Project No. 01-59

PROPOSED ENHANCEMENTS TO PAVEMENT ME DESIGN: IMPROVED CONSIDERATION OF THE INFLUENCE OF SUBGRADE SOILS SUSCEPTIBLE TO SHRINK/SWELL AND/OR FROST HEAVE ON PAVEMENT PERFORMANCE

APPENDIX 2

EVALUATION OF THE ADEQUACY OF PAVEMENT ME DESIGN MODELS TO PREDICT THE INFLUENCE OF SUBGRADE SOIL VOLUME CHANGE ON PAVEMENT PERFORMANCE: A FEASIBILITY STUDY

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

2.1. PRELIMINARY FEASIBILITY STUDY TO ASSESS ADEQUACY OF USING DISTRIBUTIVE CHARACTERISTICS OF MULTI VARIATE MODELS OF FROST HEAVE AND HIGH-VOLUME CHANGE TO PREDICT INCREASES IN PAVEMENT ROUGHNESS

2.1.1. General Background

In the current Pavement ME Design approach, there is only one indirect process that considers the influence of shrink/swell and frost/heave on pavement performance. This analysis is accounted for by the Site Factor (SF) variable in the series of regression developed models used to predict the change in the International Roughness Index (IRI). The effects of soil volume changes are empirically predicted from climatic variables and subgrade soil properties including freezing index, average annual precipitation, soil plasticity index, and percent passing the No. 200 sieve. These variables are incorporated into a Site Factor term that is included in the determination of the IRI. The regression coefficients that relate the Site Factor and IRI were found by calibration with the data collected from the Long-Term Pavement Performance (LTPP) program. The equations are embedded in the Pavement ME Design guide and predict the IRI over time for new and existing flexible or rigid pavements.

The objective of Task 2.1 was conducting an initial feasibility effort to assess the adequacy and accuracy of using first and second order moments (μ and σ^2) of a continuous frequency distribution associated with the slope (Θi) variable, measured at one-foot intervals along a pavement section, to predict potential increases in the longitudinal profile roughness of the pavement system. Simulation studies previously conducted led to the development of accurate relationships between the statistical variance of the slope distribution (SV) to the statistical variance of the distribution of elevation changes or heaves (Y_{hi}). This Slope Variance (SV) variable is the same variable developed by Carey and Irick (1960) in their classic development of the AASHO Functional pavement design concept using Present Serviceability Ratings (PSR) and subsequently present serviceability index (PSI). Task 2.1 effort has been led by one of our senior advisors, Professor Matthew Witczak.

To accomplish this goal, a Monte Carlo simulation spreadsheet solution was developed, and a matrix of Slope Variance (SV) values and simulation numbers were used to assess the validity of the proposed approach. This solution will allow for the “bridge” between the advanced, mechanistic Frost Heave and High-Volume Change distress heave predictions, developed as part of this study, and their induced pavement roughness (changes in PSI and IRI).

It was concluded that the prediction of the slope distribution mean and variance, from the Monte Carlo simulation approach, was accurate and clearly supports the conceptual mathematical methodology proposed by the project team. The predicted Slope Variance can then be used with existing and widely accepted relationships to predict pavement roughness quantified by either the Present Serviceability Index (PSI) or IRI variables.

This second study developed a Monte Carlo simulation spreadsheet solution program that could be used to predict the SV, PSI and IRI, based directly upon the input of the 1st and 2nd Moments of the elevation change (heave) frequency distribution. Based upon the analysis of the initial study, the simulation model was developed to accommodate a user input Ns (number of simulation computations), not to exceed 10,000 simulation runs. The following section presents details of the study.

2.1.2. Relationship of Slope Variance (SV) to PSI and IRI

The solution sequence for the simulation process is based upon the fact that each successive simulation of the y_h (elevation change) distribution occurs at 1 ft intervals. Thus, for each simulated value of Y_{hi}, developed for each random simulation from the Monte Carlo analysis, the "ith" interval slope (Θ_i), can be computed from:

$\Theta_i = \tan^{-1}((\Delta y_{hi})/(12 \text{ in}))$ with (Δy_{hi}) (inches)

As the value of Θ_i will be in degrees; it is then converted into radians. Finally, it is important to note that the AASHO Slope Variance value (SV) used in the historic PSI equations is expressed in terms of $*10^{-6}$ radians. Therefore, the computed Θ_i value should be expressed in terms of $*10^{-3}$ radians, between unit intervals.

The subsequent analysis used in the second Monte Carlo Simulation study involves the use of several key relationships between the SV (Slope Variance), PSI (Present Serviceability Index) and the IRI (International Roughness Index) used and developed in the initial study. The specific equation relating PSI to the SV variable is the one developed by Yoder and Milhous in NCHRP Report No 7 for "Flexible and Flexible Overlays", using only the SV variable for the prediction of the PSI. This equation was:

$PSI = 4.89 - 1.92 * \text{Log}(1+SV)$ $\quad s_e = 0.40 \quad R^2 = 0.89$

The equation used to relate PSI to IRI (currently used in the AASHTO MEPDG) was the Omari and Darter equation, modified to predict the IRI in units of "in/mi". Thus, the final equation used in this study to relate PSI to IRI (in/mile) is:

$IRI = 63.36*(1/0.26) \ln(5/PSI)$ (in/mile)

Finally, the relationship of the statistical variance (standard deviation) of the y_{hi} heave (elevation change) variable to increases in IRI (or decreases in PSI) was obtained from the findings (conclusions) of the initial study. The resulting equations were found to be:

$\Delta PSI = -0.681 * \ln(\text{Var } Y_{hi}) - 6.5369$ $\quad R^2 = 0.9949$
$\Delta IRI = 3955.9 * (\text{Var } Y_{hi})^{0.5246}$ $\quad R^2 = 0.9949$

Based upon the R^2 values obtained, it can be observed that both expressions are extremely accurate predictors. These relationships were then incorporated into the Simulation program developed as the major objective of the second Technical Study conducted.

2.1.3. Simulation Spreadsheet Solution

As previously noted, the spreadsheet solution was developed to accommodate up to a level of Ns = 10,000 simulations. In this spreadsheet solution, the user inputs the mean and variance properties of the Y_{hi}

distribution, to determine the distribution properties of the slope value (Θi). Once the individual simulated interval Θi values are computed, the mean and variance (SV) of the total simulated sampling estimates is then made. This predicted value of the SV is then used to predict the increases in pavement roughness, as quantified by the PSI and IRI variables.

Table 2.1 is a partial view of the entire simulation program. Included in this table are cell results for the first 5 simulations (Ns = 1 – 5) of a Ns=1000 analysis (see cell F22). The entire program, if printed, would require over 300 pages of cell row entries for the entire Ns = 10,000 simulation possibilities.

As shown in cells C4: H12, the first source of information is to aid the user in using typical input values that are practical ranges of the most likely actual field conditions that will be encountered. In the eventual, final use of this simulation; the input values (mean and variance of the Y_{hi} distribution, will be obtained from a statistical analysis of the final multi variate heave prediction models developed from the project study.

Columns C9:C12 and D9:D12 illustrate several typical values of the expected Y_{hi} variances (in both units of in^2 and 10^{-6} in^2) that are equivalent to the ranges of computed SV values, identified in cells F9:F12. The standard deviation is shown in Cells E9:E12 and simply represent the square root of the variance values. Using the equations previously defined, the typical value of the PSI and IRI are then shown in Cells G9:G12 and H9:H12.

Note that the full simulation solution requires user input for <u>only</u> three input cells:

Mean Heave Value (μ_{yhi})	Cell G16
Heave Variance (σ^2_{yhi})	Cell G17
No of Simulations Desired (Ns)	Cell F22

Once the variance is entered in Cell G17, the standard deviation is computed and displayed in Cell G18. Once the Ns value is entered in Cell F22 by the user, the entire simulation will be completed. A cell entry decision will occur in Cell G22 for the Ns input. If the Ns value input is a number greater than 10,000, a note will be shown that an "incorrect data entry "has been made. If Ns is <= 10,000, an "Okay" will appear.

