IRI	Condition Score for surface; scale of 20 Roughness; scale of 10	Pavement Serviceability Rating (PSR) PSR=(2×roughness score)+(condition score)
Montana	Miscellaneous cracking, alligator cracking, rut, ride quality	Ride Index (RI); scale of 100 Rut; scale of 100 Alligator Cracking Index (ACI); scale of 100 Miscellaneous Cracking Index (MCI); scale of 100	Overall Performance Index (OPI); combined weighted amounts of four indices; scale of 100

State	Data Collected	Individual Indices	Overall Index
Nebraska	Roughness/ride quality (IRI), percentage of bituminous surfacing (BIT) that is cracked, percentage of Portland cement concrete (PCC) panels that are cracked, cracking and rutting of hot mix asphalt (HMA), faulting, joint distress, slab cracking and repair amount for Portland cement (PC)	Cracking Index: % cracked surface Present Serviceability Index (PSI): function of IRI; scale of 5	Nebraska Serviceability Index (NSI); scale of 100
Nevada	Roughness IRI, rut depth, fatigue, block cracking, non-wheel path transverse block cracking, patching, bleeding, raveling, and friction number		Present Serviceability Index (PSI); scale of 5 $PSI = 5 \times e^{(-0.0041 \times IRI)} - 1.38 \times RD^2$
New Hampshire	Roughness (IRI), surface distress, rutting	Rut Rate Index (RRI) Surface Distress Index (SDI) Riding Comfort Index (RCI) All scale of 5	Decision tree dominated by SDI

State	**Data Collected**	**Individual Indices**	**Overall Index**
New Jersey	Roughness IRI, surface distress, non load related distress, load related distress includes fatigue cracking and rutting	Surface Distress Index (SDI); scale of 5 Non Load Related Distress Index (NDI) Load Related Distress Index (LDI); LDI includes fatigue cracking and rutting; deducts from 500; divided by 100 HMA: SDI=(NDI×LDI)÷5 PC: SDI=NDI	Pavement Condition based on IRI and SDI; poor, fair, good
New Mexico	Roughness (IRI), surface distress, rutting	Distress Rating	Pavement Serviceability Index (PSI); 60% IRI and 40% distress; scale of 5 $PSI = 0.041666\,X, \quad \text{if } X \le 60$ $PSI = [0.0625(X - 60)] + 2.4999, \quad \text{if } X > 60$ $X = 100 - \left[\frac{0.6(IRI - 25) + (0.4DR)}{2.9}\right]$
New York	Roughness (IRI), surface distress (alligator cracking, faulting, spalling and widening drop-off), rut depth	Pavement Surface Rating/Surface Distress Rating; scale of 10	Pavement Condition Index (PCI); scale of 100; deducts for surface distress, ride quality, rutting, faulting, and dominant distresses

State	**Data Collected**	**Individual Indices**	**Overall Index**
North Carolina	Alligator cracking, transverse cracking, rutting, raveling, oxidation, bleeding, ride quality (bumpiness during driving), patching		Pavement Condition Rating (PCR); scale of 100; deducts for eight major distresses
North Dakota	Roughness (IRI), alligator cracking, patching and rutting for hot mix asphalt (HMA), corner breaks, longitudinal cracking, broken slab, patching and transverse cracking for Portland cement concrete (PCC)	Structural Index (SI) for HMA for distress; deducts due to alligator cracking, patching, rutting; subtract from 99 Slab Cracking Index (SCI) for PC; deducts for corner breaks, longitudinal cracking, broken slab, patching, transverse cracking	Public Ride Perception Index (PRPI); scale of 3 based on IRI value (<0.95, 0.96-1.57, 1.58-2.3 and >2.4m/km)

State	Data Collected	Individual Indices	Overall Index
Ohio	Roughness (IRI), raveling, bleeding, patching, debonding, crack sealing, deficiency, rutting, settlement, potholes, wheel track cracking, block and transverse cracking, longitudinal joint cracking, edge cracking, and thermal cracking for asphalt pavement; raveling, bleeding, patching, debonding, rutting, pumping, shattered slab, settlement, transverse cracking, longitudinal cracking, corner breaks, and punch-outs for composite pavement; longitudinal joint spalling, patching, pumping, faulting, settlement, transverse joint spalling , transverse cracking for jointed reinforced or plain concrete pavement; pop-outs, patching, pumping, settlements and waves, transverse crack spacing, longitudinal cracking, punch-outs or edge breaks, and spalling for continuously reinforced concrete pavements		Pavement Condition Rating (PCR); scale of 100

State	Data Collected	Individual Indices	Overall Index
Oklahoma	Distress, rutting, and functional cracking for hot mix asphalt (HMA); fault, slab cracking, and joint cracking for Portland cement (PC); structural distress for continuously reinforced concrete pavement (CRCP); ride quality (IRI) for all types	Indices for HMA: Ride (IRI) Structural Index (100 – Min[∑Fatigue Deduct Values) Rutting Functional Cracking Indices for PC: Ride, Fault, Slab, Joint Indices for CRCP: Ride, Structural	Pavement Quality Index (PQI) for HMA PQI=0.40×Ride Index+0.30×Rut Index+0.15×Functional Index+0.15×Structural Index
Oregon	Ride quality (IRI); fatigue cracking, rut, patching, raveling and no-load/environmental cracking for hot mix asphalt (HMA); fatigue, rut and patching for jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP)	Indices for HMA: Fatigue Rut Patching Raveling No-load Indices for JPCP and CRCP: Fatigue Rut Patching IRI for Roughness	Overall Index for HMA; Min (Rut×100, Fatigue×Patching×Raveling×No-Load×100); scale of 100; also good-fair-poor

State	Data Collected	Individual Indices	Overall Index
Pennsylvania	Ride quality (IRI); transverse cracking, transverse joint spalling, joint faulting, broken slab, bituminous patching, shoulder drop-off and surface defect for Portland cement concrete (PCC); surface distress, joint seal failure, longitudinal joints palling, transverse cracking, transverse joint spalling, surface defects and rutting for hot mix asphalt (HMA)	Ride Index (RI) Structural Index: 20% transverse cracking, 15% transverse joint spalling, 15% joint faulting, 25% broken slab, 20% bituminous patching, and 5% surface defect Surface Distress Index: 15% joint seal failure, 20% longitudinal joint spalling, 20% transverse cracking, 20% transverse joint spalling, 15% surface defects, and 5% rutting Safety Index: 5% longitudinal joint spalling, 5% transverse cracking, 10% transverse joint spalling, 5% faulting, 5% broken slab, 10% bituminous patching, 20% surface defect, 20% rutting, and 20% shoulder drop-off	Overall Pavement Index (OPI); scale of 100; OPI=0.45×Ride Index + 0.30×Structural Index + 0.20×Surface Distress Index + 0.05×Safety Index
South Carolina	Ride quality (IRI), distress, and rutting	Pavement Distress Index (PDI); includes rutting; based on AASHTO PCI; scale of 5 *PDI = 5.0 – [ADV: adjusted distress value]* Pavement Serviceability Index (PSI); based on IRI; scale of 5 $PSI = 5.0 \times e^{(-0.00284 \times 1IRI)}$	Pavement Quality Index (PQI); scale of 5 $PQI = 1.158 + 0.138 \times PDI \times PSI$

State	Data Collected	Individual Indices	Overall Index
South Dakota	Roughness (IRI), fatigue cracking, patching, transverse cracking, block cracking, rutting for hot mix asphalt (HMA); corner cracking, d-cracking and alkali silica reactivity (ASR), faulting, joint spalling, joint seal damage, punch-outs for Portland cement concrete (PCC)	Each is an index on a scale of 5	Pavement Serviceability Rating (PSR)
Tennessee	Ride quality (IRI), distress and rutting	Present Serviceability Index (PSI); based on roughness; scale of 5 $PSI = 5 \times e^{(-0.0055 \times IRI)}$ Pavement Distress Index (PDI); deducts; scale of 5	Pavement Quality Index (PQI); scale of 5 $\mathrm{PQI} = \mathrm{PDI}^{0.7} \times \mathrm{PSI}^{0.3}$

State	Data Collected	Individual Indices	Overall Index
Texas	Shallow rutting, deep rutting, patching, failures, block cracking, alligator cracking, longitudinal cracking, transverse cracking, raveling, and flushing for asphalt concrete pavement (ACP); spalled cracks, punch-outs, asphalt patches, concrete patches, and average crack spacing for continuously reinforced concrete pavement (CRCP); failed joints and cracks, failures, slabs with longitudinal cracks, shattered slabs, concrete patches and apparent joint spacing for jointed concrete pavement (JCP)	Distress Score (DS); scale of 100 Ride Score (RS); scale of 5 $DS = 100 \times \prod_{i=1}^{n} U_i$	Condition Score (CS); scale of 100; combines distress and roughness; based on utility values $DS = 100 \times \prod_{i=1}^{n} U_i$ CS = URide × DS $U_i = \begin{cases} 1.0 & when\ L_i = 0 \\ 1 - \alpha e^{-\left(\frac{\rho}{L_i}\right)^{\beta}} & when\ L_i > 0 \end{cases}$ *Ui: Utility value for distress type* *Li: Density of the distress*

State	Data Collected	Individual Indices	Overall Index
Utah	Roughness (IRI); longitudinal, transverse and block cracking for flexible; corner breaks and shattered slabs for rigid	RIDE: Roughness based on IRI For PC: CONK: Structural cracking from corner breaks and cracked slabs FALT: Faulting (difference in slab elevation) JONT: Joint index from spalling and asphalt patching For asphalt: RUT: Rutting ENVCK: Environmental cracking (transverse, longitudinal, and block cracking) WPCK: Wheel-path fatigue cracking Scale of 100	Overall Condition Index (OCI); scale of 100 OCI = Average of all Indices
Vermont	Roughness (IRI), structural cracking, transverse cracking, depth of wheel-path deformation and rutting	Structural Cracking Index Transverse Cracking Index Depth of Wheel path Deformation Index Rutting Roughness Index	Pavement Condition Index (PCI); scale of 100

State	Data Collected	Individual Indices	Overall Index
Virginia	Ride quality (IRI); fatigue cracking, patching, rutting, transverse and longitudinal cracking for asphalt; slab distress for jointed concrete; concrete punch-out and concrete distress for continuously reinforced concrete pavement	Pavement condition indices from individual distress data (scale of 100): For asphalt: Load-related Distress Rating (LDR) (fatigue cracking, patching, rutting), and Non-load-related Distress Rating (NDR) (transverse and longitudinal cracking) For jointed concrete pavement: Slab Distress Rating (SDR) For continuously reinforced concrete pavement: Concrete Punch-out Rating (CPR) and Concrete Distress Rating (CDR) IRI reported separately as ride quality	Critical Condition Index (CCI); lowest index based on the surface type; scale of 100
Washington	Ride quality (IRI), distress and rutting	Pavement Structural Condition (PSC) Pavement Rutting Condition (PRC) Pavement Profile Condition (PPC): ride based on IRI	Pavement Structural Condition (PSC); deducts based on surface distress; scale of 100
Washington DC	Pavement Condition Index (PCI) Visual inspection by raters		Pavement Condition Index (PCI); ASTM D 6433

State	Data Collected	Individual Indices	Overall Index
West Virginia	Alligator/longitudinal cracking, transverse/block cracking and rut for asphalt; faulting/damaged joints slab crack for Portland cement concrete (PCC)	Asphalt: Alligator/Longitudinal Cracking Index (SCI) Transverse/Block Crack Index. (ECI) Rut Index (RDI) Rigid: Faulting/Damaged Joints Index (JCI) Slab Cracking Index (CSI)	
Wisconsin	Ride quality (IRI), distress and rutting	Pavement Distress Index (PDI)	
Wyoming	Slope variance, cracking, patching, rut		Present Serviceability Rating (PSR) 0 to 5

There is a wide variety of survey or index/score names used by the states, with inconsistencies among the state agencies as to the names (or nomenclature) and practices. However, the indices that are detailed in Table 3 are fairly representative of current practices among the DOTs throughout the US.

3. DEVELOPMENT OF PAVEMENT CONDITION INDICES FOR IOWA

The primary objective of this research study was to develop new performance indicators (or pavement condition indices) for Iowa pavements. The aim is that the new indices will not require changes to the current Iowa DOT data collection practices.

The current PCI equations are based on pure regression analysis that may exclude crucial input (e.g., certain distresses) and, similarly, may include some questionable ones (e.g., aggregate class). The proposed PCIs provide a consistent unified approach in terms of inputs used to calculate the condition measures.

The literature survey showed two universal inputs for evaluating pavement condition: roughness and surface distress. The Iowa DOT measures roughness using the International Roughness Index (IRI). Surface distresses collected vary extensively based on agency experience. The Iowa DOT collects transverse cracking, longitudinal cracking, wheel-path cracking, alligator cracking, durability cracking, joint spalling, and patching as surface distress. Rut depth for asphalt, fault height for Portland cement concrete, and friction are also collected.

This study proposes individual indices to measure and evaluate surface distress (cracking), roughness (ride), rutting, faulting, and skid resistance (friction), and an overall index combining individual ones and providing a general view of pavement quality.

Five individual indices are proposed:

- Cracking Index
- Riding Index
- Rutting Index
- Faulting Index
- Friction Index

An overall PCI that combines the Cracking, Riding, and Faulting indices for Portland cement concrete (PCC) pavements, and Cracking, Riding, and Rutting indices for asphalt concrete (AC) pavements has been develeoped. This new PCI is referred to as PCI-2 hereafter.

3.1. Data and Screening

The Iowa DOT PMIS database contains every aspect of pavement data: identification information, construction history, design information, maintenance, distress, etc. The pavement network is divided into segments (pavement management sections). The Iowa DOT maintains the PMIS section data based on historical records.

Each segment has the same pavement type, maintenance, and traffic levels. The segments are identified by route, county, direction of travel, and begin and end mileposts. By 2012, the total lengths of the pavement sections in the database were 2,571 miles (44.7% PCC surface and

55.3% AC surface) for interstate and 15,699 miles (29.2% PCC and 70.8% AC) for Iowa and US (or primary) routes.

The data used in this study cover the PMIS data from the beginning of 1998 through the end of 2012, totaling to more than 50,000 data points: each pavement section constitutes one data point every other year. The condition data—ride, rutting, faulting, cracking (e.g., alligator, longitudinal, transverse, durability), patching, and joint spalling—are updated for half of the system every year. Thus, a specific section is evaluated every other year and the same condition data is maintained for the section year after. The number of the data points available for each pavement section could be seven at most if a specific section dates back to 1998.

In some instances, an improvement such as major rehabilitation or reconstruction over the span of the segment results in a different pavement type, and, hence, a different record. In other cases, an improvement does not cover the entire span of the segment, new segments are created, and each individual segment naturally has the same construction history, traffic experience, maintenance history, but possibly a different pavement type.

Further screening of the data used in the analysis was as follows:

- *Pavement type*: The PMIS database has seven different pavement codes:

  Type 1: PCC pavement
  Type 2A: Continuously reinforced concrete (CRC) with asphalt treated base
  Type 2B: CRC with granular or cement treated base
  Type 3: Composite with asphalt surface
  Type 3A: Composite built on old jointed PCC pavement
  Type 3B: Composite built on old CRC pavement
  Type 4: AC pavement

  Due to the insufficient number of data, Types 2A and 2B were not included.

- *Age*: In an effort to exclude anomalies, an age limit was determined for each pavement type. For instance, a 75-year old PCC pavement exceeding its design life is an exception. Pavement age was calculated as the difference between the PMIS year (input date) and either the construction year or the resurfacing year. 50, 25, and 30 years were used for Types 1, 3, and 4 pavements, respectively. All sections for Types 3A and 3B were used in the analysis since these pavement types have a relatively lower number of sections. (Furthermore, the oldest sections for Types 3A and 3B were 34 and 32 years, respectively.)

- *Coverage*: During the collection of condition data, some of the sections are covered partially. The sections covered 50% or less were excluded from the analysis.

3.2. Individual Condition Indices

With the input from the advisory committee, five individual indices were established:

- Cracking Index (for both PCC and AC)
- Riding Index (for both PCC and AC)
- Rutting Index (for AC)
- Faulting Index (for PCC)
- Friction Index (for both PCC and AC)

Using the screening procedure described above, two different data tables were created: one used for the Cracking, Riding, Rutting, and Faulting Indices and another for the Friction Index. The reason for the two tables was that the data collection years for friction testing did not coincide with the years for the other pavement condition measurements and, furthermore, the number of sections tested or evaluated may vary, so the total number of points in these two tables are different.

