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Calibration of WVDOH IRI-based PSI and SCI Equations

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16. Abstract

The West Virginia Department of Transportation – Division of Highways (WVDOH) uses a condition assessment manual, which engages various indices combining broad categories of distresses for evaluating asphalt/concrete pavements. The indices assist WVDOH in planning pavement management strategies in a cost-effective and timely manner. Therefore, the reliability of the condition evaluation information is essential for WVDOH to develop credible pavement management strategies. However, it has been over 20 years since the manual's development in 1997. WVDOH observed a few issues with some of the indices, particularly the present serviceability index (PSI) and structural cracking index (SCI), as follows: (1) inconsistency between the smoothness acceptance limits expressed in international roughness index (IRI) and PSI values estimated from the IRI limits and (2) the current SCI equation heavily favoring lower cracking severities since the use of automated data collection vehicles. This project was conducted to calibrate the current WVDOH PSI and SCI equations to resolve these issues. Phase 1 of this project calibrated the current PSI equation by comparing the two sets of IRI values calculated from the golden-car parameters and the quarter-car parameters of model passenger vehicles found in the literature review. The current SCI equation was calibrated in Phase 2 by analyzing the historical alligator and longitudinal crack data collected from 1998 to 2021. The results of this project will provide WVDOH with the potential to handle the issues and an opportunity to enhance the state's pavement management practices. Also, the approaches used in this project can be applied to other transportation agencies with similar issues as cost-effective methods to calibrate outdated pavement condition indices.

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Table of Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

BACKGROUND

West Virginia Department of Transportation – Division of Highways (WVDOH) uses a condition assessment manual, *Composite Condition Index for West Virginia DOT*, which engages various indices combining broad categories of distresses for evaluating asphalt/concrete pavements. The indices assist WVDOH in planning pavement management strategies in a cost effective and timely way. Therefore, the reliability of the condition evaluation information is essential for WVDOH to develop credible pavement management strategies. However, WVDOH has had a few issues regarding the applicability of the manual that was first developed in 1997, more than 20 years ago. Among the issues, WVDOH needs to take immediate actions to calibrate the indices for the present serviceability index (PSI) and structural cracking index (SCI) due to the following reasons:

- PSI was developed to predict present serviceability rating (PSR), which is a mean of individual ratings (i.e., from 0 to 5, where "0" represents very poor and "5" is very good) made by a panel of highway users on the ride quality of a given pavement section (Carey and Irick 1960, Janoff et al. 1985, Karaşahin and Terzi 2014). With the advent of the international roughness index (IRI), the most reliable pavement roughness measurement as a worldwide standard (Arhin et al. 2015), various correlations between IRI and PSI were presented. WVDOH has adopted the mathematical equation, Eq. 1, to convert IRI to PSI since 1997.

$$PSI = 5 \times e^{-0.0041 \times IRI}\text{, where } IRI \text{ in inches per mile} \qquad \text{Eq. 1}$$

- WVDOH applies PSI for general design decisions for the state's asphalt and concrete pavements. WVDOH recommends a PSI of 4.2, at which the IRI is equivalent to 42.5 inches/mile by Eq. 1 as the initial performance quality for new pavement design (WVDOH 2014). However, there is an inconsistency between the smoothness acceptance limits for some of WVDOH's paving practices and the PSIs translated for the IRI limits, as shown in Table 1.

Table 1. Acceptable smoothness limits for new asphalt overlays (WVDOH 2017).

Total New Pavement Thickness	Smoothness Limit	Converted PSI
3–4 inches	≤ 81 inches/mile	≤ 3.59
> 4 inches	≤ 65 inches/mile	≤ 3.83

- The PSR descriptions approved by the Federal Highway Administration (FHWA) define pavement surfaces of less than 4.0 inches as a starting point for visible signs of surface deterioration (e.g., rutting and fine random cracks for flexible pavements, minor cracks and spalling for rigid pavements) (FHWA 2016). According to the converted PSI values equivalent to the smoothness limits in Table 1, most of the new overlays have preservation needs for the year when they are constructed. Also, the synthesis study by Merritt et al. (2015) finds that the acceptable IRI values for new asphalt and concrete pavements range from 52 to 66 inches/mile (= 4.04 to 3.81 PSI) and from 57 to 72 inches/mile (= 3.96 to 3.72 PSI), respectively. It suggests that contractors are not building pavements with smoothness levels that are expected during design (i.e., a PSI of 4.2). Alternatively, and possibly more reasonably, there is an issue with the equation for estimating PSI from IRI.
- SCI is calculated based on the severity (e.g., low, medium, and high) and extent of the alligator and longitudinal cracking percentages in asphalt pavements. The crack extent is represented as the percentage of wheel-path areas affected by the cracks. The crack extent observed in three different severities is then calculated to the discrete SCI ratings using Eq. 2,

$$SCI = 5 - 0.21 \times AL^{0.67} - 0.24 \times AM^{0.69} - 0.40 \times AH^{0.80} - 0.28 \times LL^{0.73} - 0.32 \times LM^{0.75} - 0.60 \times LH^{0.89} \qquad \text{Eq. 2}$$

  where *AL*, *AM*, and *AH* are alligator low, medium, and high, respectively, and *LL*, *LM*, and *LH* are longitudinal low, medium, and high severity, respectively. The ratings range from 0 to 5, with “5” being the upper limit representing no distress. However, the current SCI equation favors heavily the lower cracking severities, because automated data collection vehicles in use by WVDOH are generally capable of capturing much more low- and medium-severity cracking. It results in rating SCI so low due to the low- and medium-severity cracking being overmeasured and falling in the pavement sections in early consideration for rehabilitation.

OBJECTIVES

The objective of this project was to calibrate the existing PSI and SCI equations to address the WVDOH’s needs for consistent pavement design and management decisions. The two existing equations were calibrated in two separate, consecutive phases: Phase 1 for the IRI-based PSI equation and Phase 2 for the SCI equation.

DATA AND DATA STRUCTURES

The data types utilized to calibrate the IRI-based PSI equation in Phase 1 were retrieved from two National Cooperative Highway Research Program (NCHRP) reports, NCHRP Reports 275 (Janoff et al., 1985) and 308 (Janoff, 1988), for the panel ratings and road profiles. The road profiles were the primary inputs to generate IRI values through the transition codes presented in the technical documents of Sayers (1995) and Sayers and Karamihas (1996). Also, a comprehensive literature review collected the quarter-car parameters of modern passenger vehicles. On the other hand, the data for the SCI equation data in Phase 2 were provided by WVDOH, including the alligator and transverse crack data collected from the years 1998, 2000, 2002, 2008, 2010, 2011, 2013, 2014, 2015, 2016, 2017, 2018, and 2021. The authors would like to thank Mr. Michael Troyan, P.E., head of the Asset Management Section, and Mr. Jacob Bumgarner, P.E., director of the Maintenance Division at WVDOH, for their help in obtaining the SCI-related data.

CHAPTER 2

Methodology

INTRODUCTION

This section describes the methodology used to calibrate the PSI and SCI equations through two separate phases, Phases 1 and 2. Figure 1 shows the overall methodology for these two phases.