Cells A24:J29 contain the <u>final computational results</u> of the entire simulation study. The following final simulation results are shown in Row 29:

- No of Simulations Conducted
- Interval Elevation Changes (Heaves)
    - Mean (estimates Cell G16 Input)
    - Standard Deviation (estimates Cell G18 Input)
    - Variance (estimates Cell G17 Input)
    - Cumulative Elevation Change (estimates Expected Value of 0.000)
- Slope Angle (Radians)
    - Mean (Simulated Prediction)
    - Standard Deviation (Simulated Prediction)

Table 2.1 Methods Monte Carlo Simulation of Elevation Change (Heave) – Yhi Term for Pavement Roughness

	A	B	C	D	E	F	G	H	I	J
1										
2		Monte Carlo Simulation of Elevation Change (Heave) - Yhi Term for Pavement Roughness								
3										
4			Typical Input Ranges of Variables							
5										
6			Heave Value (Yhi) : units of inches							
7			Variance		Std Dev	SV	PSI	IRI		
8			(in^2)	(10^{-6} in^2)	(in)	($*10^{-6}$ rads)		(in/mile)		
9			0.00014	140	0.01183	1.0	4.31	36.2		
10			0.00055	550	0.02345	4.0	3.55	83.5		
11			0.00229	2290	0.04785	16.0	2.53	166.0		
12			0.00513	5130	0.07162	36.0	1.88	238.4		
13										
14										
15			Specific Simulation Problem Input							
16			Mean Heave Value (μyhi) : Input in units of inches				0.000			
17			Heave Variance (σyhi^2) ; Input in units of 10^{-6} in^2:				2290.000			
18			Standard Deviation (σyhi); Units of 10^{-3} inches:				47.854			
19										
20										
21		To Initiate Simulation Program; Enter Desired Number of Simulation Runs in Cell F11								
22		Enter Number of 1 ft Simulations Desired (Ns max=10,000)				1000	Okay			
23										
24		Final (Total) Simulation Results:								
25		Interval Elev Changes (in)				Slope Angle (Radians)			Roughness Predictions	
26		Mean	Std Dev	Variance	Cum Elev	Mean	Std Dev	Variance	Predicted	Predicted
27	Ns Simulations	(inches)	(inches)	(Inches^2)	Change (in)	($*10^{-3}$ rads)	($*10^{-3}$ rads)	($*10^{-6}$ rads)	ΔPSI	ΔIRI
28										
29	1000	0.00049	0.048306	2333.449379	0.486382	0.04053	4.0254	16.20400	2.52	167.21
30										
31		Master Monte Carlo Simulation Results								
32		Simulation	Interval	Prob Soln		Predicted Yhi	Θi	Θi	Cumulative	
33		Number (No)	Xi(ft)	Random α	α' = 1- α	(inches $*10^{-3}$)	(radians)	($*10^{-3}$ rads)	ΔElev (inches)	
34										
35		0	0						0	
36		1	1	0.1390	0.8610	-0.051913	-0.00433	-4.32606	-0.051913	
37		2	2	0.4570	0.5430	-0.005168	-0.00043	-0.43066	-0.057081	
38		3	3	0.9670	0.0330	0.087976	0.00733	7.33119	0.030895	
39		4	4	0.9350	0.0650	0.072456	0.00604	6.03791	0.103351	
40		5	5	0.4830	0.5170	-0.002040	-0.00017	-0.16998	0.101311	

Variance (SV) (Simulated Prediction)

Roughness Predictions

PSI

IRI

These summary predictions are evaluated from the simulation table, generated, and shown in Cells B31:I10,035. (Ns=1 in B36 to Ns=10,000 in B10,035). Entries in Col B indicate the specific simulation number, while Col C indicates the specific 1 ft interval being simulated. The input description for Column D (36:10,035) is entitled *Random α*. This value represents the randomly selected area (in decimal form) under a Normal Probability (distribution) curve, from a "negative infinity" to the Normal Deviate Kα value. These cell values are programmed by the cell command: *RANDBETWEEN(1,999)/1000*. Thus, cell probabilities between 0.1% and 99.9% are randomly selected, and shown in each individual cell interval

.

The variable *α'*, shown in Column E (E33), is simply 1 minus the area shown in Column D. For Cell D36 = 0.1390, Cell E36 = 0.8610. Thus, the Probability of having a Y_{hi} heave less than $K\alpha$ would be 13.9% and the Probability of having a Y_{hi} heave greater than $K\alpha$ would be 86.1%. The entries in Column F (Cells F36:F10,035) are the random predictions of the individual interval elevation change (heave),Y_{hi}. These entries are determined through the cell command (for Cell F36) *NORMINV(D36,H16,H18).*

This command determines the actual value of the Y_{hi} Normal Probability Distribution in Cell F36, using the α_i value in Cell D36, based upon the mean value of the known distribution input in Cell H16 and the known standard deviation of the heave distribution, computed and shown in Cell H18. These Y_{hi} values are computed for each random area α generated in Cells D36:D10,035. Using the *arctan* relationship, the Slope Angle (Θ_i) can then be directly determined from the interval Y_{hi} simulation and shown in Cell Column G (radians) and Cell Column H (10^{-3} radians). The final Column I (I36:I10,035) is simply the cumulative elevation for the exact simulation.

Slope Angle parameters are simply computed from the *Ns* cell observations in Column H (Cell H36:H10,035); while the same statistics for the ΔY_i distribution (Interval Elevation Changes) are computed from the Column F entries (F36:F10,035). As previously noted, all of these values are summarized in the Output Cells located in A29:J29.

2.1.4. Summary of Study Results

The Simulation Spreadsheet was used to obtain results for a matrix of σ^2_{yhi} and Ns values.

Table 2.2 is a summary of the primary results (mean and variance) for the elevation change (heave) and predicted slope, for each *Ns* and *Heave Variance* values investigated.

It is observed that the average deviation in the Monte Carlo simulation results for the *interval elevation changes*, at *Ns*=10,000 simulations, over an input range of initially assumed values from 140 to 5130 ($x10^{-6}$ in^2) is in average -2.5%.

Table 2.2 Monte Carlo Simulation Analysis

	Summary of Monte Carlo Simulation Analysis									
	Input Yhi Distribution		Interval Elevation Changes			Slope Changes		Roughness Changes		
Ns	Mean	Variance	Mean	Variance	Cum Change	Mean	Variance	PSI	IRI
	(in)	($x10^{-6}$ in^2)	(in)	($x10^{-6}$ in^2)	(in)	($x10^{-3}$ rads)	($x10^{-6}$ $rads^2$)		(in/mile)
50	0	140	-0.00245	196.78	-0.1224	-0.2040	1.367	4.17	19.14
		550	-0.00432	642.36	-0.2159	-0.3599	4.461	3.47	88.70
		2290	0.01798	1858.61	0.8991	1.4984	12.907	2.70	150.61
		5130	-0.00742	3962.68	-0.3712	-0.6187	27.517	2.10	211.84
250	0	140	0.00000	134.25	-0.0010	-0.0003	0.932	4.34	34.46
		550	-0.00044	624.44	-0.1112	-0.0371	4.336	3.49	87.36
		2290	-0.00463	1680.20	-1.1567	-0.3856	11.668	2.77	143.67
		5130	-0.00571	5279.57	-1.4272	-0.4757	36.661	1.86	240.42
500	0	140	0.00011	130.75	0.0540	0.0090	0.908	4.35	33.86
		550	0.00026	541.75	0.1309	0.0218	3.762	3.59	80.83
		2290	-0.00256	2103.33	-1.2813	-0.2136	14.606	2.60	159.46
		5130	-0.00264	4585.02	-1.3198	-0.2200	31.838	1.98	225.92
1000	0	140	-0.00016	138.16	-0.1597	-0.0133	0.959	4.33	35.11
		550	0.00034	554.00	0.3356	0.0280	3.849	3.57	81.85
		2290	0.00059	2063.86	0.5864	0.0489	14.332	2.61	158.08
		5130	0.00112	5074.32	1.1213	0.0934	35.236	1.90	236.25
5000	0	140	-0.00029	137.45	-1.4685	-0.0245	0.954	4.33	34.99
		550	0.00000	557.63	0.0132	0.0002	3.872	3.57	82.12
		2290	-0.00080	2312.15	-3.9925	-0.0665	16.056	2.52	166.51
		5130	0.00000	4921.54	0.0173	0.0003	34.175	1.92	233.09
10000	0	140	0.00004	136.89	0.4042	0.0034	0.951	4.33	34.90
		550	-0.00003	546.48	-0.3382	0.0028	3.795	3.58	81.21
		2290	0.00001	2204.02	0.0583	0.0005	15.305	2.56	162.91
		5130	-0.00144	4952.95	1.4316	-0.1201	34.393	1.92	233.74

Figure 2.1 illustrates the estimate of the Slope Variance (SV), as a function of the *Ns* value used in the simulation, for the initial four assumed variances of the elevation heave distribution. Figure 2.2 illustrates the estimate of the Predicted IRI value and Predicted PSI value, as a function of Ns.

These initial results clearly show a relatively good to excellent prediction accuracy of the SV, IRI and PSI parameters from the 1st and 2nd moments of the pavement elevation heave distribution that could be caused by frost action as well as high volume change soils. As of this study, it can also be concluded that the use of a Monte Carlo *Ns* (number of simulations) of 10,000 provides a very stable estimate of the prediction of the three critical variables being determined for the NCHRP study (SV, IRI and PSI).