The Cracking, Riding, Rutting, and Faulting Indices table included a total of 11,795 data points (or pavement sections) and the Friction Index table included 8,262 data points (or pavement sections). Figures 2 and 3 show the number of data points based on pavement type, which is further divided based on highway system (interstate or primary).

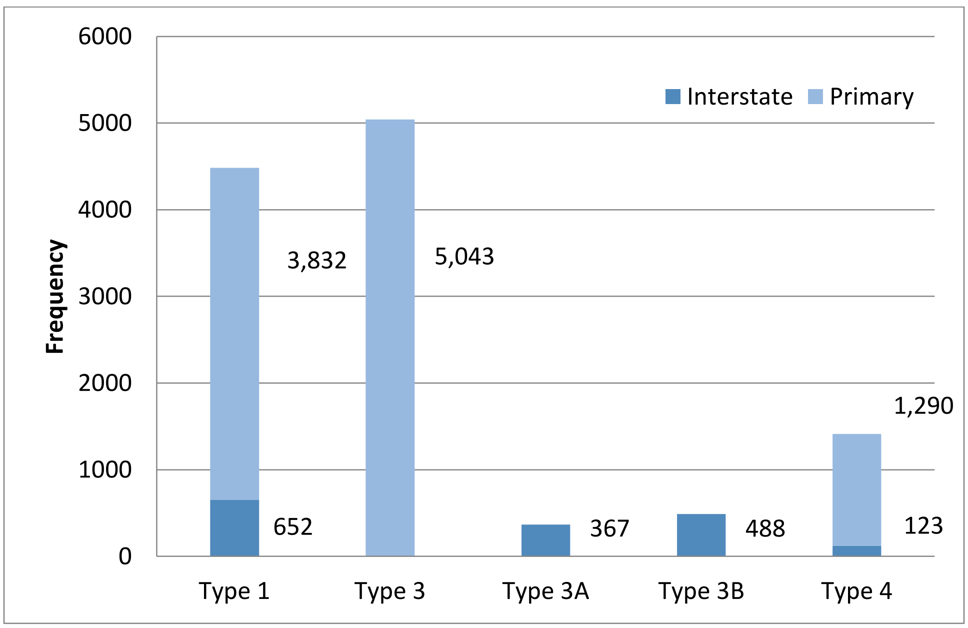


Figure 2. Frequency of data points based on pavement type used for Cracking, Riding, Rutting, and Faulting Indices

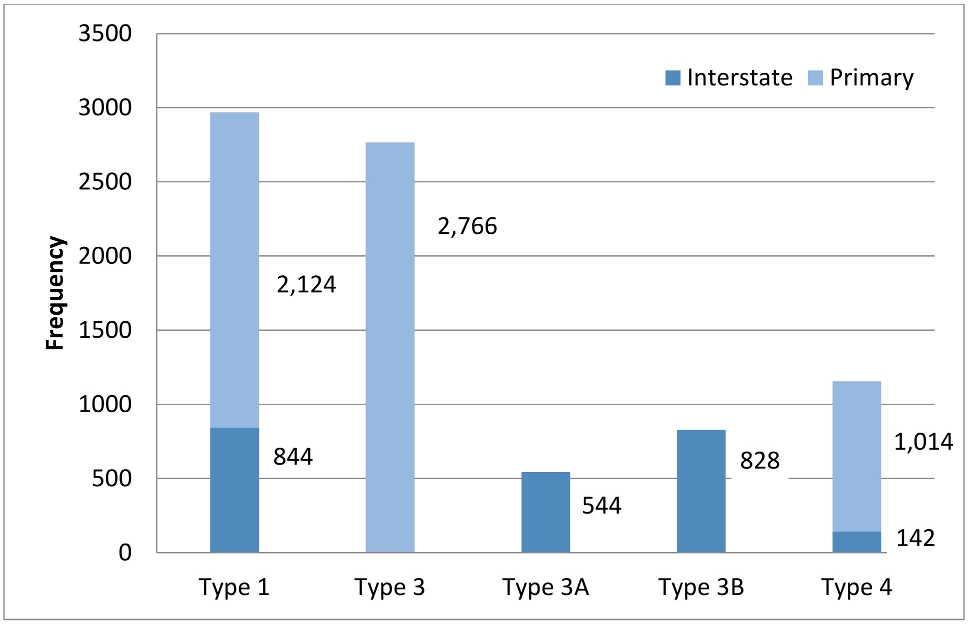


Figure 3. Frequency of data points based on pavement type used for Friction Index

By 2012, in terms of total mileage, the Iowa pavement network consisted of 1,128 miles of Type 1 (PCC)-Interstate, 4,589 miles of Type 1 (PCC)-Primary, 8,390 miles of Type 3 (composite with asphalt), 530 miles of Type 3A (composite on old jointed PCC), 694 miles of Type 3B (composite on old CRC), 197 miles of Type 4 (AC)-Interstate, and 2,720 miles of Type 4 (AC)-Primary.

3.2.1. Cracking Index

For Iowa pavements, four types of cracking (transverse, longitudinal, longitudinal-wheel-path, and alligator) are defined for AC pavements; similarly, four types of cracking (transverse, longitudinal, longitudinal-wheel-path, and durability) are defined for PCC pavements. Iowa stores the cracking information based on quantity (e.g., count per km, m per km, m^2 per km) and severity (e.g., low, medium, and high).

For this study, each cracking type was assigned to a computed sub-index, such as the Transverse Cracking Sub-index; then, all the cracking sub-indices were combined into the Cracking Index. The procedure is described below:

- *Cracking Sub-indices*:

  For PCC pavements, two sub-indices for cracking were established: Transverse Cracking and Longitudinal Cracking. For longitudinal cracking, the Iowa DOT collects both longitudinal crack data and longitudinal-wheel-path crack data. These have the same structural implication for PCC pavements; therefore, these two types were combined into one Longitudinal Cracking Sub-index for PCC pavements. Durability cracking is aggregate related and use of such material has been diminishing; therefore, durability cracking was not considered as an individual index, and hence, was not included in the Cracking Sub-index.

For AC pavements, four sub-indices were formulated: Transverse Cracking, Longitudinal Cracking, Longitudinal-wheel-path (or Wheel-path) Cracking, and Alligator Cracking.

- *Aggregating crack severities*:

  The Iowa DOT evaluates pavement cracking in three severity levels: low, medium, and high. Naturally, different severity means a different impact from a pavement management perspective. Low severity indicates cracks have become visible; whereas, high severity indicates immediate attention is needed. In order to calculate the index, these different severity levels needed to be defined as one severity level. The crack severities are aggregated using the coefficients of 1.0, 1.5, and 2.0 for low, medium, and high severities, respectively. In other words, all cracking is converted to low severity. These coefficients are selected based on past experience by the research team.

- *Indexing*:

  The researchers decided to establish the indices on a scale of 100, with 100 being the perfect, no distress condition and 0 being the worst condition. The current PCI used by the Iowa DOT is based on a scale of 100 and using the same scale would be more convenient for comparison purposes.

  A maximum value (threshold), which corresponds to a deduction of 100 points and therefore a cracking sub-index of 0, is determined for each crack type for each pavement type. These threshold values are listed in Table 4.

Table 4. Threshold values for the cracking sub-indices

Sub-Index	Type 1-Interstate	Type 1-Primary	Type 3	Type 3A	Type 3B	Type 4-Interstate	Type 4-Primary
Transverse Cracking (count/km)	150	150	500	500	500	300	300
Longitudinal Cracking* (m/km)	250	250	500	500	500	500	500
Wheel-path Cracking (m/km)	-	-	500	-	-	500	500
Alligator Cracking (m^2/km)	-	-	360	-	-	360	360

*Sum of longitudinal and longitudinal wheel-path data for PCC

Below the threshold value, reduction from a perfect score of 100 is proportional to the distress quantity. For instance, 125 m/km longitudinal cracking in Type 1 PCC pavement produces a Longitudinal Cracking Sub-index of 50. Similarly, 60 transverse cracks/km in Type 4 AC pavement results in a Transverse Cracking Sub-index of 80.

- *Calculating the Cracking Index*:

  The Cracking Index is obtained by combining weighted sub-cracking indices. The weights, which are listed in Table 5, were determined based on expert input from Iowa DOT staff.

Table 5. Cracking sub-index weights for calculating Cracking Index by pavement type

	Weight (%)	
Sub-Index	**PCC**	**AC**
Transverse	60	20
Longitudinal	40	10
Wheel-path	-	30
Alligator	-	40

The frequency distributions of the combined Cracking Index are shown in Figures 4 through 10. The histograms provide a snapshot of the data points used in the study.

For PCC (Type 1) pavements (Figures 4 and 5), 87.2% of the interstate and 58.6% of the primary pavement sections had Cracking Index values above 90. This was expected since the median transverse cracking was only 2.0 counts/km and the median longitudinal cracking was 3.0 m/km for the interstate sections. The median transverse cracking was 7.5 counts/km and the median longitudinal cracking was 13.3 m/km for the primary pavement sections.

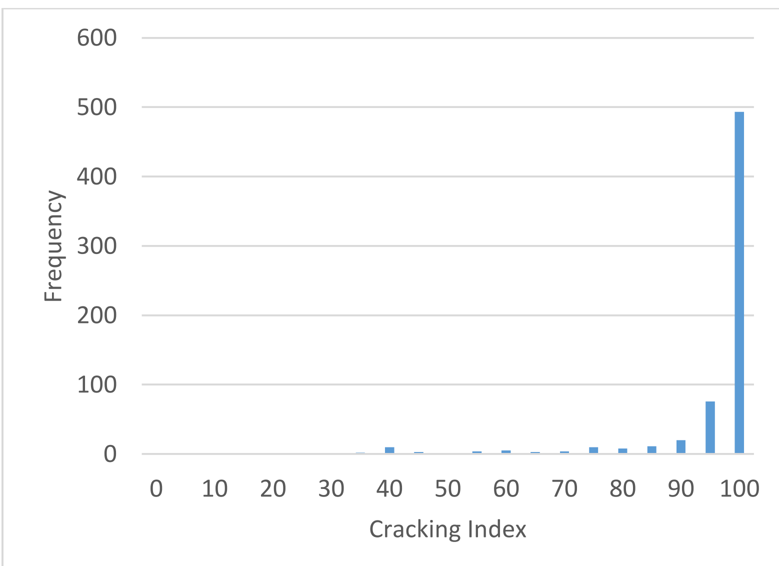


Figure 4. Cracking Index for PCC Type 1-Interstate

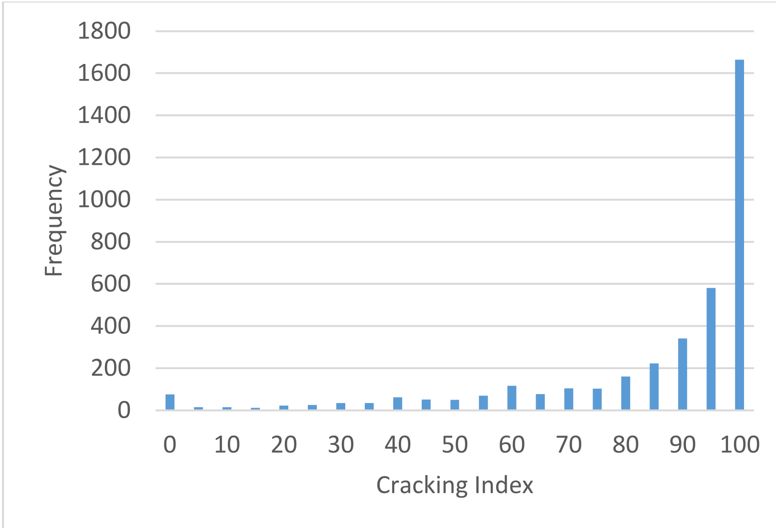


Figure 5. Cracking Index for PCC Type 1-Primary

For full-depth AC (Type 4) sections (Figures 6 and 7), 43.1% of the interstate and 30.1% of the primary sections had Cracking Index values above 90. For Type 4 interstate sections, the median cracking values were 60.0 counts/km, 204 m/km, 33.5 m/km, and 0 m^2/km for transverse, longitudinal, wheel-path, and alligator cracks. For Type 4 primary pavement sections, the median cracking values were 120.0 counts/km, 124.8 m/km, 107.0 m/km, and 1.5 m^2/km for transverse, longitudinal, wheel-path, and alligator cracks, respectively.

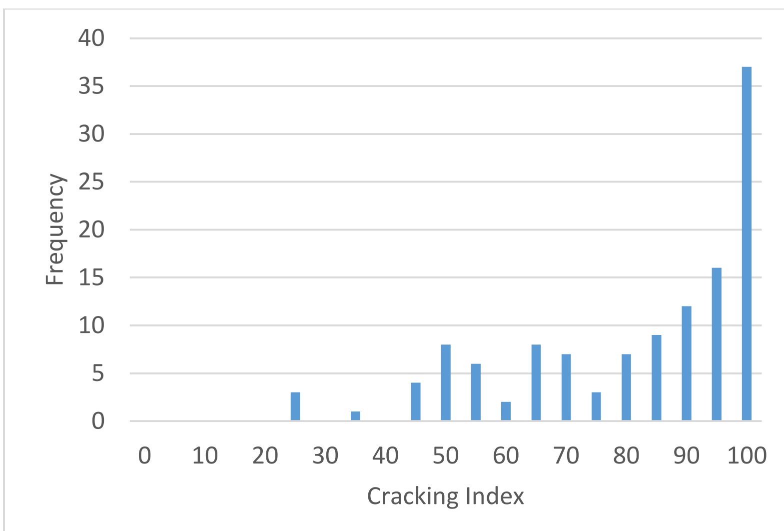


Figure 6. Cracking Index for AC Type 4-Interstate

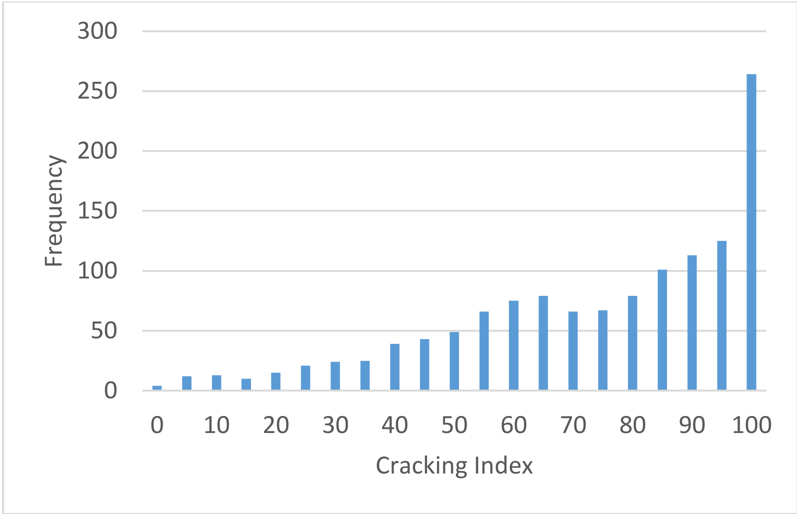


Figure 7. Cracking Index for AC Type 4-Primary

Composite with asphalt surface (Type 3) sections (Figure 8) had similar Cracking Index distribution to Type 4 primary: 29.6% of the sections had Cracking Index values above 90 and the median cracking values were 177.0 counts/km, 174.0 m/km, 90.0 m/km, and 0 m^2/km for transverse, longitudinal, wheel-path, and alligator cracks, respectively.