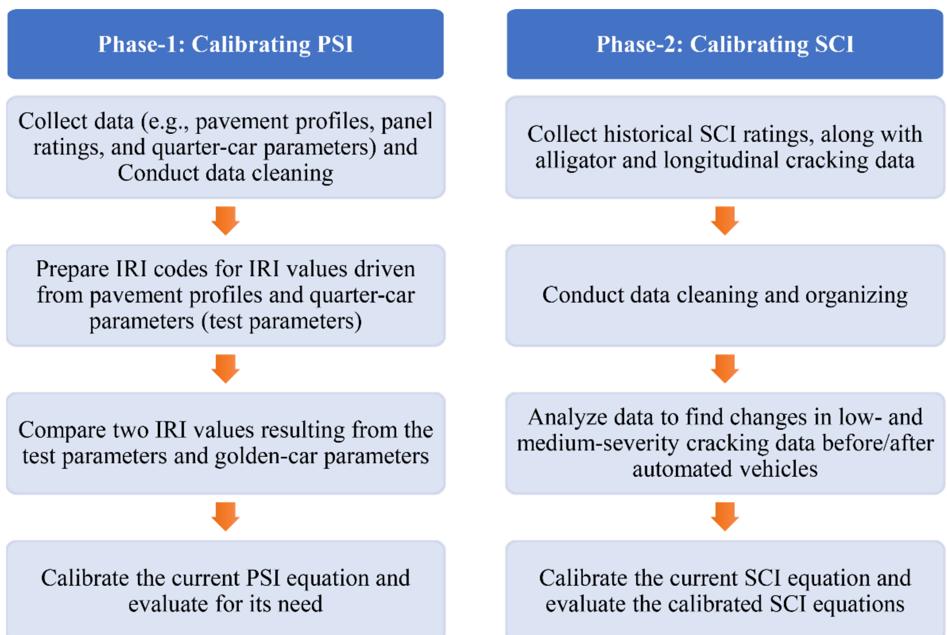

Figure 1. Overall methodology.

PHASE 1: CALIBRATING PRESENT SERVICEABILITY INDEX (PSI) EQUATION

Data Collection and Cleaning

The data types used to calibrate the current PSI equation were road profiles, panel ratings, and quarter-car parameters. These data types are defined as follows: road profiles measure the smoothness of pavement surfaces; panel ratings are the PSR inputs from field test participants driving on test pavement sections; and quarter-car parameters are the mechanical properties of sprung mass (m_s), unsprung mass (m_u), suspension spring rate (k_s), tire spring rate (k_t), and suspension damping coefficient (c_s) in a quarter-car suspension design, as shown in Figure 2. The NCHRP Reports 275 and 308 were the main data sources for profile index (PI) data, which were processed from road profiles, and panel ratings. A comprehensive literature review was conducted for quarter-car parameters. Then, data cleaning for missing and noisy raw data points was conducted for a quality data set for data analysis.

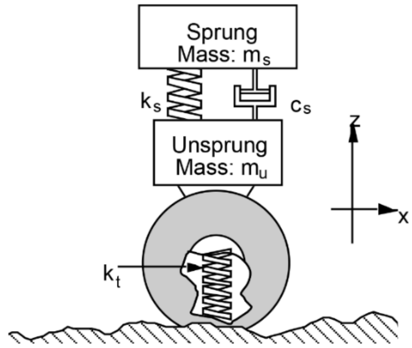

Figure 2. Quarter-car model (Sayers and Karamihas, 1996).

The data collection and cleaning resulted in obtaining a total of 281 data points for road profiles and panel ratings matching each other on the same pavement test sections of three different surface types, such as bituminous concrete (BC), portland cement concrete (PCC), and composite (COMP). The distribution of the data points for each pavement type is illustrated in Figure 3. The number of modern passenger cars found for quarter-car parameters was nine vehicles in various vehicle sizes, from mini to heavy, based on the passenger vehicle categories of the National Highway Traffic Safety Administration (NHTSA). Table 2 shows a list of the quarter-car parameters normalized by sprung masses. The average of the normalized quarter-car parameters was computed to use as test parameters in the data analysis.

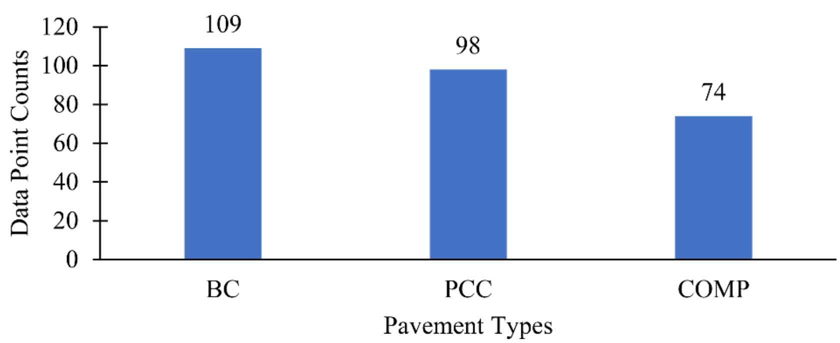

Figure 3. Data point counts for each pavement type.

Table 2. Quarter-car parameters of modern vehicles.

Vehicle Class	Code	Quarter-Car Parameter m_u/m_s	Quarter-Car Parameter k_s/m_s	Quarter-Car Parameter k_t/m_s	Quarter-Car Parameter c_s/m_s
Mini	MN1	0.07	55.41	649.35	4.20
Light	L1	0.14	73.91	727.27	7.75
Light	L2	0.13	113.21	679.25	7.55
Light	L3	0.12	78.91	500.00	4.45
Compact	C1	0.10	42.95	327.18	2.85
Compact	C2	0.13	140.12	598.80	8.98
Medium	M1	0.11	100.65	629.09	5.54
Heavy	H1	0.03	20.14	166.48	2.01
Heavy	H2	0.12	61.7	514.00	8.90
Test Parameters		0.11	76.33	532.38	5.80

IRI Calculation Codes

As the actual IRI data collected with the panel ratings were not available from the two NCHRP reports, the IRI calculation codes were prepared to generate IRI values from the road profile data. The original codes written in Fortran in the technical documents of Sayers (1995) and Sayers and Karamihas (1996) were converted into MATLAB codes. The codes consist of four subroutines, including IRI, SETABC, SETSTM, and STFILT. The IRI subroutine is a master part of computing average IRI values from profile height values, working along with the other three subroutines. The converted IRI codes are presented in the appendix.

Comparison of Two IRI Values

The retrieved PIs ranged from 0.009 to 0.269, increasing by 0.001, and summarized into 12 groups (i.e., PI-1 through PI-12). The number of PI groups was determined by considering the number of data points in each PI group. Table 3 shows the PI values associated with the PI groups. Each PI value was used to generate profile heights, assuming the sample spacing of 6 inches at a one-tenth-mile pavement section, which generated 1,024 profile height points. The profile heights inside the frequencies of 0.125 cycles/ft – 0.630 cycles/ft were used for IRI estimation through the MATLAB codes as the NCHRP studies (Janoff et al. 1985 and Janoff 1988) found that pavement roughness outside the band of the frequencies was not a good predictor of PSI.

Table 3. PI value for each PI group.