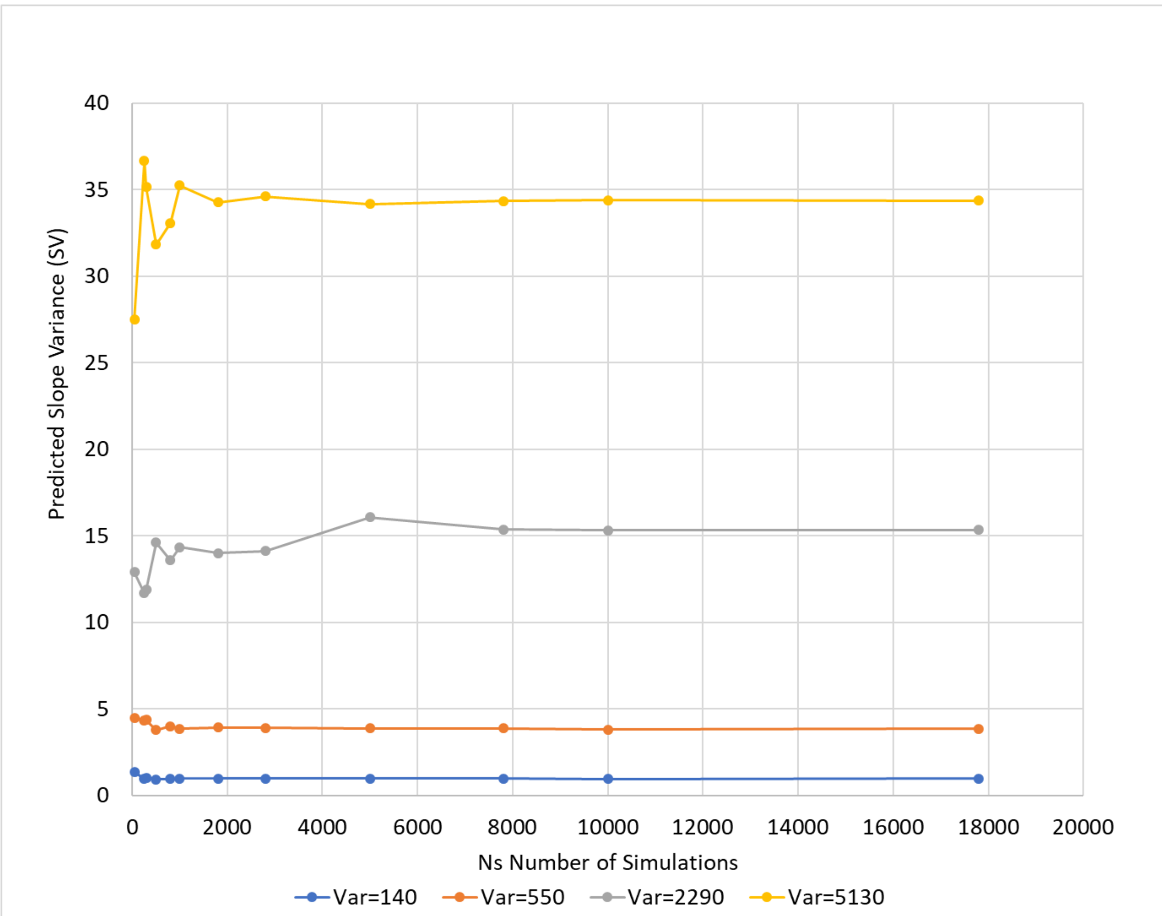
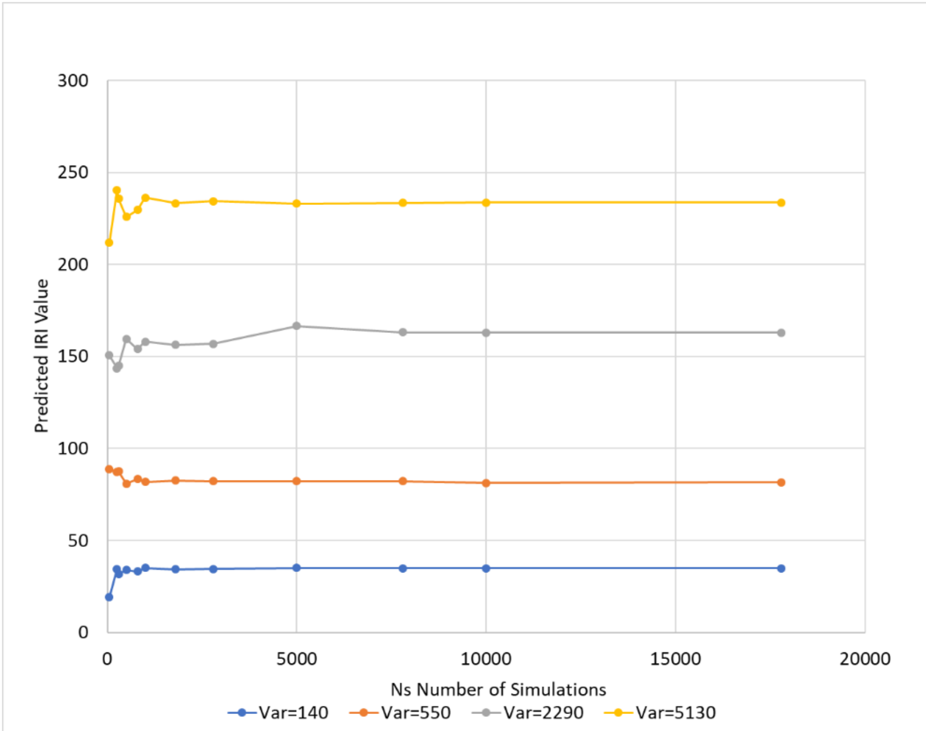
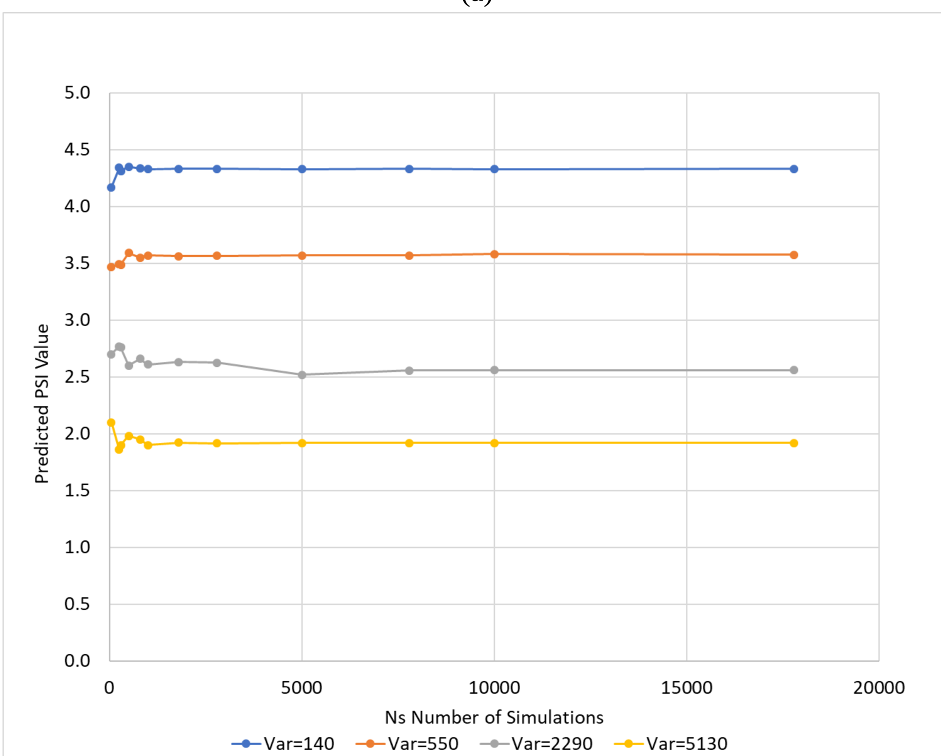


Figure 2.1 Influence of Number of Simulations upon Predicted Slope Variance (SV) due to Variance of Yhi (Heave) in units of 10^{-6} in^2



(a)



(b)

Figure 2.2 Influence of Number of Simulations upon Increase in Predicted IRI and PSI due to Variance of *Yhi* (Heave) in units of 10^{-6} in^2

2.1.5. Future Studies

It is envisioned that only a minor additional study will be conducted to see if the Relative Prediction error of the simulation can be even further reduced from 5.4% to a value closer to 0.0%.

2.2. SENSITIVITY STUDIES TO EVALUATE THE RELATIVE PERCENTAGE CONTRIBUTION TO PAVEMENT ROUGHNESS CAUSED BY THE SITE FACTOR (SF) VARIABLE IN THE MEPDG IRI EQUATIONS

2.2.1 General Background

One of the major work efforts, relative to the objective of the Task 2 activity, is to conduct a study that would provide a general assessment of the Site Factor (SF) portion of the total pavement induced roughness in the IRI, for each of the four categories of pavement types considered in the current Pavement ME Design Guide. This study had the dual goal of: (a) assessing the general reasonableness of the SF -IRI influence, and (b) obtaining some quantifiable percentage of the SF sensitivity upon the total increase in IRI (decrease in PSI), relative to certain specific SF variables used in the current Pavement ME Design Guide. This information is vital for the development of the final revised IRI increments due to roughness-induced damage by frost action and/or soil swelling.

The four specific categories considered for the IRI-SF equations are:

1. New HMA Pavements and HMA Overlays of Existing Flexible Pavements
2. HMA Overlays of Rigid Pavements
3. Jointed Plain Concrete Pavements (JPCP)
4. Continuously Reinforced Concrete Pavements (CRCP)

All of the IRI equations and those used for the SF Variable, shown in the team's proposal, were obtained from the August 2015, 2nd Edition. *Mechanistic Empirical Pavement Design Guide – Manual of Practice*. This was the case for all equations except the SF equation for the *HMA Overlays of Rigid Pavements* category. This equation <u>is not shown</u> anywhere in the latest Manual of Practice. However, the equation shown in the proposal is the same SF equation shown in the July 2008 Manual of Practice (First edition) for the *New HMA Pavements and HMA Overlays of Existing Flexible Pavements* category. Most important, the February 2006 ARA -NCHRP Document *Appendix OO-4; Revised Smoothness Prediction Models for Flexible Pavement*, clearly indicated that the <u>SF equations for categories 1 and 2 Pavements were identical</u>. This was the basis for the placement of this SF equation in the proposal as being the latest IRI-SF equation used in the Pavement ME Design Guide.