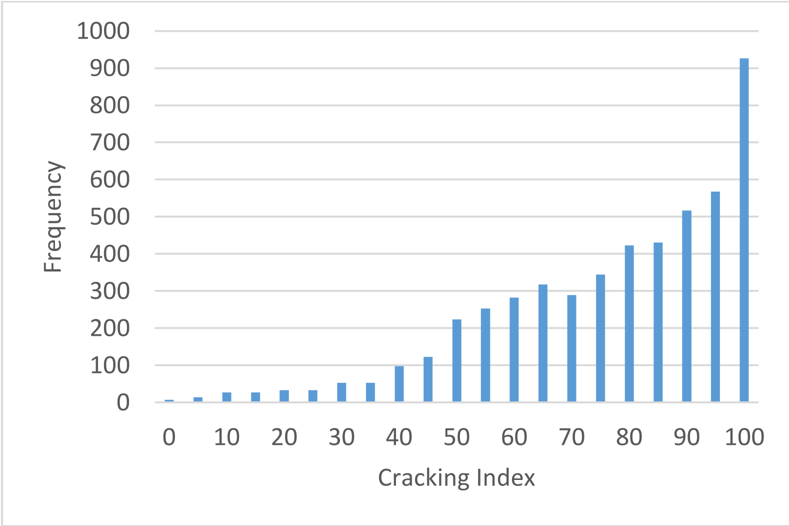


Figure 8. Cracking Index for composite with asphalt surface Type 3

Figures 8 and 9 show the Cracking Index results for composite built on old jointed PCC pavement (Type 3A) sections and composite built on old CRC pavement (Type 3B) sections, respectively.

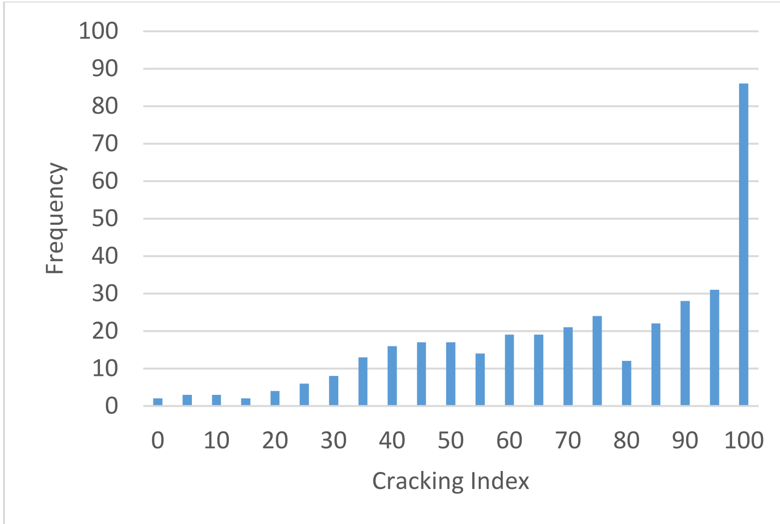


Figure 9. Cracking Index for composite built on old jointed PCC Type 3A

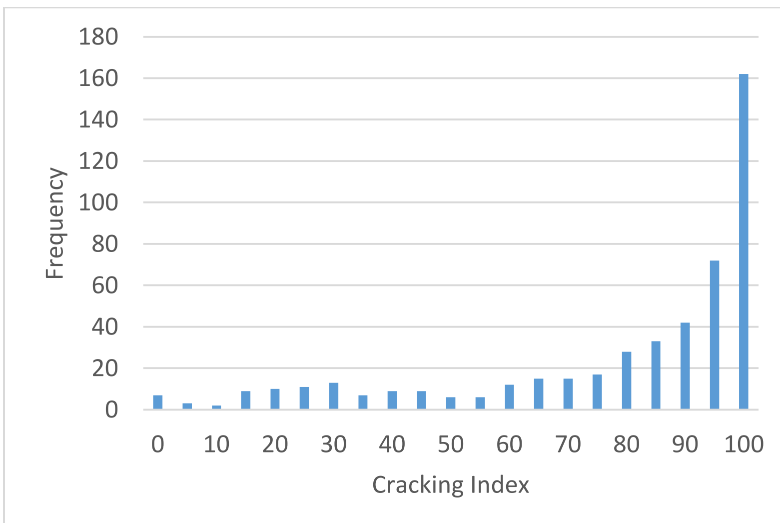


Figure 10. Cracking Index for composite built on old CRC Type 3B

3.2.2. Riding Index

The International Roughness Index (IRI) is almost unanimously accepted as the roughness measurement by highway agencies and the Iowa DOT also collects pavement IRI. Some agencies use the number directly as a measure of ride quality, some use it in a formula to scale it down, and some combine it with other measures.

The Riding Index in this study is based on the IRI measurements, as expressed on a scale of 100. IRI values below 0.5m/km are taken as a perfect 100; whereas, the values above 4.0m/km are 0 on the index scale. Although there is variation between agencies, an IRI below 1.5 m/km (95 in./mile) is generally considered as smooth (or good and very good) and an IRI above 2.7 m/km (170 in./mile) is considered as rough (poor and very poor). Based on these criteria, the proposed

Riding Index values above 65 can be taken as good or better and the values below 35 can be taken as poor or worse.

Naturally, AC surfaces have better riding as compared to PCC. Furthermore, the interstate routes have lower roughness compared to the primary roads. Figures 11 through 17 show the distribution of the Riding Index for each type of pavement section studied.

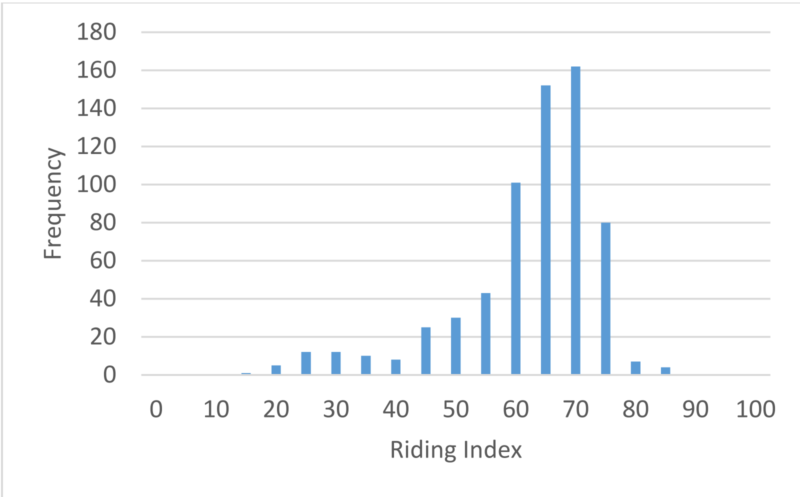


Figure 11. Riding Index for PCC Type 1-Interstate

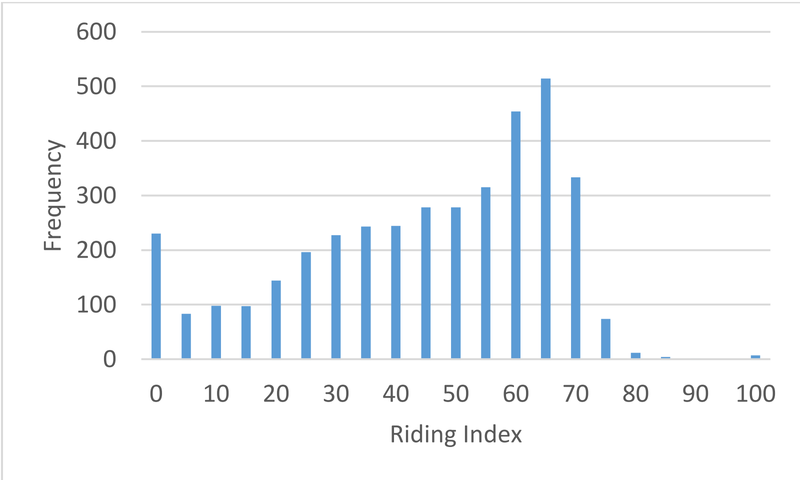


Figure 12. Riding Index for PCC Type 1-Primary

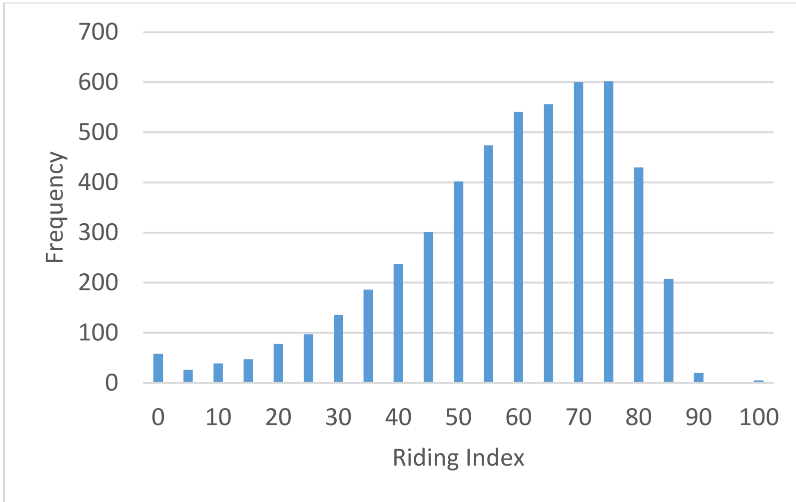


Figure 13. Riding Index for composite with asphalt surface Type 3

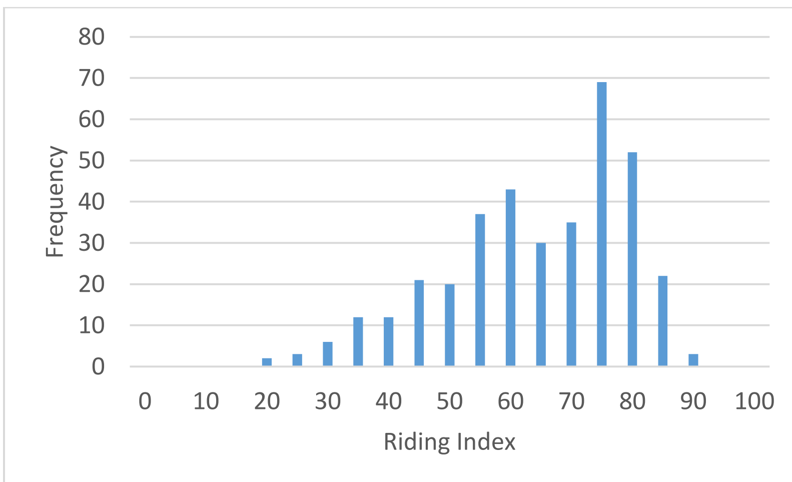


Figure 14. Riding Index for composite built on old jointed PCC Type 3A

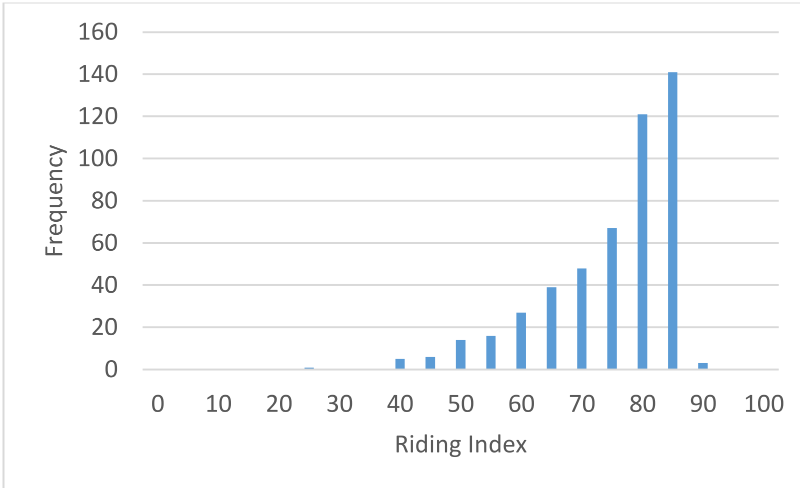


Figure 15. Riding Index for composite built on old CRC Type 3B

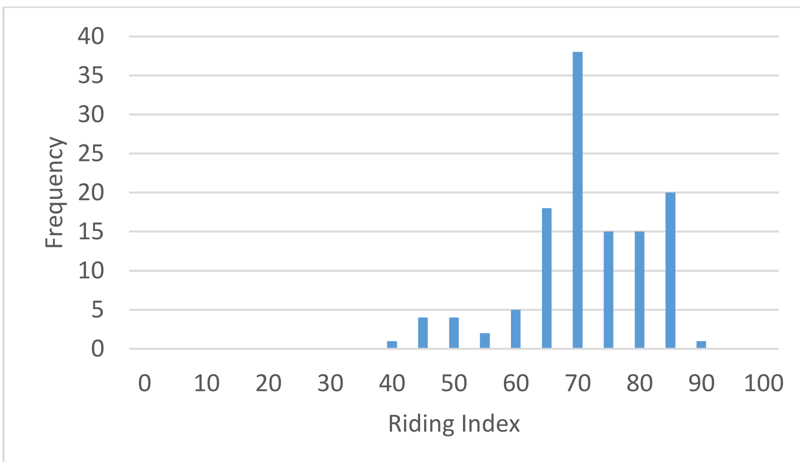


Figure 16. Riding Index for AC Type 4-Interstate

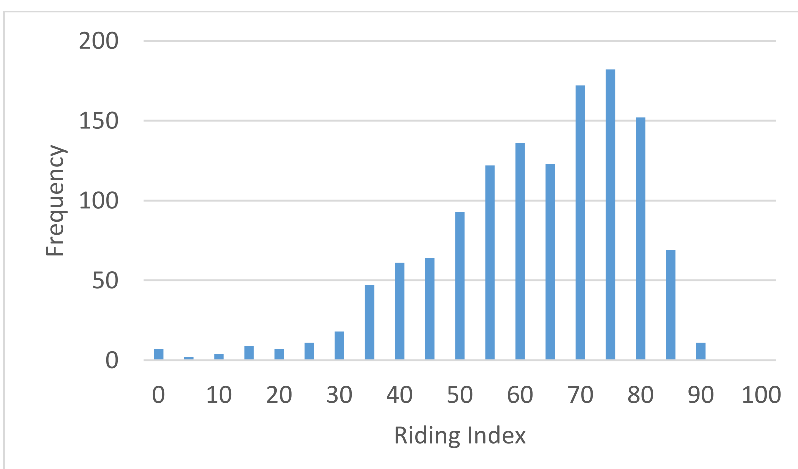


Figure 17. Riding Index for AC Type 4-Primary

Table 6 lists the median Riding Index value for each type of pavement section and the percent that were rated as good (Riding Index value above 65) and poor (Riding Index value below 35) when the data weres further analyzed.

Table 6. Median Riding Index values and rating percentages by type of pavement section

Pavement Sections	Median Value	Good or Better (%)	Poor or Worse (%)
Type 1-Interstate	62.8	38.8	6.1
Type 1-Primary	46.5	11.2	34.4
Type 3-Primary	59.3	0	13.2
Type 3A-Interstate	65.0	49.3	6.3
Type 3B-Interstate	76.4	77.9	0.2
Type 4-Interstate	68.3	72.4	0
Type 4-Primary	62.5	45.4	8.1

3.2.3. Rutting Index

Rutting, which is the depression on wheel-paths in asphalt pavements, is one of the common surface distresses collected by state agencies. The proposed Rutting Index from this study uses rut depths available in the PMIS database with threshold values and a scale of 100. A threshold value of 12 mm is set to 0 on the Rutting Index scale of 100and the values below 12 mm are applied as deductions proportionally.

The distribution of Rutting Index data points is shown in Figures 18 through 22 for the different types of pavement sections.