PI Group	PI Value (inch)
PI-1	0.010
PI-2	0.015
PI-3	0.020
PI-4	0.025
PI-5	0.030
PI-6	0.035
PI-7	0.040
PI-8	0.045
PI-9	0.050
PI-10	0.060
PI-11	0.070
PI-12	0.080

The filtered profile heights in each PI group were entered into the IRI calculation codes, applying golden-car parameters and test parameters separately. The golden-car parameters are the mechanical properties of a quarter-car suspension system for a reference passenger vehicle showing the most common response to pavement profiles (Loizos and Plati 2008, Lafarge et al. 2016, Liu et al. 2021). State DOTs use the golden-car parameters to convert road profiles into IRI values. The golden-car parameters used for this study are presented as follows:

$m_u/m_s = 0.15$ $\quad$ $k_s/m_s = 63.3$ $\quad$ $k_t/m_s = 653$ $\quad$ $c_s/m_s = 6.0$

The procedures from generating profile heights to calculating IRI values for each group were repeated 30 times for the *t*-test that evaluated the statistical difference between the IRI values from the test and golden-car parameters. Figure 4 shows the average IRI values from the two parameters for each PI group. The t-test conducted for comparison was a one-tailed test at the 95% confidence level, as the IRI values from the test parameter always were less than the golden-car parameters. Table 4 shows the t-test results. The t-critical value for 30 data samples (i.e., the degree of freedom = 29) at a 95% confidence level is 1.699. The t-values for all PI groups were far greater than the t-critical value, which was 1.699 based on the number of 30 data samples and the confidence level of 95%, resulting in extremely low p-values. Thus, it concluded that the IRI values from the test parameters could be used to calibrate the PSI equation in Eq. 1.

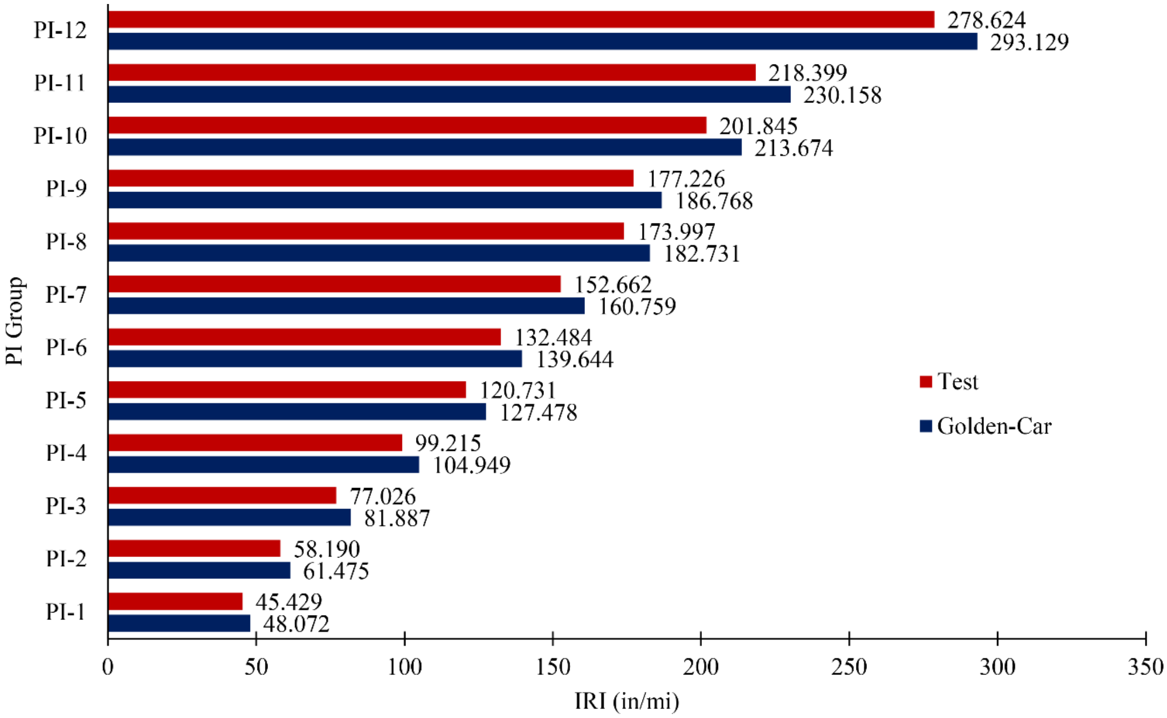

Figure 4. Comparison of average IRI values at each PI group.

Table 4. One-tailed t-test results.

PI Group	*t*-value	*p*-value
PI-1	13.432	2.79E-14
PI-2	15.946	3.43E-16
PI-3	15.497	7.23E-16
PI-4	14.057	8.85E-15
PI-5	14.257	6.18E-15
PI-6	12.842	8.58E-14
PI-7	12.043	4.15E-13
PI-8	11.561	1.11E-12
PI-9	9.8278	4.89E-11
PI-10	11.635	9.55E-13
PI-11	11.545	1.15E-12
PI-12	10.560	9.45E-12

Calibration of the WVDOH PSI Equation

The approach to calibrating the current WVDOH PSI equation took the following steps:

1. The average IRI values of test parameters were applied to Eq. 1 to compute the PSI values for all PI groups.
2. The PSI values were associated with the average IRI values of golden-car parameters at the same PI groups.
3. The power of the exponential component was adjusted, keeping the current exponential function type.

PHASE 2: CALIBRATING STRUCTURAL CRACKING INDEX (SCI) EQUATION

Collection of Historical SCI Ratings and Cracking Data

As the SCI ratings in Eq. 2 are estimated based on percent of wheel-path areas affected by the alligator and longitudinal cracks in three different severity levels such as low, medium, and high, the data collection focused mainly on securing the historical data of SCI ratings and the two types of cracking data. The research team contacted WVDOH to secure the data collected for the state pavement sections through regular pavement inspection practices. The SCI ratings and the associated cracking data were unavailable for all years after 1998, the oldest year of data available in the state pavement management database. The number of target pavement sections varied over the years, depending on the state's pavement performance monitoring cycles. Figure 5 illustrates the number of one-tenth-mile pavement sections in three different highway systems (e.g., interstate (IS), U.S. routes (US), and state routes (WV)) considered for data collection over the years. The raw data from WVDOH were stored in different worksheets in Excel for the years. Each worksheet contained the data fields such as road name (RoadName), section name (SectionID), alligator high (Alli_H), alligator medium (Alli_M), alligator low (Alli_L), longitudinal high (Long_H), longitudinal medium (Long_M), longitudinal low (Long_L), SCI rating (SCI), and highway systems (Sys).

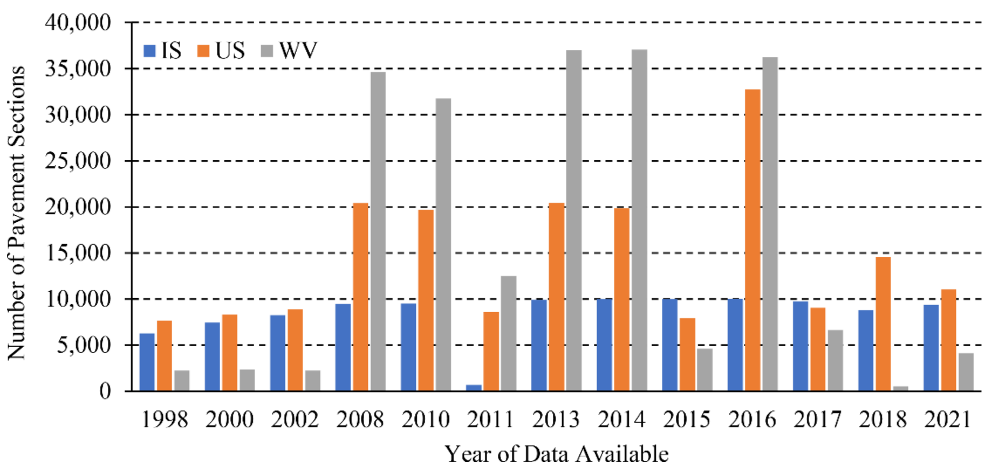

Figure 5. Number of pavement sections of the alligator and longitudinal cracking data.