Using the available equations, nearly 1,900 computational runs were performed on spreadsheets laid out for this purpose. However, the sensitivity analysis is on hold due to errors found in the IRI equations published in the 2015 AASHTO Manual of Practice (MOP) report for the SF equation for Pavement Category 1 (New HMA and HMA Overlay of Flexible Pavements). <u>The team is awaiting a response from ARA for final verification of the most current SF equations.</u> However, the analysis layout will not be impacted if it is found out that the equations are not correct.

2.2.2. *Analysis Process*

Excel spreadsheet solutions were developed for each of the four pavement categories defined by the Pavement ME Design Guide. The solutions are shown as Tables 2.3 to 2.6. As can be observed, each spreadsheet solution is comprised of an upper portion, defining either the variable input cell or the equation constants (Ci). The central portion summarizes: (a) the computed ΔIRI values associated with each variable, (b) the *% of the total IRIt* for the analysis with each variable and (c) the *% of the (IRIt-IRIo)* for each variable. The lower portion of each spreadsheet solution groups the variables into three categories and shows the group ΔIRI, and its percentage relative to the IRIt or (*IRIt-IRIo*) value. The three groups are defined as the:

a. Initial Roughness
b. Pavement ME Design Guide Distress Models
c. Site Factor Climatic Effect

Each Pavement Category spreadsheet was analyzed with a specific variable matrix array. The summary of the number of variables used in each category, along with the total number of computational runs conducted in the study were:

Pavement Category	Number of Variables	Number of Computational Runs
1	10	1215
2	8	432
3	7	180
4	5	20
	Total Computations:	1847

Table 2.3 Category 1 – New HMA and HMA Overlays of Flexible Pavements

	Group 1: New HMA Pavements and HMA Overlays of Flexible Pavements							
		IRI = IRIo+C1(RD)+C2(FCtotal)+C3(TC)+C4(SF)						
		SF=Age^1.5{ln[(Precip+1)(FI+1)p02]}+{ln[(Precip+1)(PI+1)p200]}						
	Initial IRIo							
		50						
	Structural Distress Input			IRI Constants				
	RD (in)	FCtot(% Lane)	TC (ft/mi)	C1	C2	C3	C4	
	0.4	10	4000	40.0	0.400	0.008	0.015	
	SF - Site Factor Input							
	Age (yrs)	Precip(in)	FI (deg Days)	PI (soil)	P(0.02mm)	P(0.075mm)		
	20	100	3000	0	2	6		
	Δ IRI Increments							
	IRIo	Rut	Fat Crack	Thermal Crack	Frost Heave	Hi Vol Change	IRIt	(IRIt-IRIo)
	50	16	4	32	17.86	0.10	119.96	69.96
% of IRIt	41.7%	13.3%	3.3%	26.7%	14.9%	0.1%		
% of (IRIt-IRIo)		22.9%	5.7%	45.7%	25.5%	0.1%		
			IRIt Analysis		(IRIt-IRIo) Analysis			
	Initial Roughness		50	41.7%				
	MEPDG Distress Models		52	43.3%	52	74.3%		
	Site Factor Climatic Effect		18.0	15.0%	18.0	25.7%		
		Sum	119.96	100.0%	69.96	100.0%		

Table 2.4 Category 2 - HMA Overlays of Rigid Pavements (Includes Over Any Fractured Slabs)

	Group 2: HMA Overlays of Rigid Pavements (Includes Over Any Fractured Slabs)									
		IRI = IRIo+PCC C1(RD)+PCC C2(FCtotal)+PCC C3(TC)+PCC C4(SF)								
		SF=Age[PCC C5(PI+1)+PCC C6(Precip+1)+PCC C7(FI+1)]								
	Initial IRIo									
		50								
	Structural Distress Input			IRI Constants						
	RD (in)	FCtot(% Lane)	TC (ft/mi)	C1	C2	C3	C4	C5	C6	C7
	0.5	30	4000	40.8	0.575	0.0014	0.00825	0.02003	0.007947	0.000636
	SF - Site Factor Input									
	Age (yrs)	Precip(in)	FI (deg Days)	PI (soil)						
	25	90	3000	70						
	Δ IRI Increments									
	IRIo	Rut	Fat Crack	Thermal Crack	Frost Heave	Hi Vol Change	IRIt	(IRIt-IRIo)		
	50	20.4	17.25	5.6	0.39	0.44	94.09	44.09		
% of IRIt	53.1%	21.7%	18.3%	6.0%	0.42%	0.47%				
% of (IRIt-IRIo)		46.3%	39.1%	12.7%	0.89%	1.00%				
			IRIt Analysis		(IRIt-IRIo) Analysis					
	Initial Roughness		50.00	53.1%						
	MEPDG Distress Models		43.25	46.0%	43.25	98.1%				
	Site Factor Climatic Effect		0.84	0.9%	0.84	1.9%				
		Sum	119.96	100.0%	44.09	100.0%				

Table 2.5 Category 3 - JPCP Jointed Plain Concrete Pavements

	Group 3: JPCP Jointed Plain Concrete Pavements							
		IRI = IRIo+C1(CRK)+C2(SPALL)+C3(TFAULT)+C4(SF)						
		SF=Age(1+C5*FI)(1+p200)*10^-6						
	Initial IRIo							
		50						
	Structural Distress Input			IRI Constants				
	CRK	SPALL	TFAULT	C1	C2	C3	C4	C5
	80	30	0	0.8	0.442	1.4929	25.4	0.5556
	SF - Site Factor Input							
	Age (yrs)	FI (deg Days)	p200					
	25	3000	70					
	Δ IRI Increments							
	IRIo	Crk	Spall	Tfault	Frost Heave	Hi Vol Change	IRIt	(IRIt-IRIo)
	50	65.62	13.25	0.00	75.19	NA	204.07	154.07
% of IRIt	24.5%	32.2%	6.5%	0.0%	36.8%			
% of (IRIt-IRIo)		42.6%	8.6%	0.0%	48.8%			
			IRIt Analysis		(IRIt-IRIo) Analysis			
	Initial Roughness		50	24.5%				
	MEPDG Distress Models		78.88	38.7%	78.88	51.2%		
	Site Factor Climatic Effect		75.19	36.8%	75.2	48.8%		
		Sum	204.07	100.0%	154.07	100.0%		

Table 2.6 Category 4 - CRCP Continuously Reinforced Concrete Pavements

	Group 4: CRCP Continuously Reinforced Concrete Pavements					
		IRI = IRIo+C1(PO)+C2(SF)				
		SF=Age(1+C3*FI)(1+p200)*10^-6				
	Initial IRIo					
		50				
	Structural Distress Input			IRI Constants		
	PO			C1	C2	C3
	0			3.2	28.350	0.5556
	SF - Site Factor Input					
	Age (yrs)	FI (deg Days)	p200			
	25	3000	70			
	Δ IRI Increments					
	IRIo	PO	Frost Heave	Hi Vol Change	IRIt	(IRIt-IRIo)
	50	0.00	83.93	NA	133.93	83.93
% of IRIt	37.3%	0.0%	62.7%			
% of (IRIt-IRIo)		0.0%	100.0%			
			IRIt Analysis		(IRIt-IRIo) Analysis	
	Initial Roughness		50	37.3%		
	MEPDG Distress Models		0.00	0.0%	0.00	0.0%
	Site Factor Climatic Effect		83.9	62.7%	83.9	100.0%
		Sum	133.93	100.0%	83.93	100.0%

As can be noted, this initial effort resulted in nearly 1,900 separate computational solutions for the initially proposed sensitivity analysis.

During the course of the sensitivity effort, it became obvious that the predicted results for categories 1 and 2 exhibited questionable relationships that prompted an inquiry through NCHRP to assess if any typographical errors were found/present in the Manual of Practice/Proposal equations (particularly for the Site Factor (SF) expressions (refer to October 2018 Monthly Report). This inquiry was forwarded by the NCHRP Project Manager to Mr. H. Von Quintus of ARA for his response.

At present, communications between the project team and ARA are still in progress, but hopefully should be finalized in the immediate future. Some preliminary conclusions from the initial communication are as follows:

1. There appears to be a typographical error in the 2015 AASHTO Manual of Practice (MOP) report for the SF equation for Pavement Category 1 (New HMA and HMA Overlay of Flexible Pavements).
2. The SF equation for Pavement Category 2 (HMA Overlay of Rigid Pavements), shown in the Team's proposal as the original equation in the 2008 AASHTO MOP report, has been found to have been replaced in the AASHTO 2015 MOP Report by an equation that was <u>not shown in the 2015 MOP Report</u>.

Task 2.2 effort is currently on hold, pending final verification by ARA of the most current SF equations being used in the Pavement ME Design Guide. To further complicate this matter, ARA has also indicated that some of the latest 2018 MEPDG Software solutions for the IRI (SF) equations may actually incorporate changes, from those even shown in the 2015 MOP Report, which is the latest official AASHTO Pavement ME Design Guide Report document that the team is aware of.

2.3. EVALUATION OF THE PERFORMANCE OF EXISTING IRI EQUATIONS WITH LTTP DATA

In Task 2.3, a very preliminary analysis of the performance of IRI predicting equation for cold regions was initiated, in order to have a feeling whether or not, the calibration of the final model against the existing equations is reasonable or not.