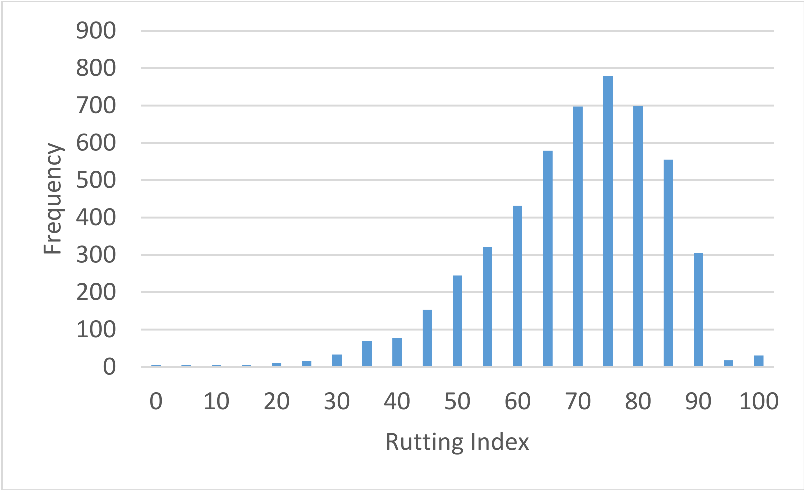


Figure 18. Rutting Index for composite with asphalt surface Type 3

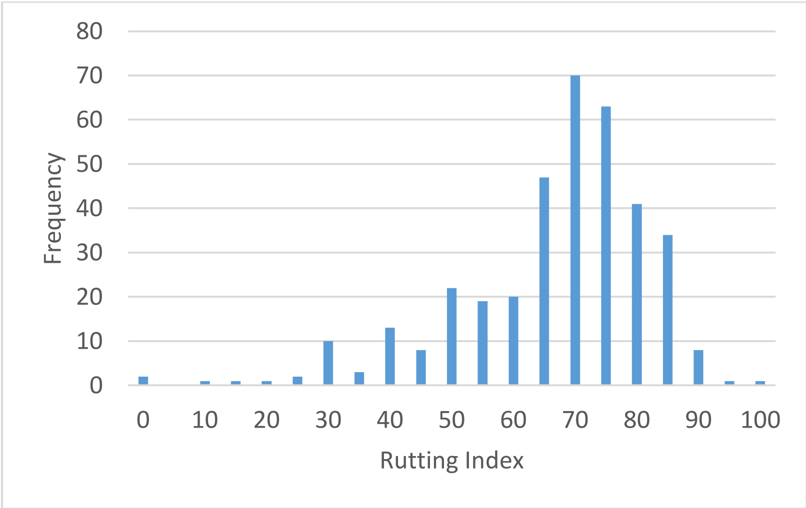


Figure 19. Rutting Index for composite built on old jointed PCC Type 3A

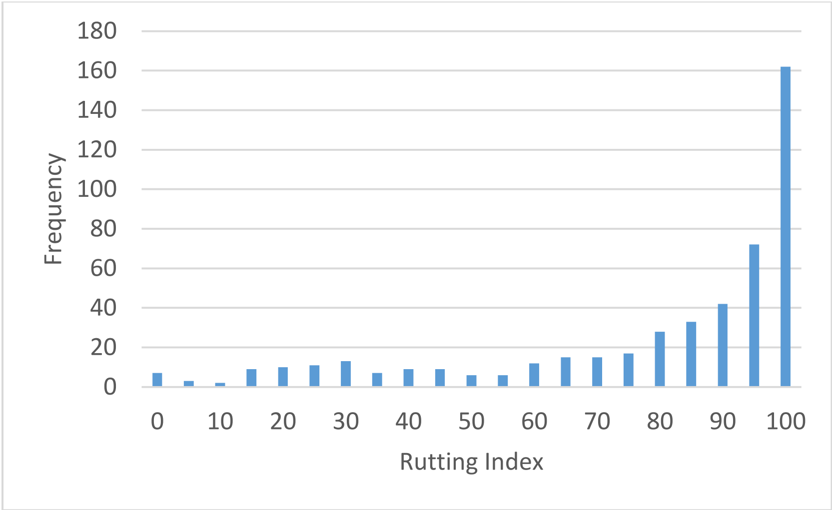


Figure 20. Rutting Index for composite built on old CRC Type 3B

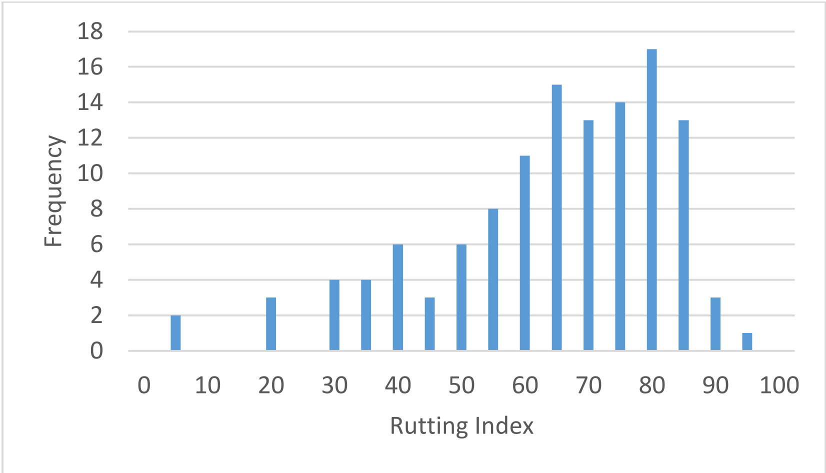


Figure 21. Rutting Index for AC Type 4-Interstate

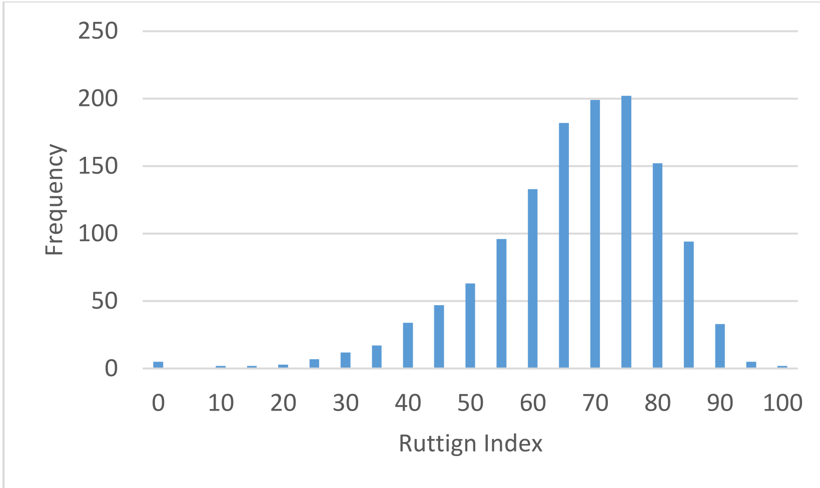


Figure 22. Rutting Index for AC Type 4-Primary

Table 7 lists the median rutting values (in mm) and the median Rutting Index values for each type of asphalt pavement section.

Table 7. Median rutting values and Rutting Index values by type of pavement section

Pavement	Median Value (mm)	Median Index Value
Type 3-Primary	3.7	69.2
Type 3A-Interstate	3.9	67.5
Type 3B-Interstate	3.5	76.4
Type 4-Interstate	4.2	65.0
Type 4-Primary	4.0	66.7

3.2.4. Faulting Index

Faulting, which affects ride quality and is the differential vertical displacement between the adjoining slabs in PCC pavement, is one of the common distress types collected by agencies. The proposed Faulting Index uses the faulting measurements available in the PMIS database and is based on a scale of 100. Again, a threshold value of 12 mm is set to 0 on the index scale of 100.

The distribution of the data points for Faulting Index is given in Figures 23 and 24 for Type 1-Interstate and Type 1-Primary pavements, respectively.

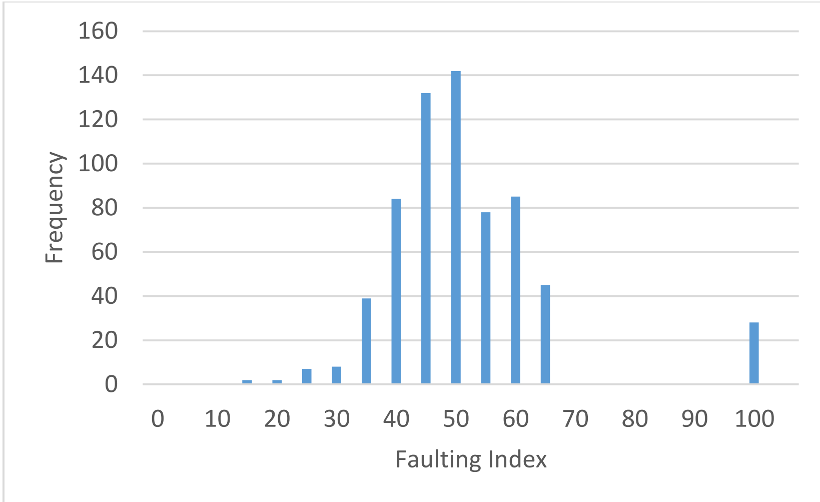


Figure 23. Faulting Index for PCC Type 1-Interstate

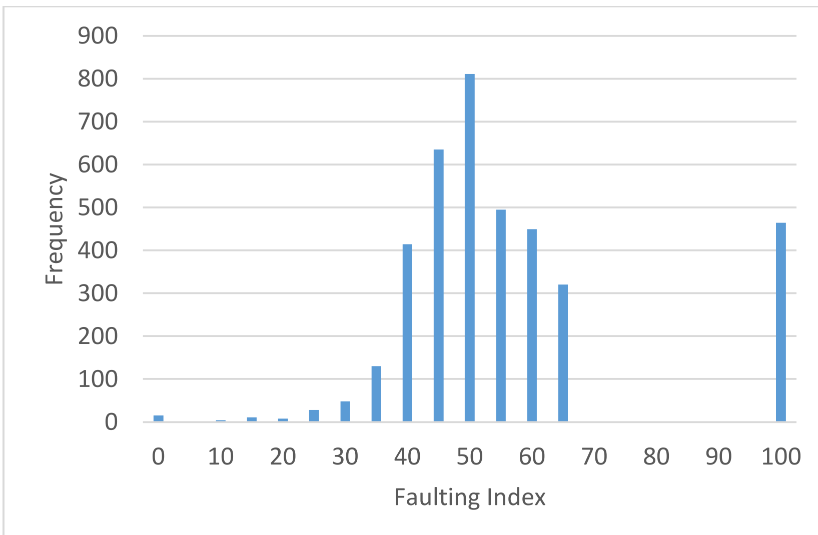


Figure 24. Faulting Index for PCC Type 1-Primary

The median faulting of the data set was 6.4 mm and 6.0 mm for Type 1-Interstate and Type 1-Primary, respectively. The median Faulting Index was 46.7 and 50.0 for Type 1-Interstate and Type 1-Primary, respectively. 4.3% of Type 1-Interstate sections and 12.1% of Type 1-Primary sections had a perfect Faulting Index of 100. However, both data sets showed a gap between 70 and 100. No in-depth analysis has been done whether the perfect scores are the result of missing data or not.

3.2.5. Friction Index

As mentioned earlier in this chapter, the testing or measurement cycle for skid resistance is different than that for distress data; therefore, a different data set containing 8,262 data points was created for the Friction Index. The Friction Index is also based on a scale of 100.

Figure 25 shows the distribution of the new pavement sections (3 years old or newer). Based on this data and input from the Iowa DOT, a threshold value of 60 was taken, equating values of 60 and higher to a perfect 100 Friction Index.

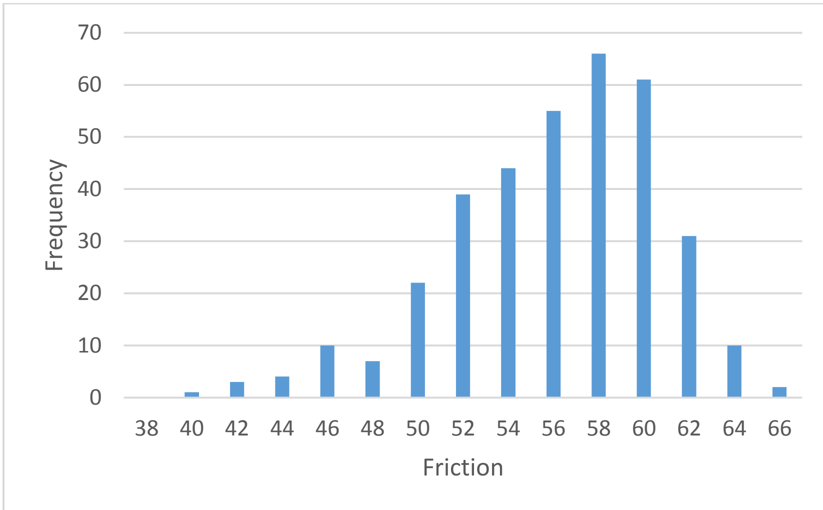


Figure 25. Friction Index for sections three years old or newer

Figures 26 through 32 show the Friction Index distribution for the different types of pavement sections.