Data Cleaning and Organizing

The data cleaning removed the duplicate pavement sections and the pavement sections with missing values in any data fields. Also, the correctness of the SCI ratings in the raw datasets was evaluated by recalculating the SCI ratings in Eq. 2 with the associated alligator and longitudinal cracking values. Then, the cleaned data were organized into the measures as follows:

- Average SCI ratings for each highway system (Figure 6)
- Average percentages of alligator cracking in each severity for each highway system (Figure 7, where AH = alligator in high severity, AM = alligator in medium severity, and AL = alligator in low severity)
- Average percentages of longitudinal cracking in each severity for each highway system (Figure 8, where LH = longitudinal in high severity, LM = longitudinal in medium severity, and LL = longitudinal in low severity)

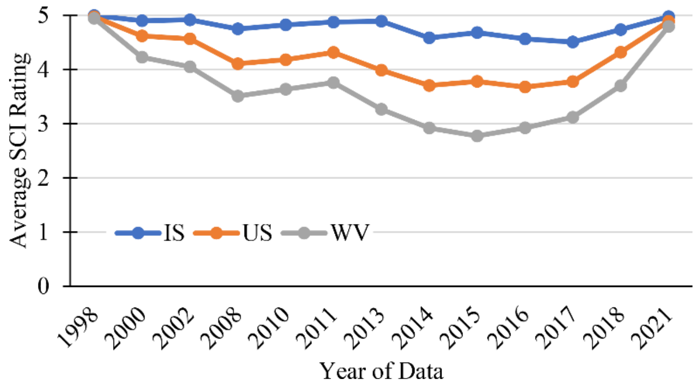

Figure 6. Average SCI ratings for each highway system.

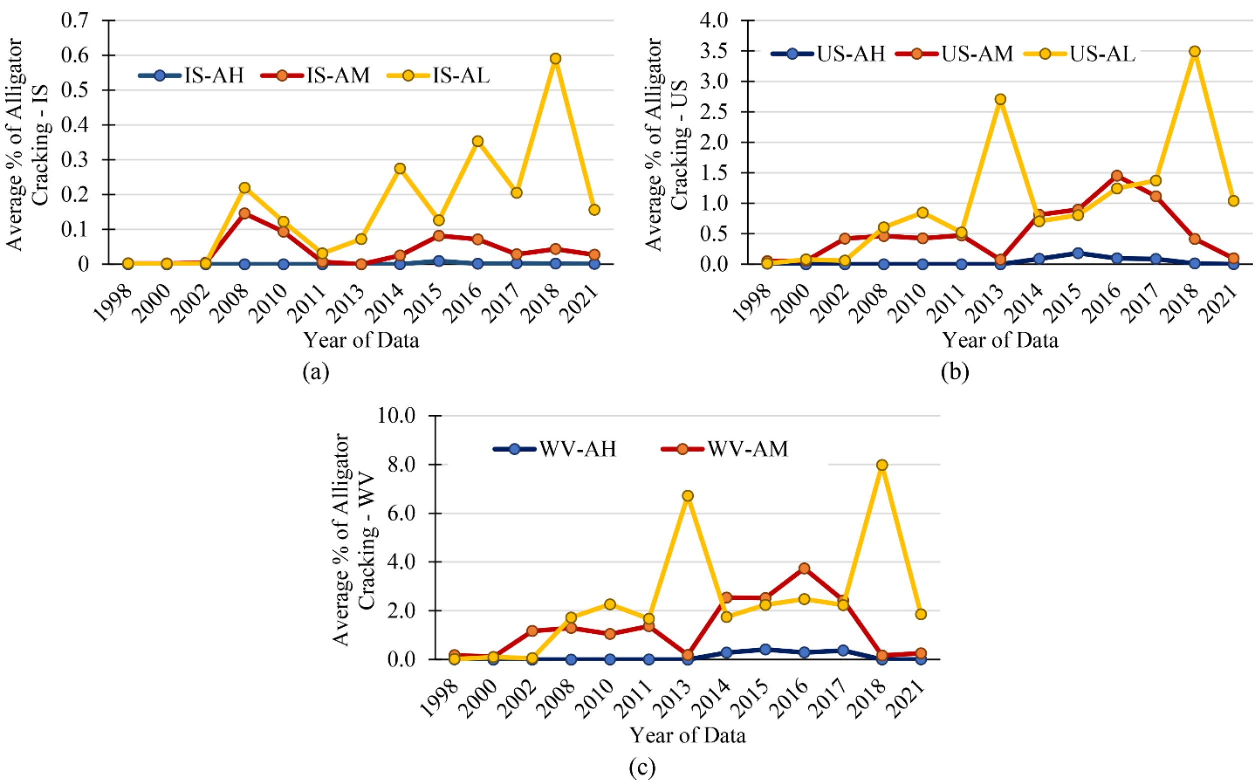

Figure 7. Average percentages of alligator cracking on (a) interstates, b) U.S. routes, and (c) state routes.

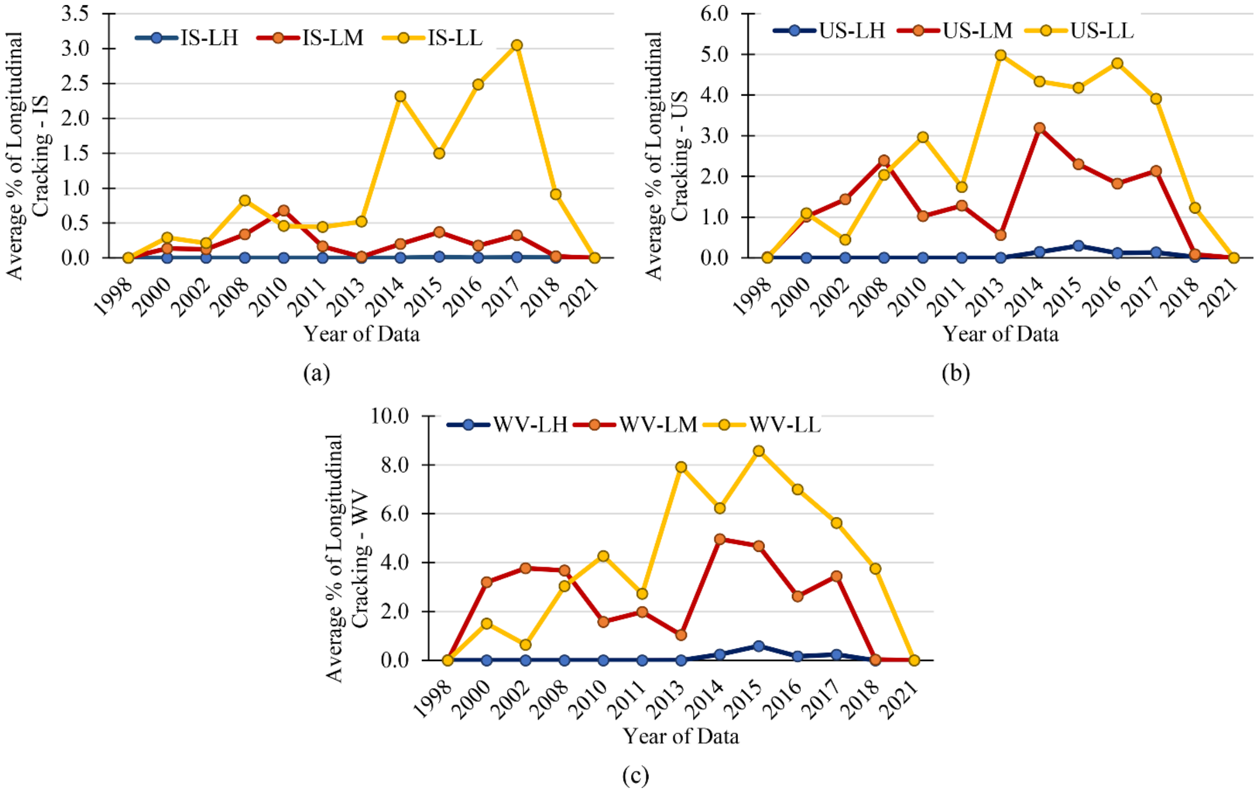

Figure 8. Average percentages of longitudinal cracking on (a) interstates, (b) U.S. routes, and (c) state routes.