LTPP data from selected pavement located in cold regions (Ohio, Michigan, Wisconsin and Canada), where frost heave might play an important role, were selected to evaluate the performance of the current IRI equations. The results indicate that the current IRI equations appeared to perform reasonably well for Jointed Plain Concrete Pavements and Continuous Reinforced Concrete Pavements. The performance is not as satisfactory for HMA overlays placed on rigid pavements. A comparative effort is in progress to determine the validity of the equations for arid regions where volume change caused by expansive soils is of concern. Details of this effort will be presented as deliverables for Task 5.

As an example to assess the performance of existing IRI equations, the calculated IRI from the Pavement ME Design Guide IRI Roughness models were compared with the measured IRI from LTPP database for Jointed Plain Concrete Pavements (JPCP), Continuous Reinforced Concrete Pavement (CRCP) and Hot Mixed Asphalt (HMA) pavements. The first set of pavement sections selected are located in cold regions such as Wisconsin (Section No. 0214, 5040, 0113), Michigan (Section No. 4015, 5363, 0115), Ohio (Section No. 0106, 0201, 0202, 5003) in the United States and Alberta (Section No. 0501) and Quebec (Section No. 3015, 0902), in Canada. Details of the datasets queried from LTTP database are provided in Tables 2.7 to 2.9.

The results indicate that the predicted IRI are scattered around the actual measured IRI (Figure 2.3 and Figures 2.4 to 2.6 below). The errors are more significant for flexible HMA pavements, whose IRI might be more susceptible to the volume change of subgrade soils. The differences between the measured IRI versus predicted values by the existing IRI equations is also partially attributed to the fact that these IRI equations were calibrated with LTPP data on pavement with relatively short service time when the calibrations were conducted.

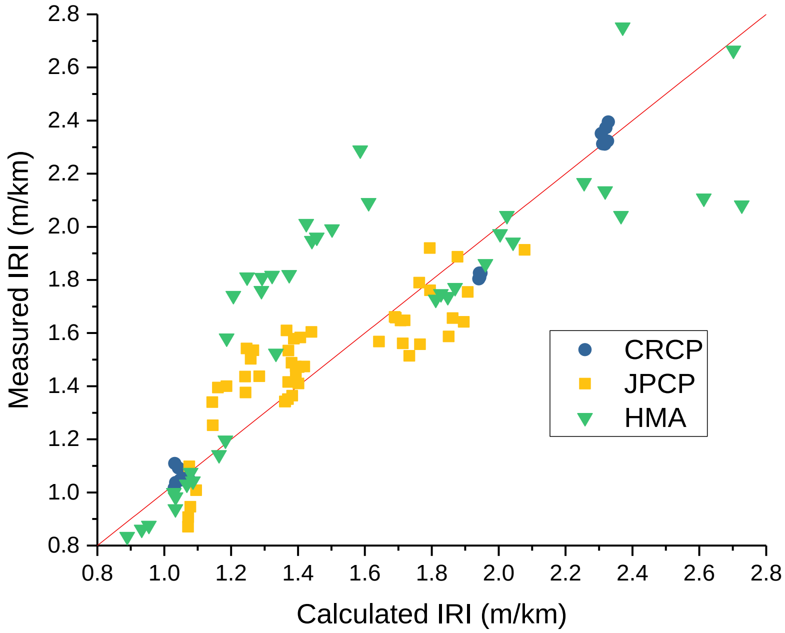


Figure 2.3 Comparison between the measured IRI and the calculated IRI for three different pavement types

Similarly, the effects of high-volume change soils due to moisture fluctuation on the pavement IRI can be evaluated by LTPP data from pavement located in regions such as Texas, North Dakota, Colorado and Louisiana, where expansive soils are documented to be present. The comparison will offer similar insight on the performance of existing IRI equations for pavement supported by expansive subgrade soils.

As explained in Task 2.2, the equations used in this analysis are under revision for validity; and therefore, the results might vary if found out they are in error.

The data collected from LTTP in order to demonstrate the estimation of the frost heave approach is presented in Tables 2.7 to 2.9 below.

Table 2.7 Comparison between the predicted JPCP IRI and measured ones

LOCATION	SECTION NO.	YEAR	IRIi	CRK	SPALL	TFAULT	AGE	FI	$P_{0.075}$	SF	IRIc	IRIm
Wisconsin	0214	1998	1.358	0	0	0	1	945	6.9	0.0074734	1.36098936	1.342
Wisconsin	0214	1999	1.358	0	0	0	2	585	6.9	0.0092588	1.36170352	1.342
Wisconsin	0214	2000	1.358	0	0	0	3	839	6.9	0.019908	1.3659632	1.61
Wisconsin	0214	2001	1.358	0	0	0	4	1052	6.9	0.0332748	1.37130992	1.534
Wisconsin	0214	2002	1.358	0	0	0	5	772	6.9	0.0305335	1.3702134	1.351
Wisconsin	0214	2003	1.358	0	0	0	6	677	6.9	0.0321372	1.37085488	1.416
Wisconsin	0214	2004	1.358	0	0	0	7	1035	6.9	0.0572908	1.38091632	1.488
Wisconsin	0214	2005	1.358	0	0	0	8	971	6.9	0.0614304	1.38257216	1.364
Wisconsin	0214	2008	1.358	0	0	0	11	1027	6.9	0.0893332	1.39373328	1.449
Wisconsin	0214	2009	1.358	0	0	0	12	1286	6.9	0.1220076	1.40680304	1.583
Wisconsin	0214	2010	1.358	0	0	0	13	1062	6.9	0.1091701	1.40166804	1.41
Wisconsin	0214	2011	1.358	0	0	0	14	792	6.9	0.0877058	1.39308232	1.474
Wisconsin	0214	2012	1.358	0	0	0	15	926	6.9	0.1098495	1.4019398	1.472
Wisconsin	0214	2013	1.358	0	0	0	16	584	6.9	0.073944	1.3875776	1.579
Wisconsin	0214	2014	1.358	0	0	0	17	1128	6.9	0.1516247	1.41864988	1.474
Wisconsin	0214	2015	1.358	0	0	0	18	1443	6.9	0.2053368	1.44013472	1.604
Michigan	4015	1990	1.618	0	8.3	0	1	597	67.3	0.0408434	1.69243736	1.658
Michigan	4015	1991	1.618	0	8.3	0	2	235	67.3	0.0322376	1.68899504	1.661
Michigan	4015	1992	1.618	0	8.3	0	3	377	67.3	0.0774522	1.70708088	1.647
Michigan	4015	1994	1.618	0	8.3	0	5	311	67.3	0.106548	1.7187192	1.648
Michigan	4015	1997	1.618	0	8.3	0	8	543	67.3	0.2972416	1.79499664	1.761
Michigan	4015	1998	1.618	0	8.3	0	9	351	67.3	0.2163744	1.76264976	1.79
Michigan	4015	1999	1.618	0	8.3	0	10	430	67.3	0.294373	1.7938492	1.92
Ohio	0201	1997	1.235	0	0	0	1	277	71.1	0.0200438	1.24301752	1.376
Ohio	0201	1998	1.235	0	0	0	2	121	71.1	0.0175924	1.24203696	1.436
Ohio	0201	1999	1.235	0	0	0	3	275	71.1	0.0596988	1.25887952	1.503

LOCATION	SECTION NO.	YEAR	IRIi	CRK	SPALL	TFAULT	AGE	FI	$P_{0.075}$	SF	IRIc	IRIm
Ohio	0201	2000	1.235	0	0	0	4	425	71.1	0.1228584	1.28414336	1.437
Ohio	0201	2001	1.235	0	0	0	5	217	71.1	0.078589	1.2664356	1.535
Ohio	0201	2002	1.235	29	0	0	6	174	71.1	0.075705	1.642282	1.568
Ohio	0201	2003	1.235	32	0	0	7	405	71.1	0.2049082	1.73296328	1.514
Ohio	0201	2004	1.235	41	0	0	8	358	71.1	0.2070712	1.85082848	1.587
Ohio	0201	2005	1.235	41	0	0	9	363	71.1	0.2361996	1.86247984	1.656
Ohio	0201	2006	1.235	47	0	0	10	106	71.1	0.077147	1.8768588	1.887
Ohio	0202	1997	1.137	0	0	0	1	277	71.1	0.0200438	1.14501752	1.253
Ohio	0202	1998	1.137	0	0	0	2	121	71.1	0.0175924	1.14403696	1.34
Ohio	0202	1999	1.137	0	0	0	3	275	71.1	0.0596988	1.16087952	1.395
Ohio	0202	2000	1.137	0	0	0	4	425	71.1	0.1228584	1.18614336	1.4
Ohio	0202	2001	1.137	6	0	0	5	217	71.1	0.078589	1.2464356	1.542
Ohio	0202	2002	1.137	42	0	0	6	174	71.1	0.075705	1.713282	1.561
Ohio	0202	2003	1.137	42	0	0	7	405	71.1	0.2049082	1.76496328	1.558
Ohio	0202	2004	1.137	52	0	0	8	358	71.1	0.2070712	1.89582848	1.642
Ohio	0202	2005	1.137	52	0	0	9	363	71.1	0.2361996	1.90747984	1.755
Ohio	0202	2006	1.137	70	0	0	10	106	71.1	0.077147	2.0778588	1.913
Quebec	3015	2007	0.815	0	35.4	0	3	1219	4.7	0.020862	1.0711448	0.871
Quebec	3015	2010	0.815	0	35.4	0	6	671	4.7	0.0229824	1.07199296	0.907
Quebec	3015	2011	0.815	0	35.4	0	7	955	4.7	0.0381444	1.07805776	0.946
Quebec	3015	2015	0.815	0	35.4	0	11	1295	4.7	0.0812592	1.09530368	1.008
Quebec	3015	2017	0.815	0	35.4	0	13	417	4.7	0.0309738	1.07518952	1.098