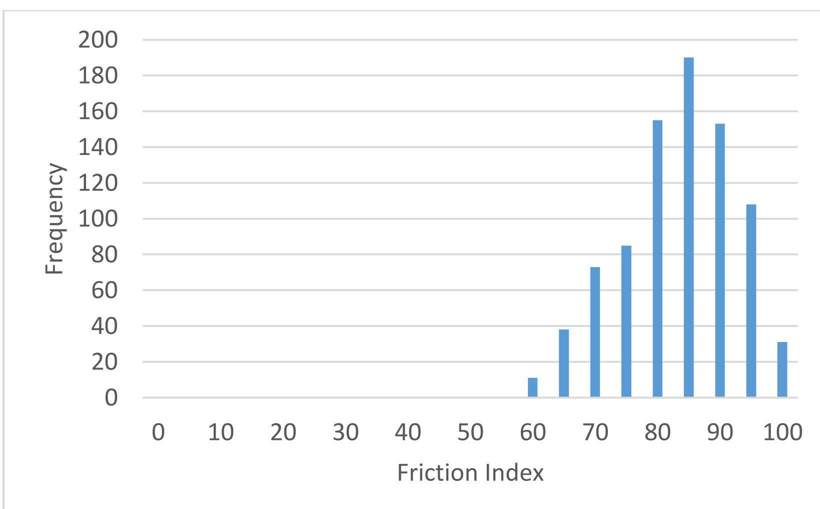


Figure 26. Friction Index for PCC Type 1-Interstate

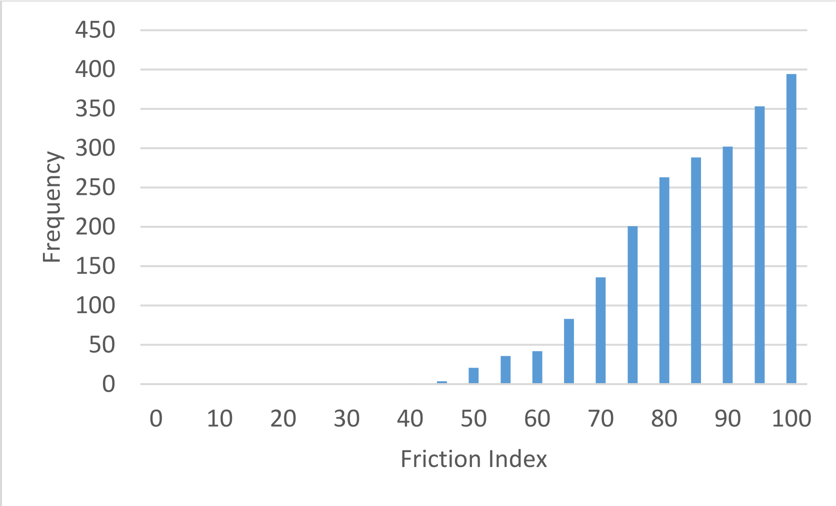


Figure 27. Friction Index for PCC Type 1-Primary

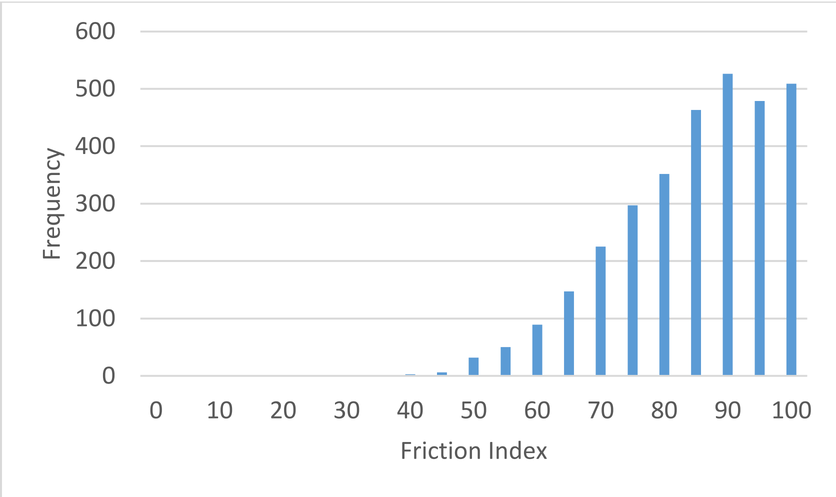


Figure 28. Friction Index for composite with asphalt surface Type 3

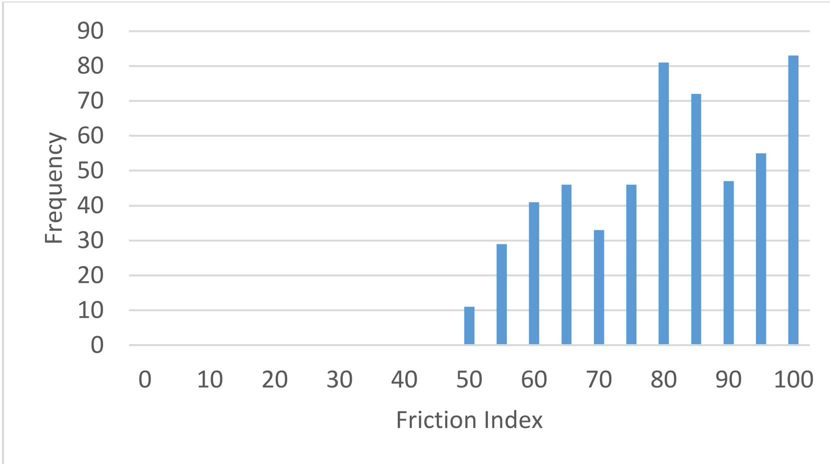


Figure 29. Friction Index for composite built on old jointed PCC Type 3A

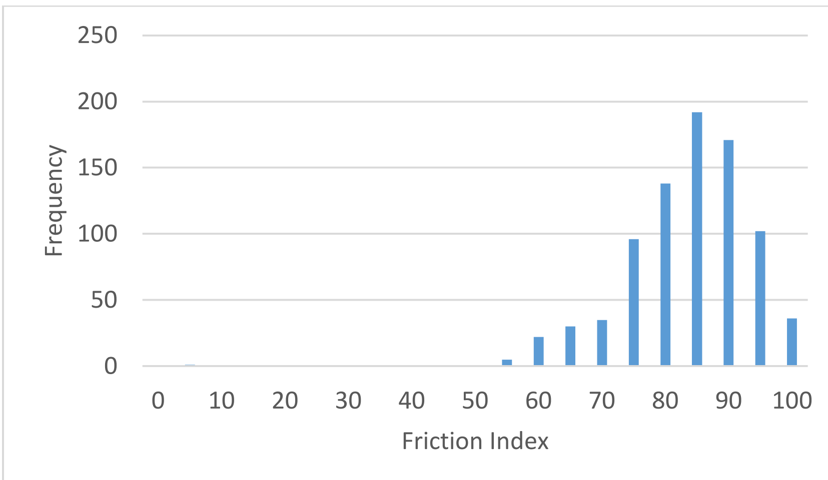


Figure 30. Friction Index for composite built on old CRC Type 3B

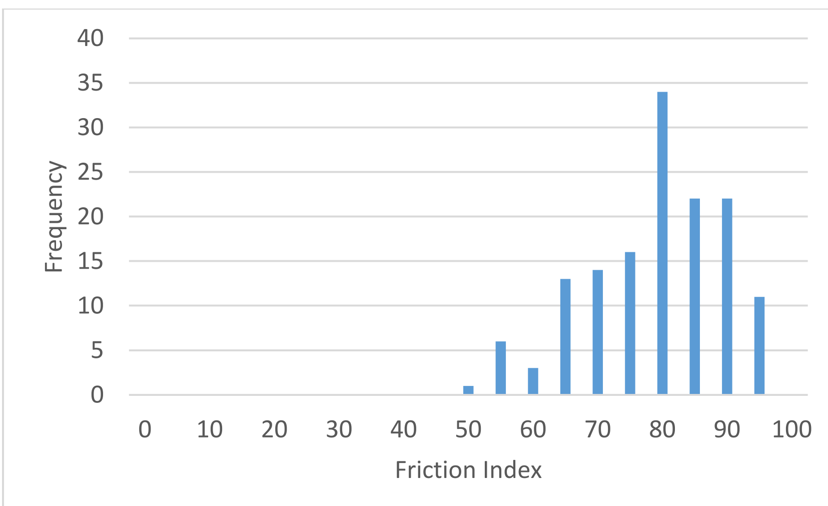


Figure 31. Friction Index for AC Type 4-Interstate

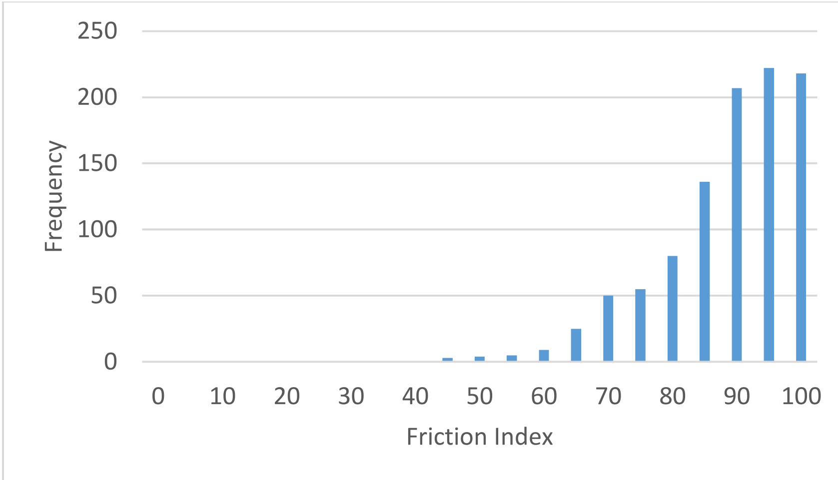


Figure 32. Friction Index for AC Type 4-Primary

Table 8 lists the median Friction Index values for each type of pavement section.

Table 8. Median Friction Index values by type of pavement section

Pavement Sections	Median Value
Type 1-Interstate	81.7
Type 1-Primary	85.0
Type 3-Primary	85.0
Type 3A-Interstate	80.0
Type 3B-Interstate	83.3
Type 4-Interstate	78.3
Type 4-Primary	88.3

3.3. Overall Pavement Condition Index

The current PCI used by the Iowa DOT is based on pure statistical regression anaylysis where the variables (e.g., crack type and severity, traffic, structural data, material propery, and age) may differ based on the pavement type. The proposed overall condition index, PCI-2, combines the individual indices described in the previous sections and provides an overall assessment of the pavement condition. PCI-2 is comprised of the Cracking Index, Riding Index, and Faulting Index for PCC pavements and the Cracking Index, Riding Index, and Rutting Index for AC pavements. The technical advisory committee decided not to include the Friction Index in PCI-2.

The weighting factors to combine the individual indices are based on experience in Iowa. The research team started with intial numbers and finalized them through comparative analysis using the current (or old) PCI as a benchmark. PCI-2 was finalized as follows:

$PCI\text{-}2_{PCC}$ = 0.40 × (Cracking Index) + 0.40 × (Riding Index) + 0.20 × (Faulting Index)

$PCI\text{-}2_{AC}$ = 0.40 × (Cracking Index) + 0.40 × (Riding Index) + 0.20 × (Rutting Index)

Figures 33 through 39 provide snapshots of the distribution of data points based on the type of pavement section.

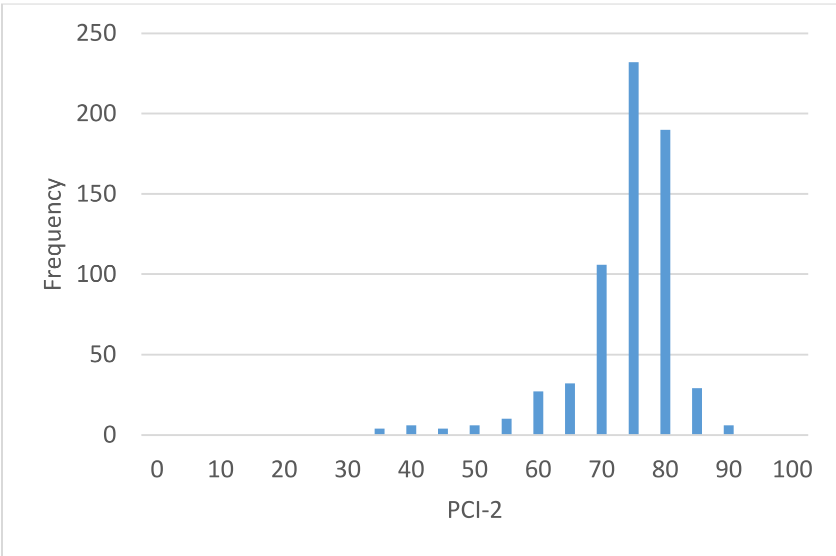


Figure 33. PCI-2 for PCC Type 1-Interstate

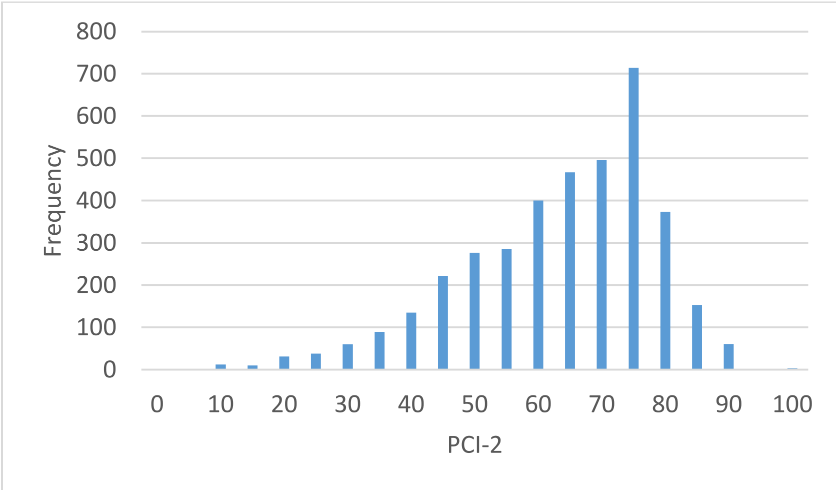


Figure 34. PCI-2 for PCC Type 1-Primary

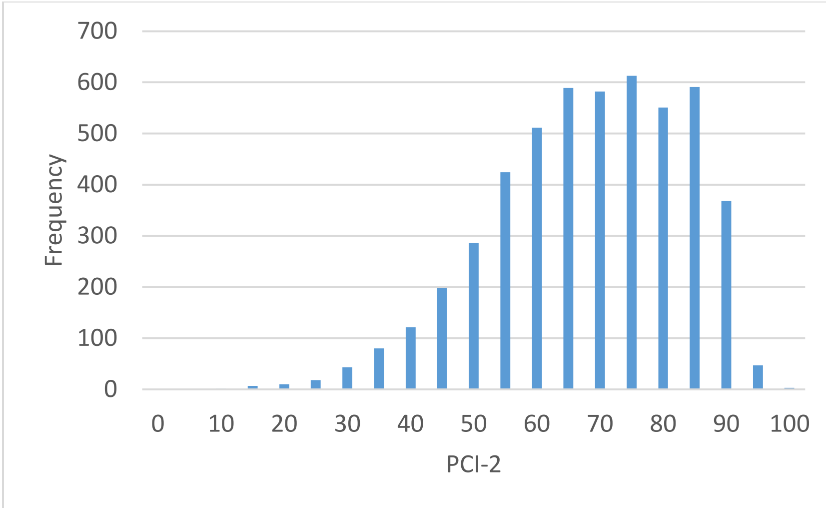


Figure 35. PCI-2 for Type 3

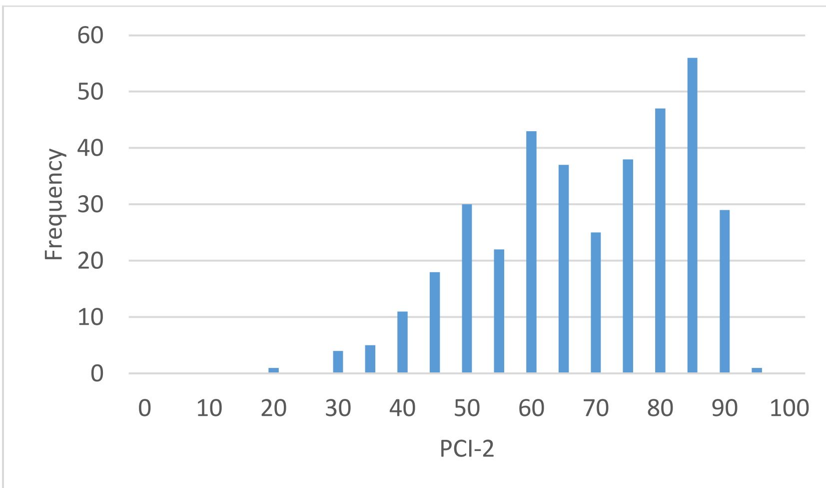


Figure 36. PCI-2 for Type 3A

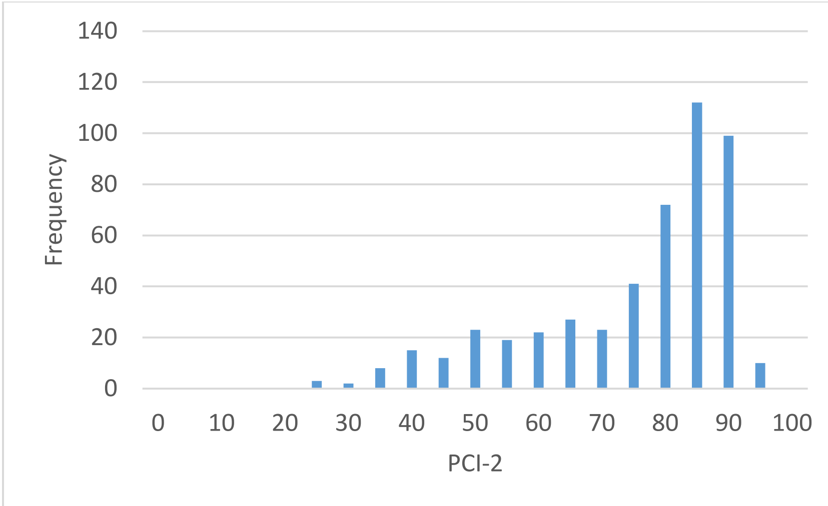


Figure 37. PCI-2 for Type 3B

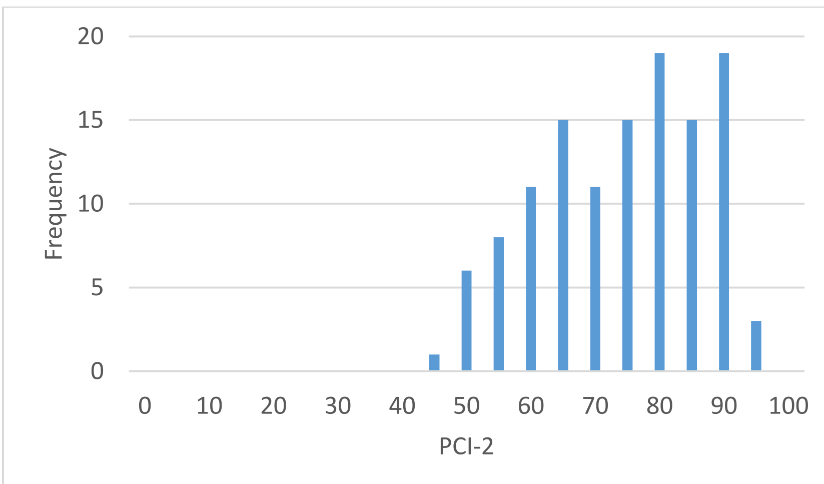


Figure 38. PCI-2 for AC Type 4-Interstate

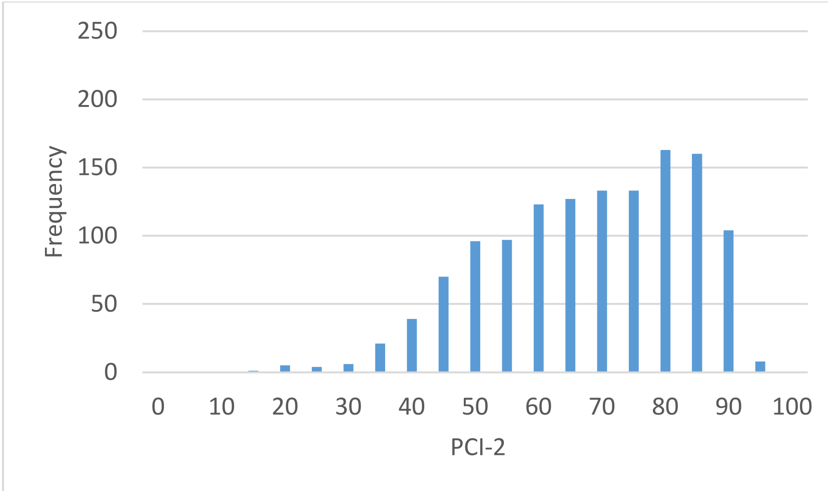


Figure 39. PCI-2 for AC Type 4-Primary

The median and weighted average values for the 2012 highway network condition using PCI-2 are listed in Table 9 by type of pavement section.