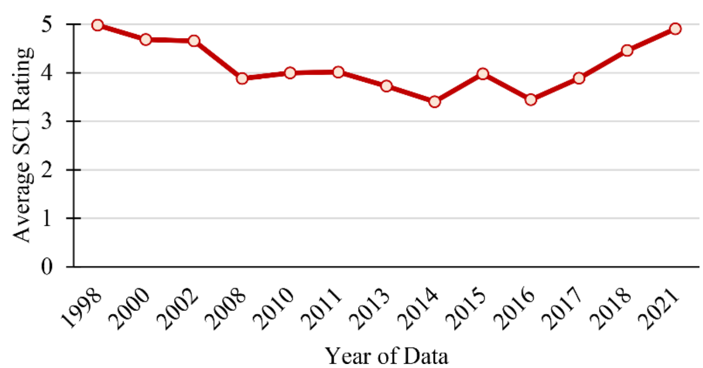

Figure 9. Average SCI ratings for highway systems combined.

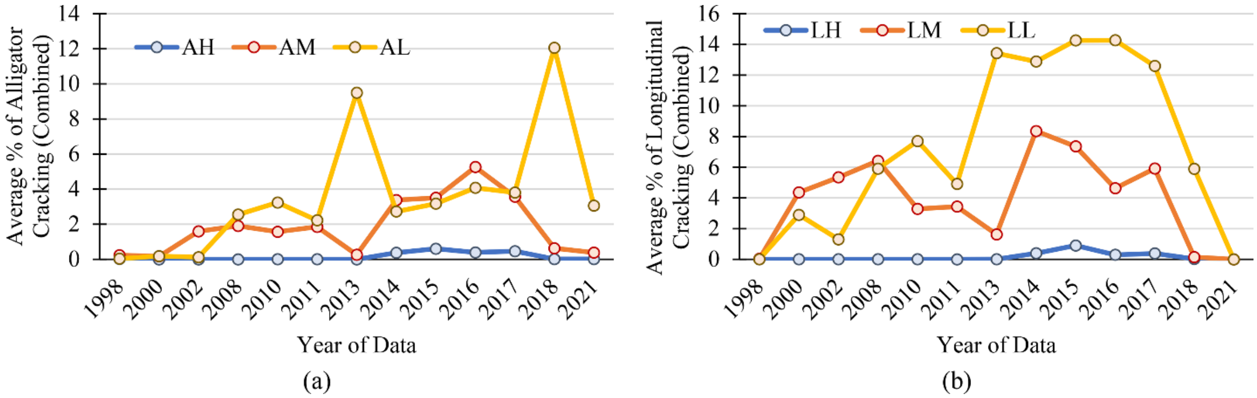

Figure 10. Average percentages of (a) alligator and (b) longitudinal cracking on highway systems combined.

Data Analysis for Cracking Data Changes and Ratios

WVDOH has been observing higher values in low- and medium-severity alligator and longitudinal cracking data since automated data collection vehicles were employed for pavement performance monitoring. The data analysis focused on investigating the changes in cracking data in two severity levels by taking the following steps:

- Process the annual average measures (e.g., average SCI ratings and average percentages of alligator and longitudinal cracking) into the average measures before and after the year of automated data collection vehicles.
- Calculate the changes in the before and after average measures.
- Analyze the ratios of low- and medium-severity cracking changes to high-severity cracking changes.

According to the historical contract records of WVDOH for automatic cracking data collection, the first contract appeared in 2004. The contracts were solicited every 4 to 5 years with three different consultants. As the first year of the contract was not confirmed as the exact year when WVDOH started using an automated data collection vehicle through personal communications with WVDOH, the research team used secondary information in published documents to specify the year. The research report (Timm and McQueen, 2004), prepared for Alabama DOT in 2004, found that WVDOH was collecting pavement performance data on a biannual cycle and planned to do it annually starting from 2003. The report also indicated that the pavement condition data types being collected automatically were IRI and rut. The performance audit report for Ohio DOT in 2021 (Kercher Group, 2021) clarified that West Virginia was using a van equipped with Pavemetrics Laser Crack Measurement System (LCMS) for collecting cracking data on the National Highway System (NHS) annually, non-NHS biennially, and county roads every five years. Considering the WVDOH contract records, secondary information, and the years of data collected from the WVDOH database, it was reasonable for the research team to assume that the automated data collection vehicle for cracking data was introduced in 2004.

Table 5 shows the changes in the weighted average SCI ratings before and after 2004 by highway systems. The weighted average SCI ratings were computed by applying annual weights of different numbers of pavement sections to annual average SCI ratings. Table 6 and Table 7 show the changes in the weighted average alligator and longitudinal cracking data before and after 2004, respectively. The ratios of the changes in the low- and medium-severity cracking to the change in the high-severity cracking were estimated for alligator and longitudinal cracks separately in Table 6 and Table 7. The changes showed a higher increase in the low- and medium-severity cracking data compared to the changes in the high-severity cracking data for both alligator and longitudinal across all highway systems. The ratio results clearly indicated a greater increase in the low-severity cracking data for both alligator and longitudinal compared to the medium-severity cracking data. The increase was more prominent on the pavement section of the interstate highway system.

Table 5. Changes in the weighted average SCI ratings before and after 2004 by highway systems.

Highway System	Before 2004	After 2004	Change +/-
IS	4.94	4.72	-4.29%
US	4.71	4.02	-14.76%
WV	4.41	3.29	-25.35%

Table 6. Changes in the weighted average alligator cracks and ratios by highway systems.

Highway System-Crack Severity	Before 2004	After 2004	Change +/-	Ratio over AH
IS-AH	0.00005	0.00186	+0.0018	1.00
IS-AM	0.00323	0.05687	+0.0536	29.64
IS-AL	0.00204	0.23062	+0.2286	126.29
US-AH	0.00281	0.04543	+0.0426	1.00
US-AM	0.18405	0.67789	+0.4938	11.59
US-AL	0.05292	1.36691	+1.3140	30.83
WV-AH	0.00395	0.12589	+0.1219	1.00
WV-AM	0.47932	1.75867	+1.2794	10.49
WV-AL	0.06094	2.88981	+2.8289	23.20

Table 7. Changes in the weighted average longitudinal cracks and ratios by highway systems.

Highway System-Crack Severity	Before 2004	After 2004	Change +/-	Ratio over LH
IS-LH	0.00005	0.00385	+0.0038	1.00
IS-LM	0.09248	0.23704	+0.1446	38.04
IS-LL	0.1785	1.3523	+1.1738	308.89
US-LH	0.00056	0.06538	+0.0648	1.00
US-LM	0.8593	1.5421	+0.6828	10.53
US-LL	0.52614	3.32101	+2.7949	43.12
WV-LH	0.00058	0.09673	+0.0962	1.00
WV-LM	2.34985	2.75543	+0.4056	4.22
WV-LL	0.73564	5.52125	+4.7856	49.77

The data analysis shown in Table 5 through Table 7 also was performed for the combined highway systems, which are presented in Table 8 through Table 10.