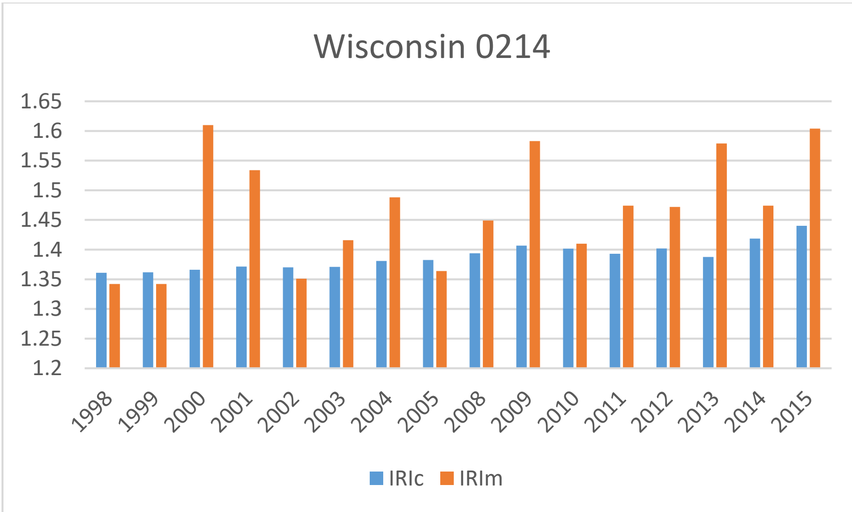
Table 2.8 Comparison between the predicted CRCP IRI and measured ones

LOCATION	SECTION NO.	YEAR	IRIi	PUNCH	AGE	FI	$P_{0.075}$	SF	IRIc	IRIm
Wisconsin	5040	1991	2.305	0	1	334	12	0.004355	2.30695975	2.351
Wisconsin	5040	1992	2.305	0	2	517	12	0.013468	2.3110606	2.312
Wisconsin	5040	1993	2.305	0	3	707	12	0.027612	2.3174254	2.311
Wisconsin	5040	1994	2.305	0	4	668	12	0.034788	2.3206546	2.373
Wisconsin	5040	1995	2.305	0	5	782	12	0.050895	2.32790275	2.395
Wisconsin	5040	1997	2.305	0	7	507	12	0.046228	2.3258026	2.323
Michigan	5363	1990	1.78	2	1	160	10.5	0.0018515	1.94083318	1.804
Michigan	5363	1991	1.78	2	2	269	10.5	0.00621	1.9427945	1.826
Michigan	5363	1992	1.78	2	3	227	10.5	0.007866	1.9435397	1.81
Michigan	5363	1993	1.78	2	4	352	10.5	0.016238	1.9473071	1.826
Ohio	5003	1991	1.028	0	1	269	16.3	0.004671	1.03010195	1.017
Ohio	5003	1992	1.028	0	2	242	16.3	0.0084078	1.03178351	1.109
Ohio	5003	1994	1.028	0	4	469	16.3	0.032524	1.0426358	1.092
Ohio	5003	1998	1.028	0	8	104	16.3	0.014532	1.0345394	1.037
Ohio	5003	1999	1.028	0	9	294	16.3	0.0459315	1.04866918	1.046
Ohio	5003	2000	1.028	0	10	462	16.3	0.080099	1.06404455	1.055
Ohio	5003	2001	1.028	0	11	230	16.3	0.0439593	1.04778169	1.047
Ohio	5003	2004	1.028	0	14	412	16.3	0.1000286	1.07301287	1.052

Table 2.9 Comparison between the predicted HMA IRI and measured ones

State	SHRP_ID	YEAR	IRI_i	Age	RD	TCS_{MH}	R_{SD}	R_m	$P_{0.075}$	$P_{0.02}$	PI	FI	SF	IRI_c	IRI_m
Wisconsin	0113	1998	0.909	1	5	0	48.41	884.763	11	6.8	6	634.8	5.948871093	1.034037738	0.983
Wisconsin	0113	1999	0.909	2	4	0	79.28	1017.9	11	6.8	6	874.1	6.400422634	1.028899104	0.999
Wisconsin	0113	2000	0.909	3	5	0	51.6	931.097	11	6.8	6	1103	6.381037778	1.06772864	1.031
Wisconsin	0113	2001	0.909	4	5	0	49.53	1170.53	11	6.8	6	901	6.437947018	1.085911058	1.043
Wisconsin	0113	2002	0.909	5	4	0	73.5	924.36	11	6.8	6	759	6.198281851	1.079242542	1.075
Wisconsin	0113	2004	0.909	7	6	0	36.13	858.826	11	6.8	6	1133	6.270334412	1.163761417	1.142
Wisconsin	0113	2005	0.909	8	6	0	31.38	888.431	11	6.8	6	973	6.180716278	1.182843279	1.197
Michigan	0115	1997	0.72	1	4	0	46.38	984.266	57.5	42.29999924	9	454.8	8.038185627	0.827814261	0.754
Michigan	0115	1998	0.72	2	6	0	37.49	894.819	57.5	42.29999924	9	316.4	7.4640238	0.889444618	0.834
Michigan	0115	1999	0.72	3	7	0	38.52	830.031	57.5	42.29999924	9	462.2	7.673722468	0.93278103	0.861
Michigan	0115	2000	0.72	4	7	0	25.26	964.147	57.5	42.29999924	9	623	7.677652662	0.953985616	0.876
Michigan	0115	2002	0.72	6	9	0	21.07	860.399	57.5	42.29999924	9	327	7.016637218	1.033307537	0.938
Ohio	0106	1997	1.141	1	1	0	66.38	1246.09	70.6	58.4	12	306.4	9.846555532	1.186557463	1.581
Ohio	0106	1998	1.141	2	1	0	61.92	1117.65	70.6	58.4	12	134.4	8.972726945	1.206875118	1.741
Ohio	0106	1999	1.141	3	2	0	38.09	969.709	70.6	58.4	12	293.2	8.355183979	1.247971171	1.811
Ohio	0106	2000	1.141	4	3	0	23.99	1091	70.6	58.4	12	425	8.123433176	1.290822489	1.76
Ohio	0106	2001	1.141	5	2	0	32.86	1210.17	70.6	58.4	12	221	8.14679209	1.292499786	1.809
Ohio	0106	2002	1.141	6	2	0	46.1	1020.35	70.6	58.4	12	193	8.460446108	1.322412621	1.817
Ohio	0106	2003	1.141	7	3	0	30.44	1243.78	70.6	58.4	12	438	8.554713338	1.373535227	1.82
Ohio	0106	2004	1.141	8	3	0	52.77	1408.31	70.6	58.4	12	379	9.535596401	1.424689276	2.012
Ohio	0106	2005	1.141	9	3	0	40.38	1103.56	70.6	58.4	12	463	8.899010974	1.441707978	1.948
Ohio	0106	2006	1.141	10	5	0	40.75	1542.72	70.6	58.4	12	128	8.317336378	1.501733809	1.992

State	SHRP_ID	YEAR	IRI_i	Age	RD	TCS_{MH}	R_{SD}	R_m	$P_{0.075}$	$P_{0.02}$	PI	FI	SF	IRI_c	IRI_m
Ohio	0106	2008	1.141	12	5	0	52.69	1288.18	70.6	58.4	12	376	9.437172278	1.611133474	2.091
Alberta	0501	1991	1.639	1	7	0	38.72	790.939	38.9	32.70000076	5	1084	7.398816788	1.811846094	1.727
Alberta	0501	1992	1.639	2	7	0	25.16	587.71	38.9	32.70000076	5	873	6.814233584	1.827463721	1.748
Alberta	0501	1993	1.639	3	7	0	37.18	677.909	38.9	32.70000076	5	996	7.166684287	1.847981831	1.737
Alberta	0501	1994	1.639	4	7	0	34.88	731.114	38.90000153	32.70000076	5	1232	7.36267101	1.869756755	1.771
Alberta	0501	1995	1.639	5	10	0	41.75	782.031	38.90000153	32.70000076	5	1389	7.582306926	1.960542193	1.861
Alberta	0501	1997	1.639	7	10	0	44.82	770.47	38.90000153	32.70000076	5	1017	7.389958762	2.004218095	1.974
Alberta	0501	1998	1.639	8	10	0	34.73	664.038	38.90000153	32.70000076	5	1140	7.208477064	2.024979717	2.042
Alberta	0501	1999	1.639	9	10	0	34.29	616.297	38.90000153	32.70000076	5	843.1	6.931733465	2.043225692	1.942
Alberta	0501	2000	1.639	10	12	0.4545	39.34	707.106	38.90000153	32.70000076	5	989	7.227491049	2.726953183	2.082
Alberta	0501	2001	1.639	11	13	0.147	65.91	595.964	38.90000153	32.70000076	5	775	7.15902555	2.365998029	2.042
Alberta	0501	2002	1.639	12	14	0.3	21.85	648.186	38.90000153	32.70000076	5	976	6.953986914	2.613385056	2.108
Alberta	0501	2003	1.639	13	14	0	31.92	688.963	38.90000153	32.70000076	5	1142	7.220378907	2.255633343	2.166
Alberta	0501	2004	1.639	14	15	0	50.48	847.102	38.90000153	32.70000076	5	802	7.38534534	2.318392111	2.135
Alberta	0501	2005	1.639	15	16	0	46.3	779.541	38.90000153	32.70000076	5	834	7.284952578	2.370687827	2.752
Alberta	0501	2006	1.639	16	16	0.2326	26.9	659.797	38.90000153	32.70000076	5	984	7.028096091	2.702176625	2.665
Quebec	0902	1999	1.215	2	4	0	33.18	1108.78	3.799999952	3.099999905	10	1596	6.240997972	1.3341228	1.524
Quebec	0902	2001	1.215	4	8	0	43.57	1047.79	3.799999952	3.099999905	10	1548	6.194957606	1.455969786	1.961
Quebec	0902	2003	1.215	6	12	0	45.34	1156.75	3.799999952	3.099999905	10	2041	6.480670806	1.586175305	2.289