Table 9. 2012 PCI-2 median values and weighted averages by type of pavement section

Pavement Sections	Median Value	Weighted Average Value
Type 1-Interstate	73.3	74.1
Type 1-Primary	63.8	67.4
Type 3-Primary	67.4	67.2
Type 3A-Interstate	67.0	75.1
Type 3B-Interstate	78.6	81.5
Type 4-Interstate	71.8	78.2
Type 4-Primary	67.1	62.2

The weighted average of PCI-2 was calculated as follows:

(PCI × Section length) ÷ (Total length)

4. COMPARISON OF PCI AND PCI-2

In evaluating pavement condition, the Iowa DOT has been using the current PCI for several decades and it serves the purpose fairly well; therefore, PCI was used as a benchmark to test PCI-2 in this study. The old and new values for each data point (specific pavement section in a specific year) were compared for analysis.

Figure 40a shows the comparison of the old and new PCIs for PCC Type 1-Interstate pavement sections.

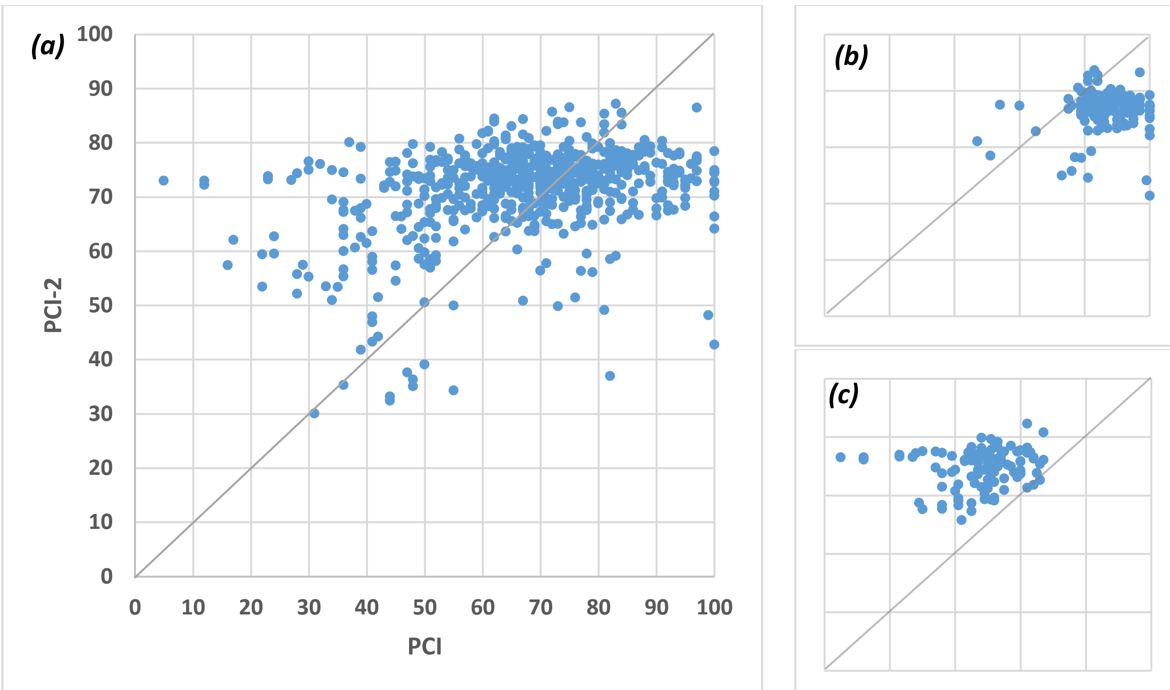


Figure 40. Comparison of PCI and PCI-2 for PCC Type 1-Interstate: (a) complete data set, (b) sections less than10 years old, (c) sections 20 to 30 years old

The medians for PCI and PCI-2 s were 69.0 and 73.3, respectively, indicating that PCI-2 tends to predict a better pavement condition (with higher values). The weighted averages were 66.7 and 72.0 for PCI and PCI-2, respectively, implying that PCI-2 provides higher values.

Figures 40b and 40c show that old pavement sections are rated high and young sections are rated low with PCI-2 compared to the ratings using PCI. The reason is that the PCI equation (given below) uses age and cumulative traffic, which is also related to age, as a deduct factor; whereas, PCI-2 uses only the distress parameters (measured values such as rutting, cracking, and IRI).

$$PCI_{\text{Type 1-Interstate}} = 102.24 - 1.03 \times (\text{Pavement age}) - 0.23 \times (\text{Percent life used based on ESALs}) - 0.13 \times (\text{Longitudinal cracking}) \quad \textbf{(6)}$$

Figure 41 presents the comparison of the new and old PCIs for Type 1-Primary pavement sections.

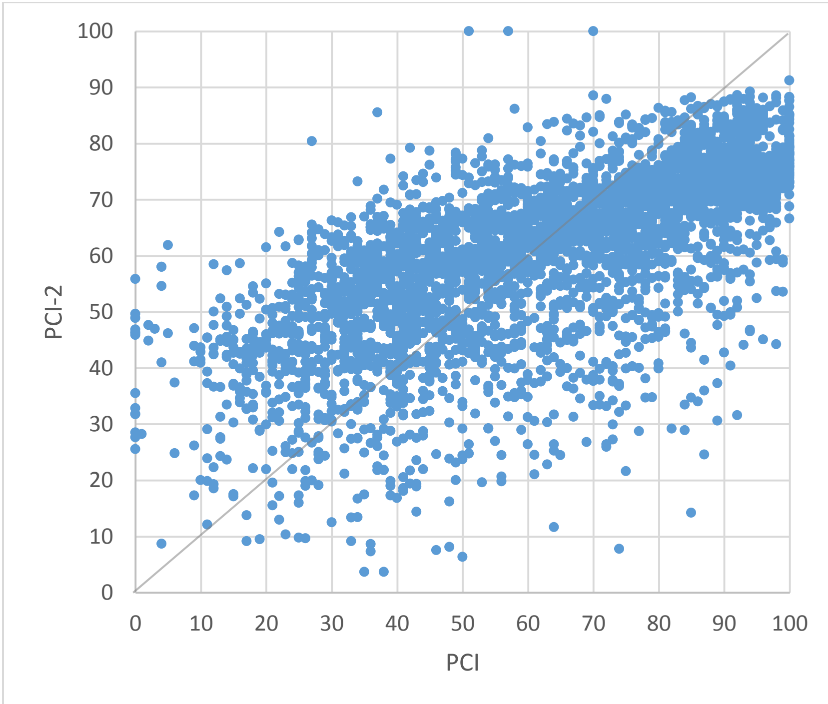


Figure 41. Comparison of PCI and PCI-2 for PCC Type 1-Primary

The data show a fair scatter around the equity line. PCI-2 predicts lower values compared to PCI: the medians are 67.0 and 63.8 for PCI and PCI-2, respectively; similarly, the weighted averages are 67.9 and 64.7 for PCI and PCI-2, respectively. The differences might be due to the fact that the current PCI equation (below) relies heavily on IRI and age and considers only durability cracking as a distress variable; whereas, PCI-2 uses only distresses as input.

$$PCI_{\text{Type 1-Primary}} = 92.56 - 10.08 \times (\text{IRI}) - 0.52 \times (\text{Pavement age}) - 118.40 \times (\text{Durability cracking}) + 3.24 \times (\text{Structural rating at joints}) \quad \textbf{(7)}$$

Figure 42 compares PCI and PCI-2 for Type 3 composite pavement sections.

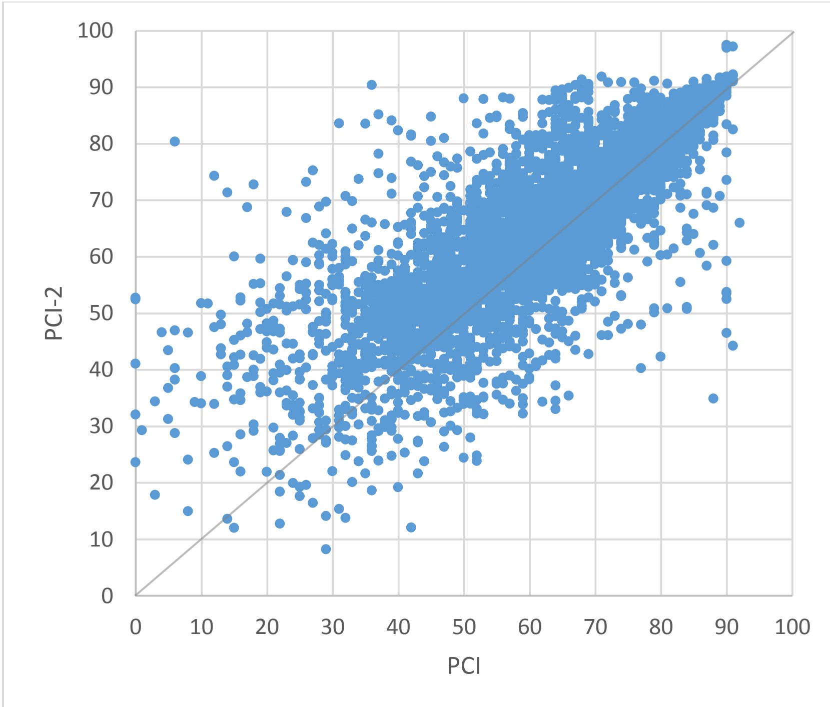


Figure 42. Comparison of PCI and PCI-2 for Type 3 composite with asphalt surface

The data presents a fairly dense scatter around the equity line indicating good correlation. PCI-2 predicts a slightly higher condition rating. The medians for PCI and PCI-2 are 64.0 and 67.4, respectively. The weighted averages for PCI and PCI-2 are 63.0 and 66.9, respectively. The Type 3 PCI equation below also includes age as a deduct factor, resulting in a shift to comparatively lower values, particularly for the old sections.

$$PCI_{Type\ 3} = 95.00 - 7.18 \times (IRI) - 0.92 \times (Pavement\ age) - 0.96 \times (Transverse\ cracking) - 0.22 \times (Wheel\text{-}path\ cracking) - 0.07 \times (Percent\ life\ used\ based\ on\ ESALs) \qquad \mathbf{(8)}$$

Figure 43 plots PCI-2 versus PCI for Type 3A composite built on old jointed PCC pavement sections.

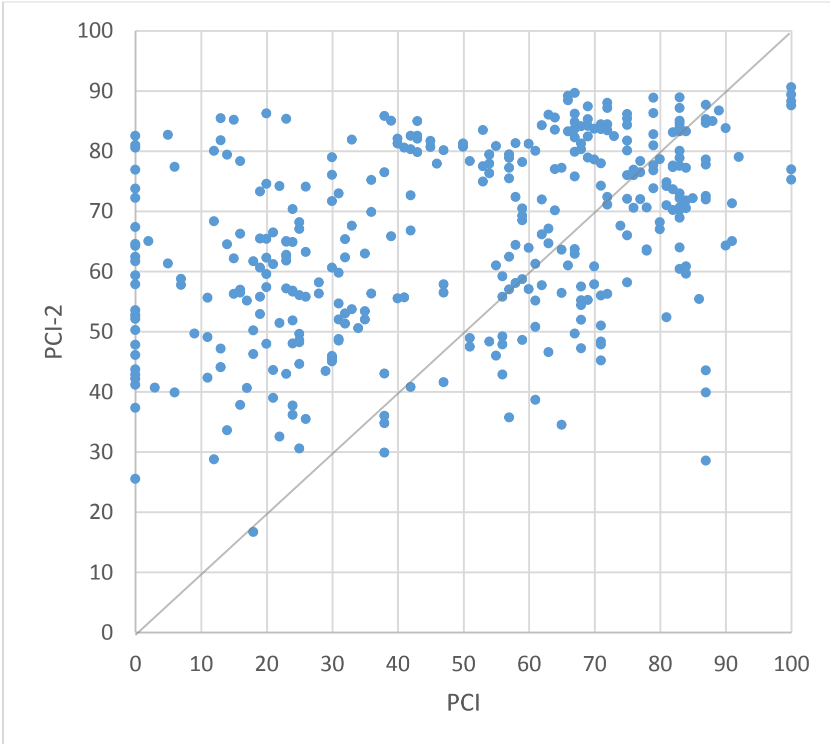


Figure 43. Comparison of PCI and PCI-2 for Type 3A composite built on old jointed PCC

There is no clear trend; however, the plot suggests PCI-2 predicts higher ratings. The medians are 55.0 and 67.0 for PCI and PCI-2, respectively, and the weighted averages are 50.6 for PCI and 64.5 for PCI-2. The equation below shows the current PCI calculation used for Type 3A pavements.

$$PCI_{\text{Type 3A}} = 74.60 + 0.38 \times (\text{Rating based on age}) - 0.88 \times (\text{Friction}) - 0.04 \times (\text{Patching}) + 0.14 \times (\text{Surface layer thickness}) + 0.15 \times (\text{Total asphalt depth}) \quad \textbf{(9)}$$

The poor correlation is attributed to the fact that the current Type 3A PCI equation does not include distress data as input; whereas, the PCI-2 calculation solely utilizes distress data.

Figure 44 demonstrates the comparison between PCI and PCI-2 for Type 3B composite built on old CRC pavement sections.

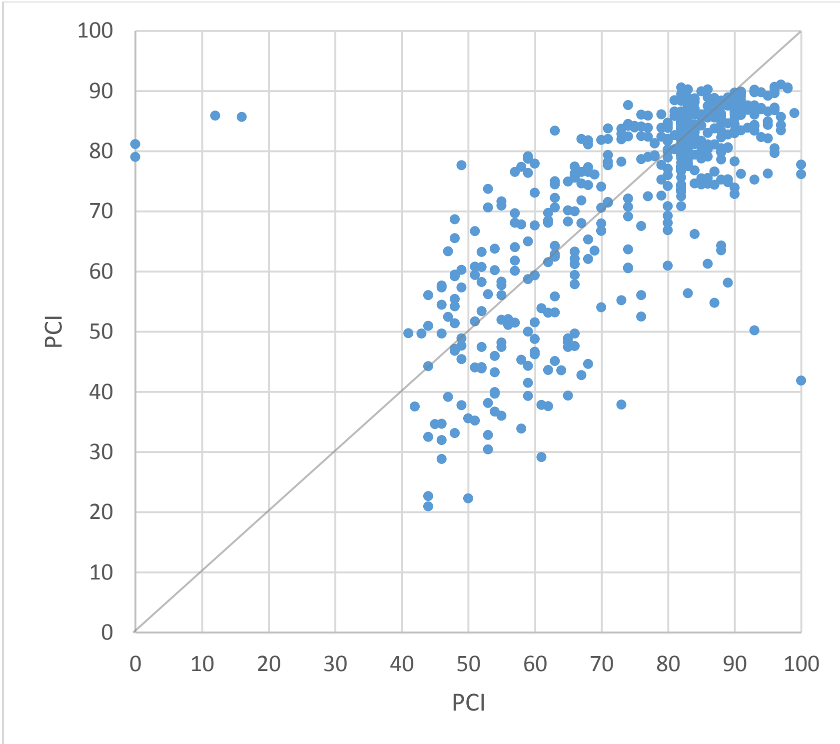


Figure 44. Comparison of PCI and PCI-2 for Type 3B composite built on old CRC

The median values are 81.0 and 78.6 for PCI and PCI-2, respectively. Moreover, the weighted averages are 73.1 and 70.1 for PCI and PCI-2, respectively. Except for a few outliers, the general trend is that PCI-2 rates the pavement lower compared to PCI. Equation 10 is the current PCI equation for Type 3B.