Table 8. Change in the weighted average SCI ratings before and after 2004 for the combined highway system.

Highway System	Before 2004	After 2004	Change +/-
All	4.76	3.83	-19.71%

Table 9. Changes in the weighted average alligator cracks and ratios for the combined highway systems.

Severity of Alligator Crack	Before 2004	After 2004	Change +/-	Ratio over AH
AH	0.00644	0.18112	0.1747	1.00
AM	0.7029	2.43379	1.7309	9.91
AL	0.11684	4.56359	4.4468	25.46

Table 10. Changes in the weighted average longitudinal cracks and ratios for the combined highway systems.

Severity of Longitudinal Crack	Before 2004	After 2004	Change +/-	Ratio over LH
LH	0.00117	0.17686	0.1757	1.00
LM	3.40859	4.46989	1.0613	6.04
LL	1.45013	10.13965	8.6895	49.46

Calibration of the WVDOH SCI Equation and Evaluation

The approach to calibrating the current WVDOH SCI equation and evaluating the possibility of combining the calibrated SCI equations took the following steps:

1. The ratios of low- and medium-severity cracking data were normalized to calculate their contributions to the changes in weighted average SCI ratings.
2. The coefficients of low- and medium-severity cracks in Eq. 2 were adjusted by multiplying (1 + contributions) by the current coefficients.
3. Statistical analysis was conducted to evaluate the SCI equations calibrated for different highway systems for combining.

Table 11 through Table 13 show the results of the first step. For example, for the interstate highway system (IS), the ratios of the low- and medium-severity alligator and longitudinal cracks in Table 6 and Table 7 were normalized by their total of 502.86 (= 126.29 + 29.64 + 308.89 + 38.04), resulting in 0.251 for AL, 0.059 for AM, 0.614 for LL, and 0.076 for LM in Table 11. Then, the normalized ratios were multiplied by the SCI rating change, which was -4.29% for IS in Table 5. Thus, the sum of the contributions in the last column in Table 11 should be equal to the SCI rating change.

Table 11. Normalized ratios and contributions to SCI change for interstate.

Crack Severity	Ratio over H-Severity	Normalized Ratio	Contribution to SCI Change
AL	126.29	0.251	-1.08%
AM	29.64	0.059	-0.25%
LL	308.89	0.614	-2.64%
LM	38.04	0.076	-0.32%

Table 12. Normalized ratios and contributions to SCI change for U.S. routes.

Crack Severity	Ratio over H-Severity	Normalized Ratio	Contribution to SCI Change
AL	30.83	0.321	-4.74%
AM	11.59	0.121	-1.78%
LL	43.12	0.449	-6.62%
LM	10.53	0.110	-1.62%

Table 13. Normalized ratios and contributions to SCI change for state routes (WV).

Crack Severity	Ratio over H-Severity	Normalized Ratio	Contribution to SCI Change
AL	23.20	0.265	-6.71%
AM	10.49	0.120	-3.03%
LL	49.77	0.568	-14.39%
LM	4.22	0.048	-1.22%

CHAPTER 3

Findings

CALIBRATED PSI EQUATION AND EVALUATION

Following the approach to calibrating the current WVDOH PSI equation, the PSI values of the test parameters were associated with the average IRI values of golden-car parameters at the same PI groups, as shown in Table 14. The PSI values for the average IRI values from the test parameters (see Figure 4) were calculated using Eq. 1. For example, the average IRI value in PI-1 was 45.429 for the test parameters, and the PSI value was 4.15 by Eq. 3. Then, the PSI value was associated with the average IRI value of golden-car parameters, which was 48.072.

$$PSI = 5 \times e^{-0.0041 \times IRI} = 5 \times e^{-0.0041 \times 45.429} = 4.150293 \approx 4.15 \qquad \text{Eq. 3}$$

Table 14. PSI values from the golden-car and test parameters.

IRI (in/mile)	PSI from the Golden-Car Parameters	PSI from the Test Parameters
0.000	5	5
48.072	4.11	4.15
61.475	3.89	3.94
81.887	3.57	3.65
104.949	3.25	3.33
127.478	2.96	3.05
139.644	2.82	2.90
160.759	2.59	2.67
182.731	2.36	2.45
186.768	2.32	2.42
213.674	2.08	2.19
230.158	1.95	2.04
293.129	1.50	1.60

The PSI values in Table 14 are graphically illustrated in Figure 11, showing the calibrated PSI equation, PSI^*, in Eq. 4.

$$PSI^* = 5 \times e^{-0.00389 \times IRI} \qquad \text{Eq. 4}$$

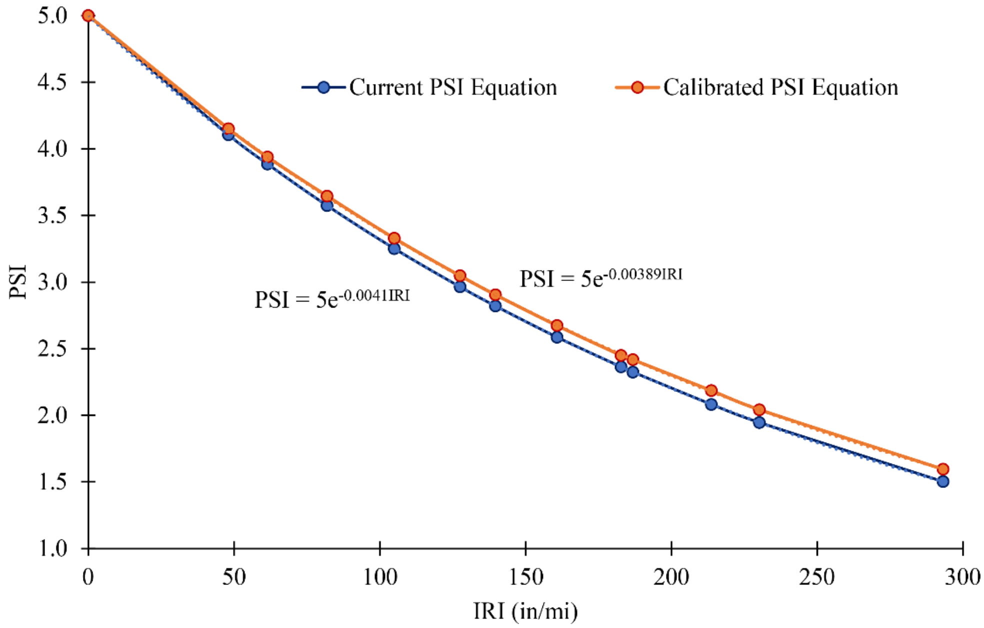

Figure 11. Current and calibrated PSI equations.