Wisconsin 0214
1.65
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1998
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2001
2002
2003
2004
2005
2008
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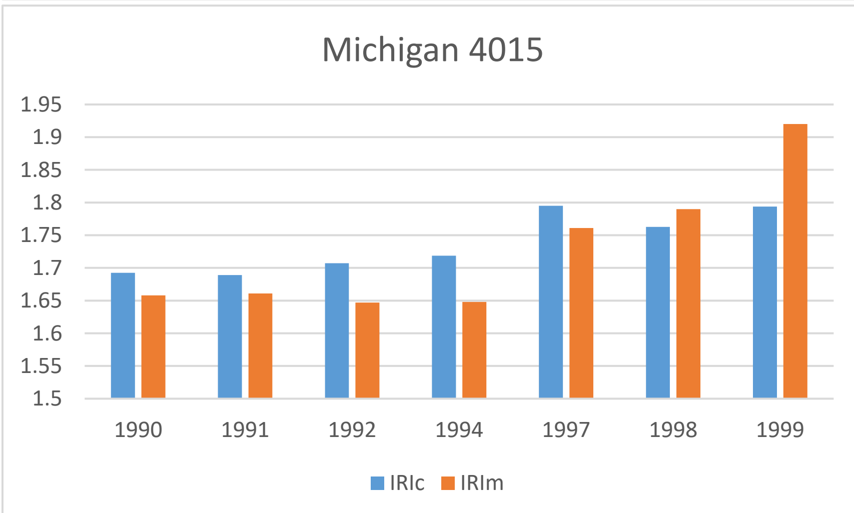
2011
2012
2013
2014
2015
IRIc
IRIm


Michigan 4015
1.95
1.9
1.85
1.8
1.75
1.7
1.65
1.6
1.55
1.5
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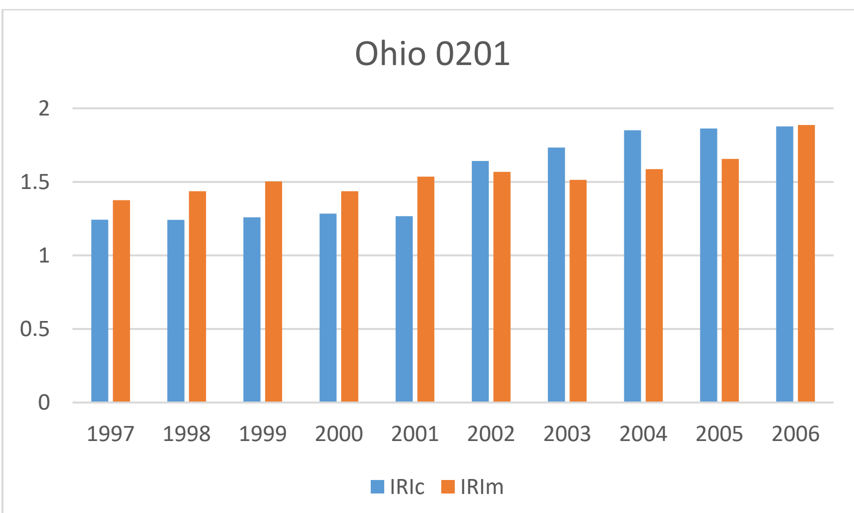
1991
1992
1994
1997
1998
1999
IRIc
IRIm


Ohio 0201
2
1.5
1
0.5
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
IRIc
IRIm

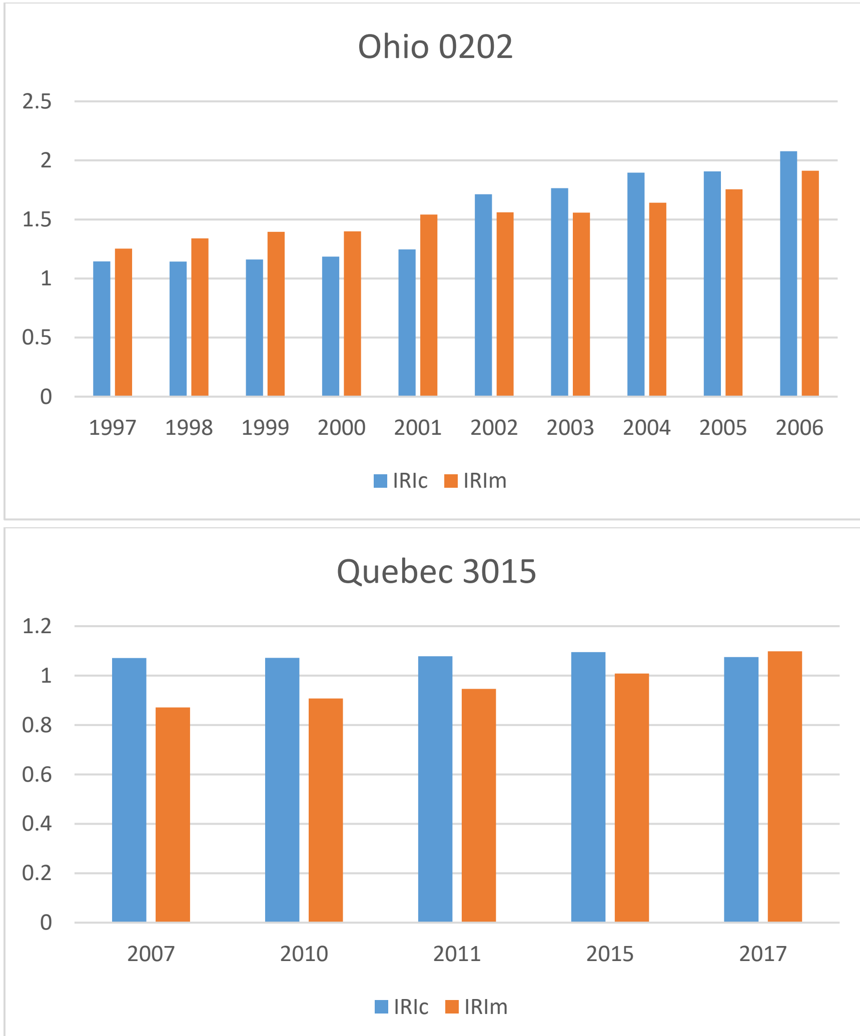


Figure 2.4 Comparison between the measured IRI with the calculated IRI for Jointed Plain Concrete Pavements