$PCI_{\text{Type 3B}}$ = 28.60 – 8.73 × (Aggregate durability class) – 10.63 × (IRI) + 0.04 × (Percent life used based on ESALs**)** + 0.42 × (Relative structural ratio) + 0.51 × (Total asphalt depth) **(10)**

Figure 45 plots PCI-2 versus PCI for AC Type 4-Interstate pavement sections.

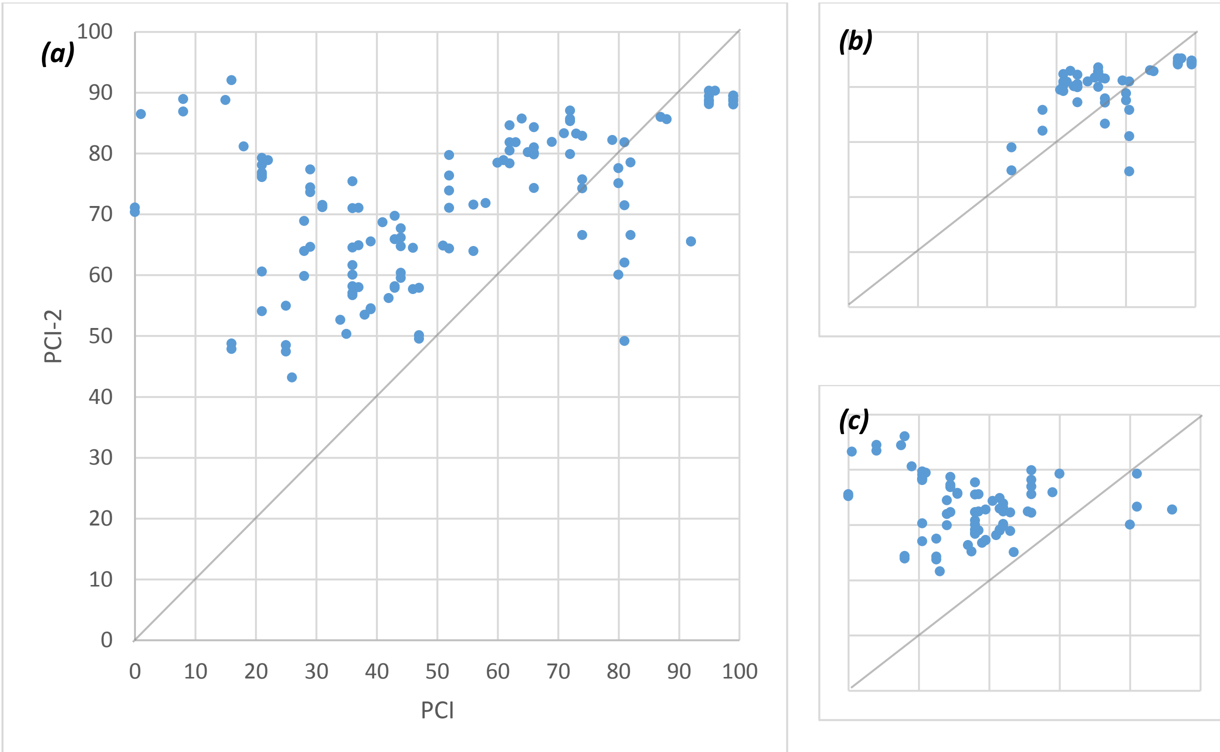


Figure 45. Comparison of PCI and PCI-2 for AC Type 4-Interstate: (a) complete data set, (b) sections less than 10 years old, (c) sections 10 to 25 years old

PCI-2 results in considerably higher values compared to PCI. The median of PCI-2 is 71.8 compared to 47.0 for PCI. The weighted averages are 49.6 and 70.5 for PCI and PCI-2, respectively. In the current PCI equation (below), pavement age is an important deduction factor and this reflects in the older sections (Figure 44c), where the rating is higher with PCI-2.

$$PCI_{\text{Type 4-Interstate}} = 23.07 - 3.77 \times (\text{Pavement age}) - 4.04 \times (\text{IRI}) + 0.23 \times (\text{Base thickness}) \qquad \textbf{(11)}$$

Figures 46 shows the comparison of PCI and PCI-2 for AC Type 4-Primary pavement sections.

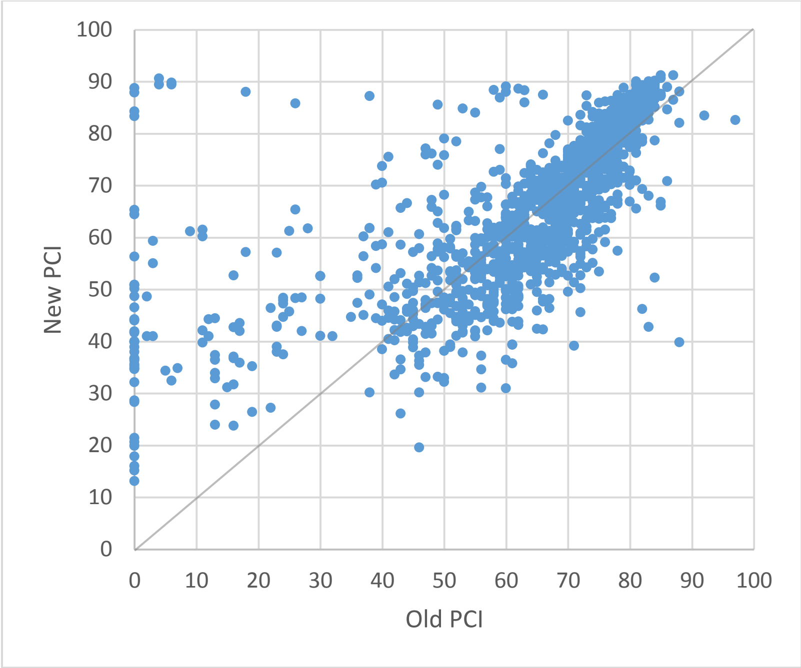


Figure 46. Comparison of PCI and PCI-2 for AC Type 4-Primary

The median values are 68.0 and 67.1 for PCI and PCI-2, respectively. Moreover, the weighted averages are 64.7 and 65.9 for PCI and PCI-2, respectively. The data shows a relatively good correlation as the current PCI calculation includes IRI and alligator cracking as the major deducts similar to the PCI-2 calculation. The current PCI equation for Type 4-Interstate pavements is given below.

$$PCI_{\text{Type 4-Primary}} = 92.34 - 0.36 \times (\text{Pavement age}) - 11.11 \times IRI - 2.041 \times (\text{Alligator cracking}) + 0.55 \times (\text{Patching}) \quad \textbf{(12)}$$

Highway agencies use pavement performance curves to predict the future pavement condition and develop maintenance strategies. Pavements deteriorate over time and, ideally, the performance indicators (using the condition indices) reflect the time-dependent behavior, so that deterioration models can be developed. Figures 47 through 53 show the differences between using the existing PCI and the proposed PCI-2 based on pavement section age for each pavement type included in this study.

While developing performance curves was not the objective of this study, the plots were used to confirm whether the proposed PCI-2 could better reflect pavement aging. In general, the researchers found that PCI-2 captures pavement performance fairly well, particularly, considering there is no database manipulation involved.

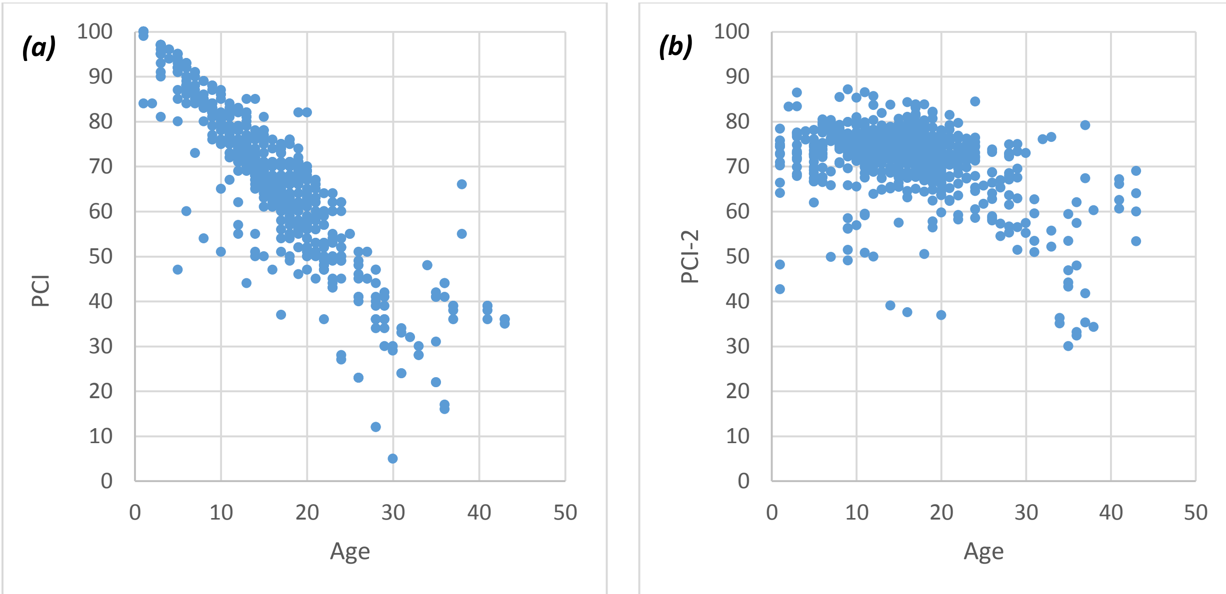


Figure 47. Deterioration of pavement condition by pavement age for PCC Type 1-Interstate: (a) using PCI, (b) using PCI-2

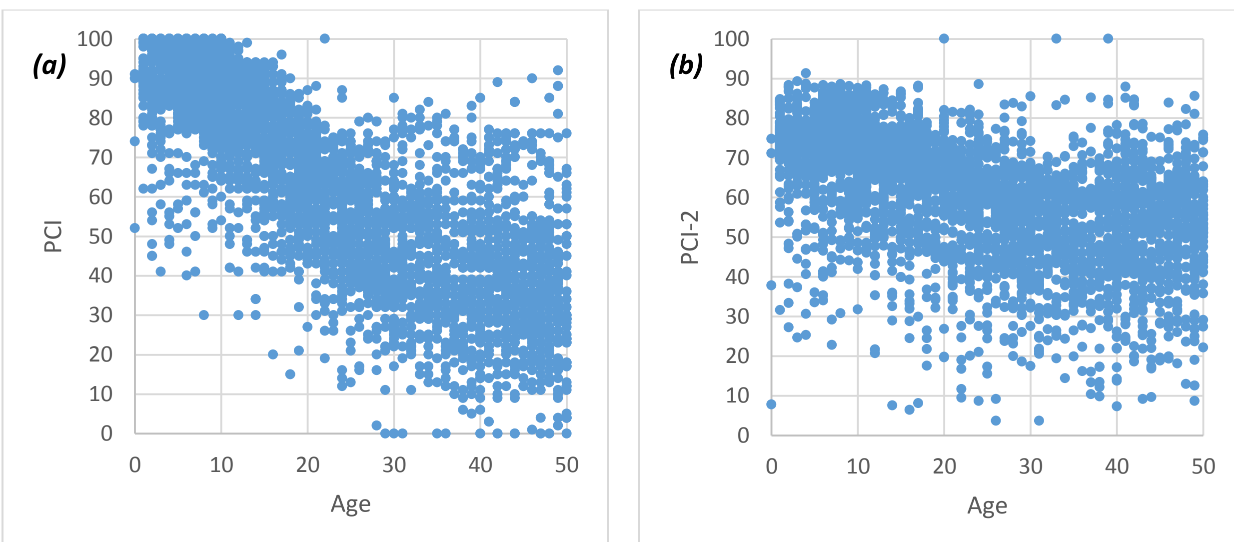


Figure 48. Deterioration of pavement condition by pavement age for PCC Type 1-Primary: (a) using PCI, (b) using PCI-2

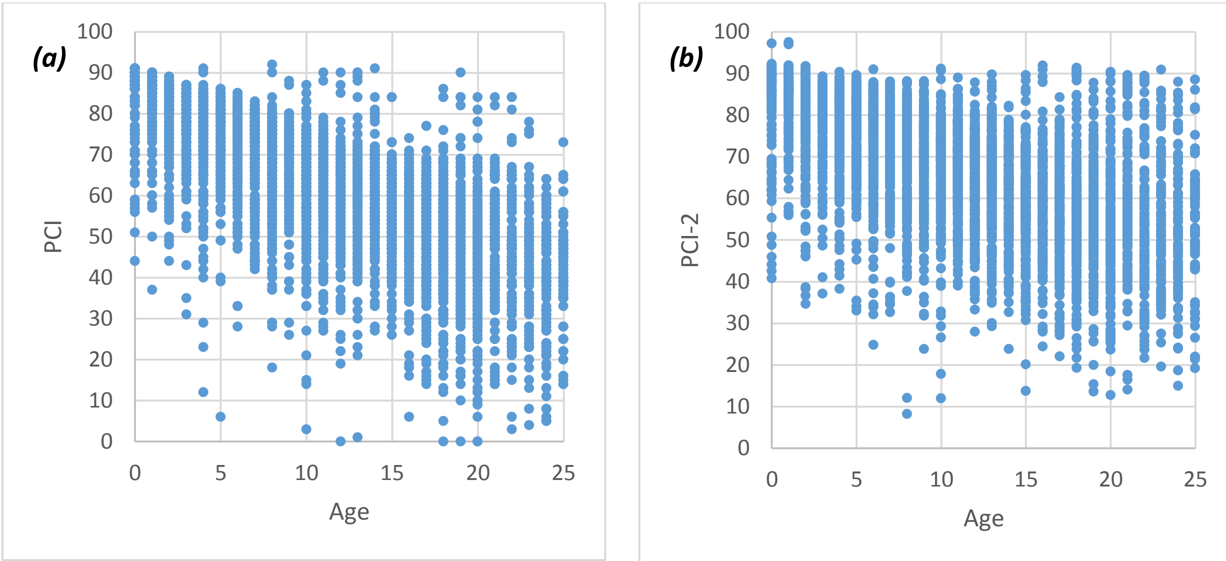


Figure 49. Deterioration of pavement condition by pavement age for Type 3 composite with asphalt surface: (a) using PCI, (b) using PCI-2

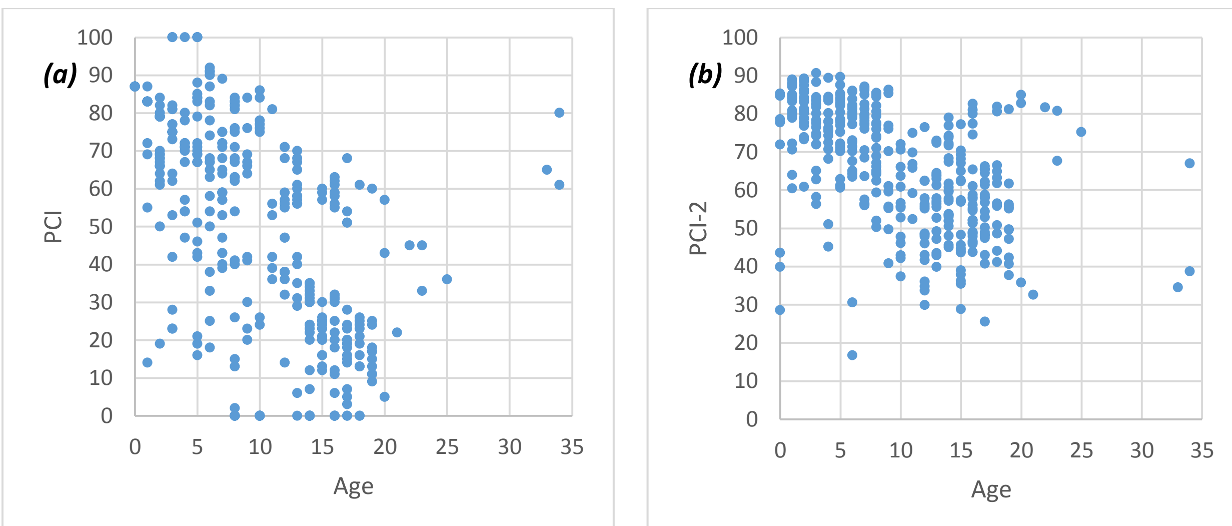


Figure 50. Deterioration of pavement condition by pavement age for Type 3A composite built on old jointed PCC: (a) using PCI, (b) using PCI-2