The evaluation of the calibrated PSI equation investigated the consistency between IRI requirements for new pavements and the FHWA PSR definitions. Using the current PSI equation, the average IRI limits of many states for new asphalt and concrete (i.e., 66 inches/mi for asphalt and 72 inches/mi for concrete) are translated to 3.81 PSI and 3.72 PSI, respectively. The translated PSI values indicate that the new pavements might have a maintenance need in the year when they are constructed. The calibrated PSI equation estimates the same average IRI limits as 3.87 PSI for asphalt and 3.78 PSI for concrete, which are slightly higher than the current PSI equation but still show an inconsistency between the IRI acceptance limits for new pavements and the FHWA definitions for PSR values. Based on the evaluation results, the calibrated PSI equation is insufficient to solve the inconsistency. However, this study found that there is still a need to calibrate the current PSI equation based on a statewide field survey for PSR and IRI data for the following two reasons:

- Advanced suspension systems of modern passenger cars to make drivers feel more comfortable today, as the current PSI equation was developed based on data collected in the 1980s
- Even a slight increase in acceptable ride quality (i.e., an IRI of 170 inches/mi) from the calibrated PSI equation for significant cost savings in pavement rehabilitation

Regarding the second reason in more detail, this study estimated the rehabilitation cost savings from the calibrated PSI equation as $592,957,200 per year. The IRI of 170 inches/mi at 2.5 PSI, which is the FHWA criterion for acceptable pavement ride quality, was equivalent to 178.2 inches/mi by the calibrated PSI equation. The FHWA's *Highway Statistics 2019* (https://www.fhwa.dot.gov/policyinformation/statistics/2019/) recorded 6,941 miles on the NHS in an IRI range of 171–194 inches/mi. Assuming the NHS miles in the range were equally distributed, the increased IRI by the calibrated PSI equation rated an additional 31.3% (= (178.5 – 171.0) × (194 – 171) × 100%) of the NHS miles in the IRI range as acceptable ride quality. As a result, the rehabilitation cost savings for the percentage of the NHS miles newly rated as an acceptable ride quality were estimated as shown in Table 15.

Table 15. Rehabilitation cost savings due to the increased acceptable IRI threshold.

Item	Cost ($)	Note
Unit rehabilitation cost per mile	34,078,000	Rehabilitation cost per square yard: $11, from FHWA (2015)
Rehabilitation total for additional NHS miles	592,957,200	Addition NHS miles: 6,941 miles × 31.3% Average lanes per mile: 3.54 lanes/mile Width per lane: 12 feet Additional NHS area: 17.4 mi^2

CALIBRATED SCI EQUATION AND EVALUATION

The coefficients of the low- and medium-severity crack terms in Eq. 2 were calibrated for each highway system. Table 16 shows the calibrated coefficients, along with the coefficients of the current SCI equation. The coefficients are displayed in three decimal places to clarify their differences.

Table 16. Coefficients of current and calibrated SCI equations.

Term	Current SCI	Calibrated for IS	Calibrated for US	Calibrated for WV
AL	-0.210	-0.208	-0.200	-0.196
AM	-0.240	-0.239	-0.236	-0.233
AH	-0.400	-0.400	-0.400	-0.400
LL	-0.280	-0.273	-0.261	-0.240
LM	-0.320	-0.319	-0.315	-0.316
LH	-0.600	-0.600	-0.600	-0.600

The SCI equations calibrated for each highway system were evaluated for combining each other through hypothesis testing using a paired two-sample t-test for means in Excel. The hypothesis test used the 2016 cracking data, which included the most diverse values of low-, medium-, and high-severity alligator and longitudinal cracks, to generate the SCI ratings from each calibrated SCI equation. The null hypothesis was that there was no difference between the two sample means in comparison at the confidence level of 95%. Table 17 shows the test results of t-statistics and p-values. Based on the p-values, the null hypotheses for all comparisons were rejected, indicating the SCI equations calibrated for each highway system were statistically significant as the separate equations, as shown in Eq. 5 through Eq. 7.

Table 17. Hypothesis test results.

Comparison	t	$p > \|t\|$
IS-US	-211.977	0.000
IS-WV	-213.883	0.000
US-WV	-210.550	0.000

$$SCI^{*} \text{ for IS} = 5 - 0.208 \times AL^{0.67} - 0.239 \times AM^{0.69} - 0.400 \times AH^{0.80} - 0.273 \times LL^{0.73} - 0.319 \times LM^{0.75} - 0.600 \times LH^{0.89} \quad \text{Eq. 5}$$

$$SCI^{*} \text{ for US} = 5 - 0.200 \times AL^{0.67} - 0.236 \times AM^{0.69} - 0.400 \times AH^{0.80} - 0.261 \times LL^{0.73} - 0.315 \times LM^{0.75} - 0.600 \times LH^{0.89} \quad \text{Eq. 6}$$

$$SCI^{*} \text{ for WV} = 5 - 0.196 \times AL^{0.67} - 0.233 \times AM^{0.69} - 0.400 \times AH^{0.80} - 0.240 \times LL^{0.73} - 0.316 \times LM^{0.75} - 0.600 \times LH^{0.89} \quad \text{Eq. 7}$$

In comparison with the current SCI equation, the calibrated SCI equations generated higher SCI ratings for the pavement sections of lower highway systems (i.e., local level) and with more extensive crack percentages, as shown in Table 18 and Figure 12, respectively. The calibrated SCI equations for the highway systems, IS, US, and WV, increased the SCI ratings by 0.18%, 1.25%, and 4.07% on the 2016 cracking data, respectively. Also, there were upward patterns in the SCI rating percentage increase for the alligator and longitudinal cracks of larger extents.

Table 18. SCI ratings increased by the calibrated SCI equation.

Highway System	Current SCI	Calibrated SCI	After SCI Calibrated	% Increase
IS	4.566	4.574	+0.008	0.18%
US	3.678	3.724	+0.046	1.25%
WV	2.924	3.043	+0.119	4.07%

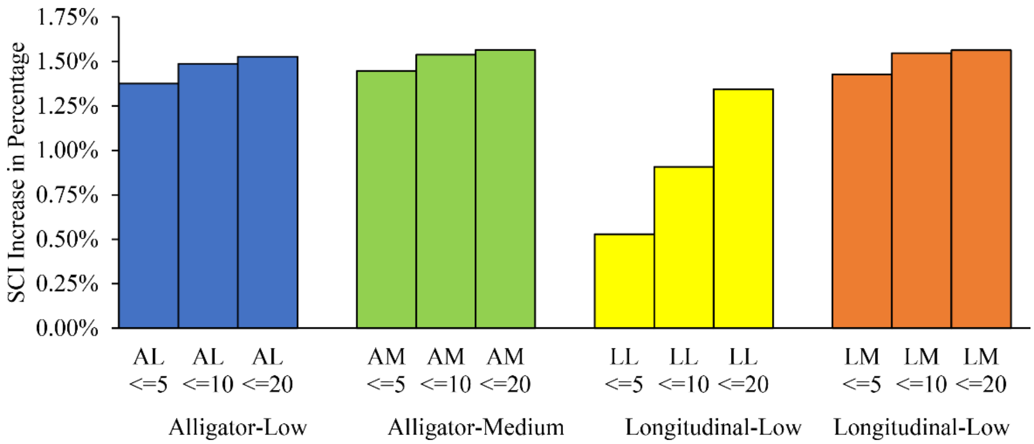

Figure 12. SCI increase in percentages by different crack extensions.

CHAPTER 4

Conclusions and Recommendations

CONCLUSIONS

This research calibrated the two pavement performance indices, PSI and SCI, of WVDOH to address the Department's concerns: (1) inconsistency between the state's IRI-based acceptable smoothness limits for new pavement surfaces and the PSI estimated from the IRI limits and (2) automated data collection vehicles capable of detecting alligator and longitudinal cracks in low- and medium-severity. The current PSI equation was calibrated by recalculating IRI values based on the test quarter-car parameters, given the PIs retrieved from two previous NCHRP reports. The assumption for the primary research approach was that the suspension systems of passenger vehicles had evolved to make highway users feel more comfortable in modern vehicles compared to the vehicles about 30 years ago on the same pavement surface conditions. The WVDOH's SCI equation was calibrated based on the data analysis that focused on capturing the increases in low- and medium-severity crack percentages over high-severity ones before and after the year when the automated data collection vehicles were employed.