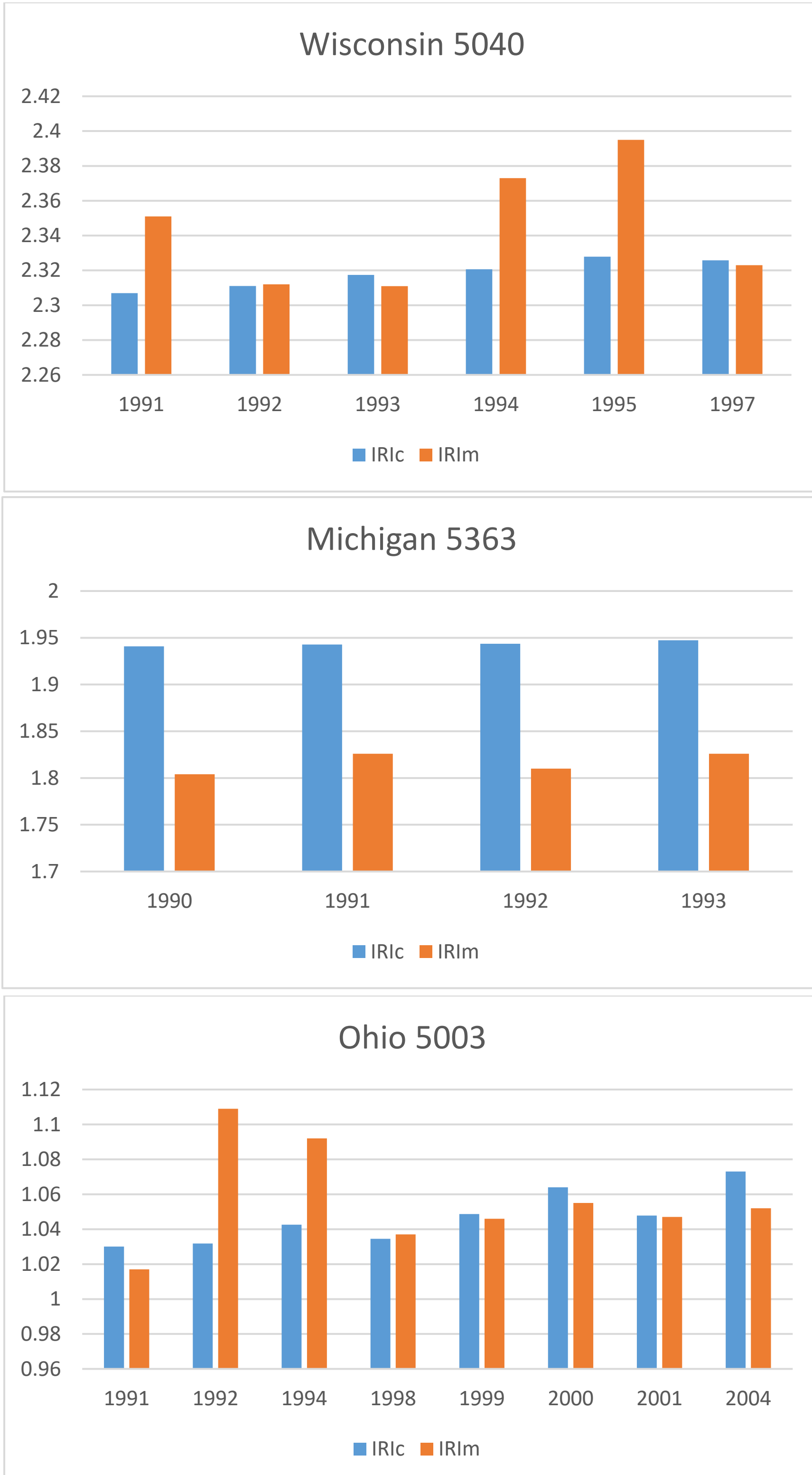
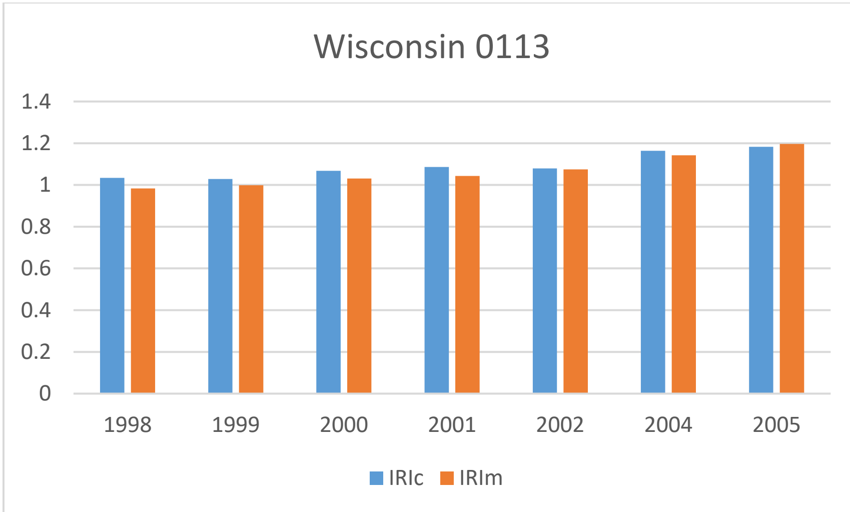
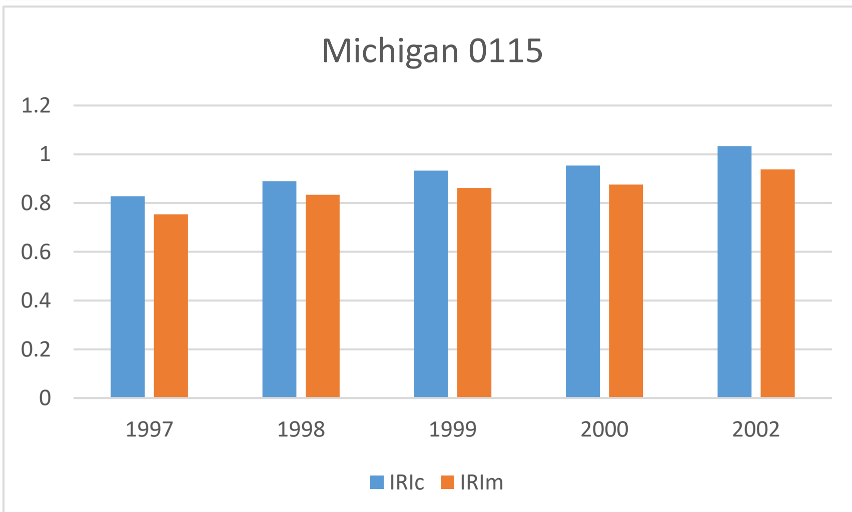
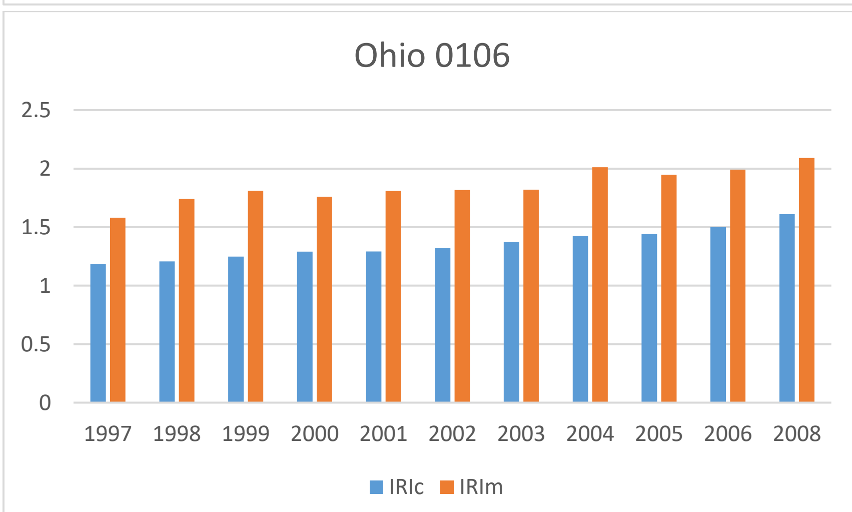
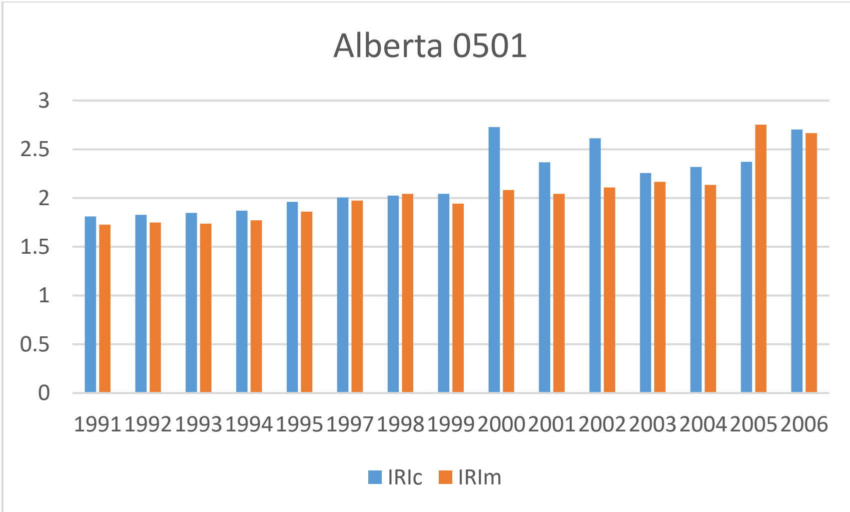


Figure 2.5 Comparison between the measured IRI with the calculated IRI for Continuous Reinforced Concrete Pavements


Wisconsin 0113
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1998
1999
2000
2001
2002
2004
2005
IRIc
IRIm


Michigan 0115
1.2
1
0.8
0.6
0.4
0.2
0
1997
1998
1999
2000
2002
IRIc
IRIm


Ohio 0106
2.5
2
1.5
1
0.5
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2008
IRIc
IRIm



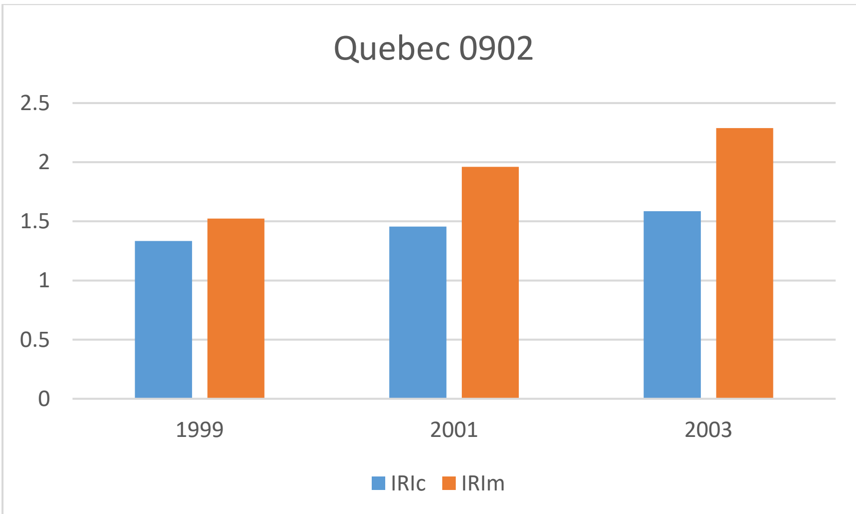


Figure 2.6 Comparison between the measured IRI with the calculated IRI for HMA Overlays Placed on Rigid Pavement