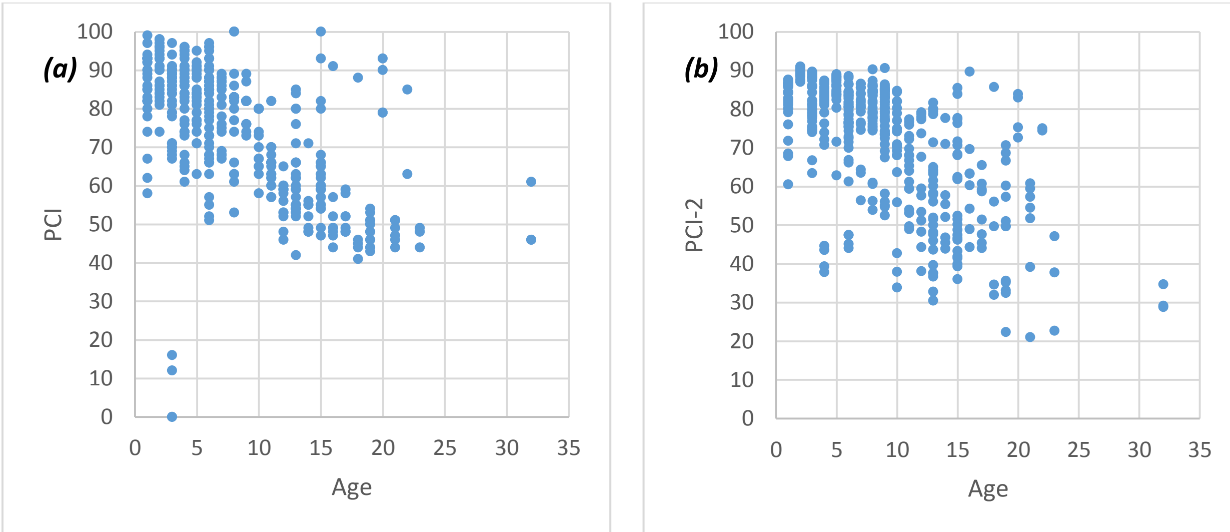


Figure 51. Deterioration of pavement condition by pavement by age for Type 3B composite built on old CRC: (a) using PCI, (b) using PCI-2

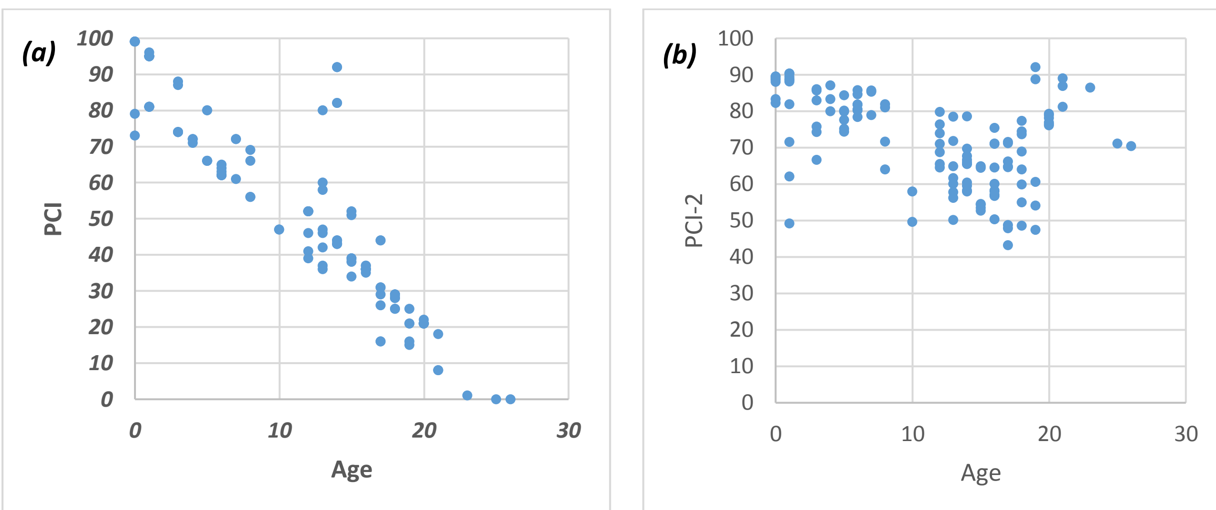
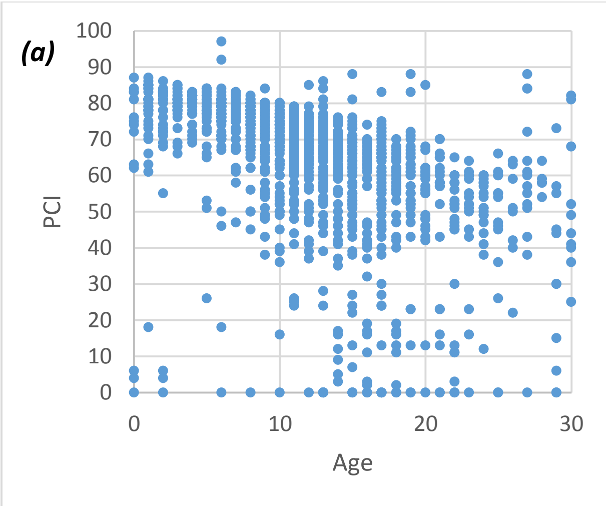


Figure 52. Deterioration of pavement condition by pavement age for AC Type 4-Interstate: (a) using PCI, (b) using PCI-2



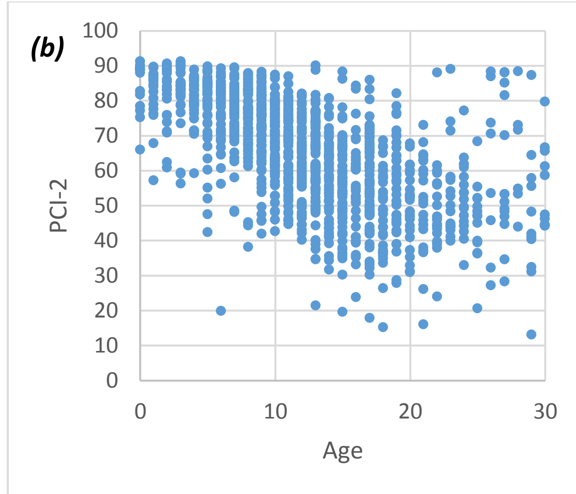


Figure 53. Deterioration of pavement condition by pavement age for AC Type 4-Primary: (a) using PCI, (b) using PCI-2

5. SUMMARY AND RECOMMENDATIONS

The aim of this study was to establish a new system to assess and rate the condition of Iowa pavements. The Iowa PMIS database stores data relating to every aspect of pavement and data are updated annually. The Iowa DOT uses a Pavement Condition Index (PCI) as an overall rating of pavement condition. The current PCI is calculated using statistical regression equations that include variables differing for pavement families: the input may vary from traffic data to materials property.

In this study, a data set of 11,795 data points that include pavement sections from 1998 through 2012 was created.

Five individual indices on a scale of 100 were established based on the distress type with a Cracking Index, Riding Index, Rutting Index, Faulting Index, and Friction Index. The Cracking Index was formed combining the Transverse, Longitudinal, Wheel-path, and Alligator Cracking sub-indices, based on the pavement type.

The Cracking Index is composed of 60% transverse cracking and 40% longitudinal cracking for PCC pavements and, similarly, 20% transverse cracking, 10% longitudinal cracking, 30% wheel-path cracking, and 40% alligator cracking for AC surfaces. Furthermore, the Riding, Rutting, and Faulting indices utilize roughness, rut depth, and fault height, respectively. An overall pavement condition index, PCI-2, is established by combining individual indices with weight factors:

$$\text{PCI-2}_{PCC} = 0.40 \times (\text{Cracking Index}) + 0.40 \times (\text{Riding Index}) + 0.20 \times (\text{Faulting Index})$$

$$\text{PCI-2}_{AC} = 0.40 \times (\text{Cracking Index}) + 0.40 \times (\text{Riding Index}) + 0.20 \times (\text{Rutting Index})$$

The researchers compared PCI-2 results to PCI results and found that, in general, PCI-2 offers fairly good correlation to PCI condition results, particularly, for the pavement types where PCI utilizes distress and roughness data. The poorly related ones are due to the fact that some of the current PCI is heavily characterized by pavement age with various other data, such as material property and traffic and is characterized less than PCI-2 by the pavement distress and roughness data.

The information in the database was accepted as it is; so, there was no effort to improve the data quality, such as removing the outliers, and data screening for the new equation was kept to a minimum.

There are sections where the PCI and PCI-2 are in disagreement by more than 30 to 40 points. Similarly, there are very old sections showing extremely high PCI values and young ones with low values. These sections could be investigated further to improve data quality and, therefore, PCI-2.

Moreover, PCI-2 offers a dynamic model that can be further tweaked based on response from the field (such as modifying the weight factors for combination indices). Furthermore, PCI-2 is currently based on distress (cracking, rutting, faulting) and roughness and additional input such as patching and structural soundness could be added.

REFERENCES

American Association of Highway Transportation Officials. *AASHTO Transportation Asset Management Guide–A Focus on Implementation*, AASHTO, Washington DC, 2011.

Carey, W. N., and P. E. Irick. The Pavement Serviceability–Performance Concept. *Highway Research Bulletin 250*, Highway Research Board, Washington, DC, 1962.

McNeil, S., M. Markow, L. Neumann, J. Ordway, and D. Uzarski. Emerging Issues in Transportation Facilities Management. *Journal of Transportation Engineering*, 1992, 118(4): 477-495.

ODOT. *2012 Pavement Condition Report*, Oregon Department of Transportation, Pavement Services Unit, Salem, OR, 2012.

PB Consult Inc., PricewaterhouseCoopers LLP, Cambridge Systematics Inc., and NuStats Inc. *A Review of DOT Compliance with GASB 34 Requirements*. NCHRP Report 522, Transportation Research Board, Washington, DC, 2004.

Shahin, M. Y., M. I. Darter, and S. D. Kohn. Condition Evaluation of Jointed Concrete Airfield Pavement. *Transportation Engineering Journal*, 1980, 106(4): 381-399.

Shahin, M. Y., M. I. Darter, and S. D. Kohn. Pavement Condition Evaluation of Asphalt Surfaced Airfield Pavements. *Proc., Association of Asphalt Paving Technology*, 1978, Vol. 47-78, pp. 190.

REFERENCES FOR TABLE 3

Bandini, P., S. B. Halter, K. R. Montoya, H. V. Pham, and G. C. Migliaccio. *Improving NMDOT's Pavement Distress Survey Methodology and Developing Correlations between FHWA's HPMS Distress Data and PMS Data*. Report NM10MNT-01, New Mexico State University, Las Cruces, NM, 2012.

California Department of Transportation. *2011 State of the Pavement Report*, California Department of Transportation, Division of Maintenance, Pavement Program, Sacramento, CA, 2011.

Flora, W. F., G. P. Ong, and K. C. Sinha. *Development of a Structural Index as an Integral Part of the Overall Pavement Quality in the INDOT PMS*. Report FHWA/IN/JTRP-2010/11, Purdue University, West Lafayette, IN, 2010.

Florida Department of Transportation. *Flexible Pavement Condition Survey Handbook*, Florida Department of Transportation, State Materials Office, Tallahassee, FL, 2012.

Florida Department of Transportation. *Rigid Pavement Condition Survey Handbook*, Florida Department of Transportation, State Materials Office, Tallahassee, FL, 2012.

George, K. P. *MDOT Pavement Management System: Prediction Models and Feedback System*. Report FHWA/MS-DOT-RD-00-119, University of Mississippi, Jackson, MS, 2000.

Gharaibeh, N. G., T. Freeman, A. Wimsatt, and Y. Zou. *Evaluation and Development of Pavement Scores, Performance Models and Needs Estimates for the TxDOT Pavement Management Information System: Phase I*. Report FHWA/TX-11/0-6386-2, Texas Transportation Institute, College Station, TX, 2011.

Gransberg, D., M. Zaman, and B. Aktas. *Performance Analysis of Aggregate/Binder Combinations Used for the ODOT Chip Seal Program*. Report FHWA-OK-10-03, University of Oklahoma, Norman, OK, 2010.

Heckel, L., and Y. Ouyang. *Update of Condition Rating Survey (CRS) Calculation/Prediction Models*. Report FHWA-ICT-07-012, Heckel Engineering, Research & Education, Inc., Springfield, IL, 2007.

Idaho Transportation Department. *Idaho Transportation System Pavement Performance Report*, Idaho Transportation Department, Division of Highways, Transportation System Section, Boise, ID, 2012.

Jackson, N. C. *Development of Revised Pavement Condition Indices for Portland Cement Concrete Pavement for the WSDOT Pavement Management System*. Report WA-RD 682.3, Washington State Transportation Center, Seattle, WA, 2008.

Khattak, M. J., G. Y. Baladi, Z. Zhang, and S. Ismail. A Review of the Pavement Management of the State of Louisiana, Phase-I. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2084, 2008, pp. 18-27.

Kreis, D., and L. O'Connell. *Kentucky Highway Rating System*. Report KTC-02-30/SPR-256-01-1F, Kentucky Transportation Center, Lexington, KY, 2003.

Massachusetts Department of Transportation. *MassDOT Highway Division ScoreCard*, Massachusetts Department of Transportation, Highway Division, Boston, MA, 2011.

Minnesota Department of Transportation. *Mn/DOT Distress Identification Manual*, Minnesota Department of Transportation, Pavement Management Unit, Saint Paul, MN, 2003.

Missouri Department of Transportation. *Missouri Guide for Pavement Rehabilitation*. Report RDT 02-013, Missouri Department of Transportation, Jefferson City, MO, 2002.

Montana Department of Transportation. *Roadway System Performance: Policy Paper*, Montana Department of Transportation, Helena, MT, 2007.

Morian, D. A., and G. C. Cumberledge. Techniques for Selecting Pavement Rehabilitation Strategies Pennsylvania Case Studies. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1568, 1997, pp. 131-138.

Nebraska Department of Roads. *State of Nebraska Pavement Management Systems*, Nebraska Department of Roads, Lincoln, NE, 2009.

New York State Department of Transportation. *NYSDOT Network Level Pavement Condition Assessment*, New York State Department of Transportation, Albany, NY, 2010.

Oregon Department of Transportation. *2012 Pavement Condition Report*, Oregon Department of Transportation, Pavement Services Unit, Salem, OR, 2012.

Papagiannakis, A., N. Gharaibeh, J. Weissmann, and A. Wimsatt. *Pavement Scores Synthesis*. Report FHWA/TX-09/0-6386-1, Texas Transportation Institute, College Station, TX, 2009.

Reza, F., K. Boriboonsomsin, and S. Bazlamit. *Development of a Composite Pavement Performance Index*. Report ST/SS/05-001, Ohio Northern University, Ada, OH, 2005.

South Dakota Department of Transportation. *Visual Distress Survey Manual*, South Dakota Department of Transportation, Pierre, SD, 2009.

Sweeney, K. L. MaineDOT View. *Maine Trails Magazine*, February - March 2011.

Timm, D. H., and J. M. McQueen. *A Study of Manual vs. Automated Pavement Condition Surveys*. Report IR-04-01, Highway Research Center, Auburn University, Auburn, AL, 2004.

Utah Department of Transportation. *Pavement Preservation Manual – Part 4: Pavement Condition Modeling with dTIMS*, Utah Department of Transportation, Office of Asset Management, 2009.

Villanueva, C., and W. Jensen. *Pavement Quality Indicators*. Report SPR- P1 (13), University of Nebraska, Lincoln, NE, 2013.

Virginia Department of Transportation. *State of the Pavement 2009*, Virginia Department of Transportation, Maintenance Division, Richmond, VA, 2010.

Wisconsin Department of Transportation. *MAPSS Performance Dashboard Report*, Wisconsin Department of Transportation, Madison, WI, 2012.

Zaghloul, S., K. Helali, and W. Bekheet. *Development and Implementation of Arizona Department of Transportation (ADOT) Pavement Management Systems (PMS).* Final Report 494, Arizona Department of Transportation, Phoenix, AZ, 2006.

Zheng, Q., and D. P. Racca. *Support of Pavement Management Systems at the Delaware Department of Transportation*, Center for Applied Demography and Survey Research, University of Delaware, Newark, DE, 1999.