The evaluation results showed that the calibrated PSI equation could increase the PSI values by 1.57% for asphalt (i.e., 3.81 PSI → 3.87 PSI) and 1.61% for concrete (i.e., 3.72 PSI → 3.78 PSI), which left the issue of WVDOH with the conversion of IRI to PSI unresolved. However, through the literature review, this research found that there had been technological advancements in the suspension systems (e.g., semi-active and active) and driver assistance systems of modern passenger vehicles to enhance the drivers' ride comfort on highways. Also, the slight increase due to the calibrated PSI equation, which raised the current 170 inches/mi to 178.2 inches/mi, confirmed significant rehabilitation cost savings. On the other hand, the SCI equations calibrated separately for each highway system, IS, US, and WV, were able to generate higher SCI ratings compared to the current SCI equation by adjusting the term coefficients of low and medium cracks lower. The effects of the calibrated SCI equations in increasing SCI ratings were more remarkable for the pavement sections of lower-level highway systems and with more extensive low- and medium-severity percentage cracks. Using the 2016 WVDOH cracking data, the increasing effects in percentages were 0.18% for IS, 1.25% for US, and 4.07% for WV. However, it should be noted that the data analysis to calibrate the WVDOH SCI equation was made on the assumption of the year of automated data collection vehicles applied first.

RECOMMENDATIONS

The findings of this research lead to recommend the following future work for WVDOH:

- A statewide field experiment to collect PSR and IRI data, including passenger vehicles with semi-active and active suspension systems and other technological advancements
- Depending on a newly calibrated PSI equation resulting from a field experiment, the reevaluation of the current WVDOH guideline for the acceptable IRI limits for new pavements
- The application of the confirmed first year of crack data with automated data collection vehicles

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Appendix

IRI Conversion Codes in MATLAB

```
%Provide variable input values
DX=input('Distance step between profile points, in meters?');
BASE=input('Distance covered by moving average, in meters?');
UNITSC=input('Product of two scale facLors: (1) meters per unit of profile height, and↙
(2) IRI units of slope.?');
K1=input('What is the tire spring rate? ');
K2=input('What is the suspension spring rate? ');
C=input('What is the suspension damper rate? ');
MU=input('What is the unsprung mass? ');

%Set parameters and arrays
%SETABC;
[AMAT, BMAT, CMAT] = SETABC2(K1, K2, C, MU);
%SETSTM;
DT = DX/(80/3.6);
ST, PR] = SETSTM3(DT, AMAT, BMAT);
IBASE=max(floor(BASE/DX+0.5),1);
SFPI=UNITSC/(DX*IBASE);

%Initialize simulation variables based on profile start
I11=min( floor(11./DX +0.5) +1 , NSAMP);
XIN(1)=(UNITSC* (PROF(I11) - PROF(1))) / (DX*I11);
XIN(2)=0.0;
XIN(3)=XIN(1);
XIN(4)=0;
XIN;

%Load road profile data
road_profile=importdata('-pastespecial');
PROF=transpose(road_profile);

%NSAMP is a number of data samples
NSAMP=length(PROF)

%Initialize simulation variables based on profile start
I11=min( floor(11./DX +0.5) +1 , NSAMP);
XIN(1)=(UNITSC* (PROF(I11) - PROF(1))) / (DX*I11);
XIN(2)=0.0;
XIN(3)=XIN(1);
XIN(4)=0;

%Convert to averaged slope profile, with IRI units
NSAMP=NSAMP-IBASE;
```

Figure A.1. IRI conversion script.

```
for i=1: NSAMP
    PROF(i)=SFPI*(PROF(i+IBASE)-PROF(i));
end

%Filter Profile
PROF_output = STFILT(PROF, NSAMP, ST, PR, CMAT, XIN);

%Compute IRI from filtered profile
AVEIRI=0;
for i = 1: NSAMP
    AVEIRI = AVEIRI + abs(PROF_output(i));
end

AVEIRI=AVEIRI/NSAMP
```

Figure A.1. IRI conversion script (continued).

```
function [AMAT, BMAT, CMAT] = SETABC(K1, K2, C, MU)

%Set default for all matrix elements to zero
for j=[1:4]; %Do 10 start
    BMAT(j)=0;
    CMAT(j)=0;
    for i=[1:4];
        AMAT(i,j)=0;
    end
end

%Put 1/4 car model parameters into the A matrix
 AMAT(1, 1) = 1;
 AMAT(3, 4) = 1;
 AMAT(2, 1) = -K2;
 AMAT(2, 2) = -C;
 AMAT(2, 3) = K2;
 AMAT(2, 4) = C;
 AMAT(4, 1) = K2/MU;
 AMAT(4, 2) = C/MU;
 AMAT(4, 3) = -(K1 + K2)/MU;
 AMAT(4, 4) = -C/MU;
 AMAT;

%Set the B matrix for road input through tire spring
BMAT(4)=K1/MU;
BMAT;

%Set the C matrix to use suspension motion as output
    CMAT(1)=-1;
    CMAT(3)=1;
    CMAT;
end
```

Figure A.2. SETABC script.

```
function [ST, PR] = SETSTM(DT, AMAT, BMAT)

A = AMAT;
B = BMAT;

for j=[1:4];
    for i=[1:4];
        A1(i,j)=0;
        ST(i,j)=0;
    end
    A1(j,j)=1;
    ST(j,j)=1;
end

%Calculate the state transition matrix ST=exp(dt*A) with a Taylor series.
%A1 is the previous term in the series. A2 is the next one.
ITER=0;
more = 1;
while more==1
    ITER = ITER + 1;
    more = 0;
    for j = [1: 4] %Do 40 start
        for i = [1: 4]
            A2(i,j) = 0;
            for k = [1: 4]
                A2(i,j) = A2(i,j) + A1(i,k)*A(k,j);
            end
        end
    end %Do 40 end

    for j=[1:4] %Do 50 start
        for i=[1:4]
            A1(i,j) = A2(i,j)*DT/ITER;
            if ST(i,j)+A1(i,j)~= ST(i,j)
                more = 1;
            end

        end
    end
end

%Calculate partial response matrix: PR=A**-1*(ST-I)*B
A=inv(A);

for i = [1:4] %Do 60 start
    PR(i)=0.0;
        for k=[1:4]
            PR(i)=PR(i)-A(i,k)*B(k);
        end
end

for j=[1:4] %Do 90 start
    for i=[1:4] %Do 70 start
        TEMP(j,i)=0.0;
```

Figure A.3. SETSTM script.

```
            for k=[1:4]
                TEMP(j,i)=TEMP(j,i)+A(j,k)*ST(k,i);
            end
        end %Do 70 end

        for k=[1:4]
            PR(j)=PR(j)+TEMP(j,k)*B(k);
        end
    end
    end
```

Figure A.3. SETSTM script (continued).

```
function PROF_output =STFILT(PROF, NSAMP, ST, PR, CMAT, XIN)

%Initialize simulation variables
for i = 1:4
    X(i)=XIN(i);
end

%Filter profile using the state transition algorithm
for i = 1:NSAMP
   for j = 1:4 %Do 20 start
      XN(j) = PR(j)*PROF(i);
      for k = 1:4
          XN(j) = XN(j) + X(k)*ST(j,k);
      end
   end %Do 20 end

   for j=1:4
       X(j)=XN(j);
   end

   PROF_output(i) = X(1)*CMAT(1) + X(2)*CMAT(2) + X(3)*CMAT(3) + X(4)*CMAT(4);
end
```

Figure A.4. STFILT script.