Prediction of Spalling and Roughness in the *Mechanistic-Empirical Pavement Design Guide*

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Abstract

This paper documents an assessment of the prediction of joint spalling and International Roughness Index (IRI) for jointed plain concrete pavements (JPCP) in the *Mechanistic-Empirical Design Guide* (MEPDG) report and software. The role of joint sealant type in the prediction of spalling is examined, as well as the sensitivity of predicted IRI to predicted spalling and other factors. Limitations of the predictive accuracy of the MEDG spalling and IRI models are detailed. Users of the MEPDG and its accompanying software should be aware of the inference space of the data from which these spalling and IRI models were developed, and the practical implications of using the MEPDG models to predict the effect of joint sealant type, joint spalling, climate, and other factors on roughness in jointed plain concrete pavements. The MEPDG software predicts essentially no spalling for joints with preformed sealant, but substantially more spalling – and exactly the same amount of spalling – for unsealed joints, hot-pour-sealed joints, and silicone-sealed joints.

Introduction

This paper documents an assessment of the prediction of joint spalling and International Roughness Index (IRI) for jointed plain concrete pavements (JPCP) in the *Mechanistic-Empirical Design Guide* (MEPDG) report and software. The *Mechanistic-Empirical Design Guide* (MEPDG) report referred to in this paper is the March 2004 Final Report on NCHRP Project 1-37A (Applied Research Associates 2004), available on the internet at http://www.trb.org/mepdg/guide.htm. Version 1.000 of the MEPDG software was used in the preparation of this paper. Personal communication with the MEPDG development team confirms that as of the end of January 2008, neither the joint spalling model nor the IRI model for JPCP had been recalibrated or modified from earlier versions of the software through version 1.000.

Roughness as a Performance Parameter

One of the ways in which the pavement design analysis approach in the MEPDG departs from that in the 1993 *AASHTO Guide* is that the adequacy of a design is not judged with respect to a single performance parameter (in the 1993 *Guide*, present serviceability index), but rather with respect to several performance parameters, depending on pavement type. For jointed concrete pavements, the performance parameters that are available to evaluate a trial design are IRI, transverse cracking, and mean joint faulting.

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The user of the MEPDG software can choose which performance parameters to use, as shown in Figure 1. It is not required that IRI be used as a performance criterion; a design can be evaluated with respect to faulting and/or cracking only.

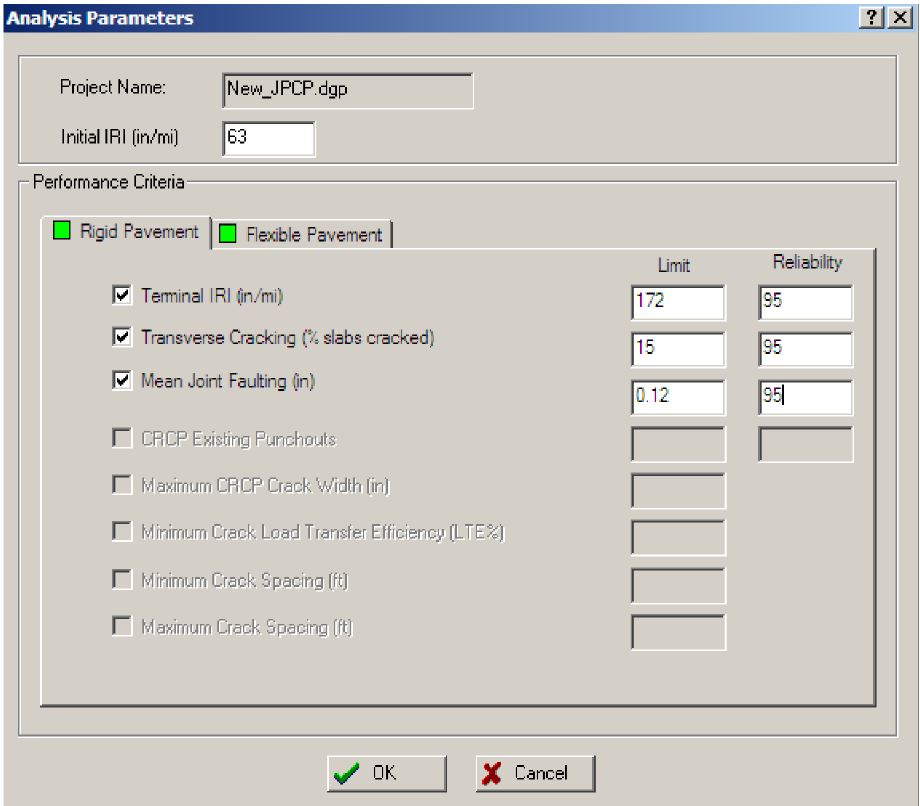

Figure 1. JPCP analysis parameters screen in the MEPDG software.

The regression model for the prediction of IRI is a function of, among other things, age, initial IRI, and quantities of transverse cracking, joint spalling, and joint faulting predicted by other regression models. Differences of opinion exist within the pavement community as to whether or not it is appropriate to use a performance parameter such as IRI, the prediction of which is not a function of a mechanistic pavement response (e.g., stress, strain, or deflection) in a mechanistically based design procedure.

That philosophical issue is not examined in this paper. Neither are the MEPDG predictions of transverse cracking and joint faulting examined in this paper. The subjects addressed here are the role of joint sealing in the MEPDG spalling model, and the prediction of roughness by the MEPDG IRI model for JPCP.

Joint Sealant Options

The *M-E Pavement Design Guide* states, on page 3.4.40:

> "Sealant type is an input to the empirical model used to predict spalling. Spalling is used in smoothness predictions, but it is not considered directly as a measure of performance in this Guide. The sealant options are liquid, silicone, and preformed."

However, the MEPDG software's user interface displays the joint sealant options as none, liquid, silicone, and preformed, as shown in Figure 2.

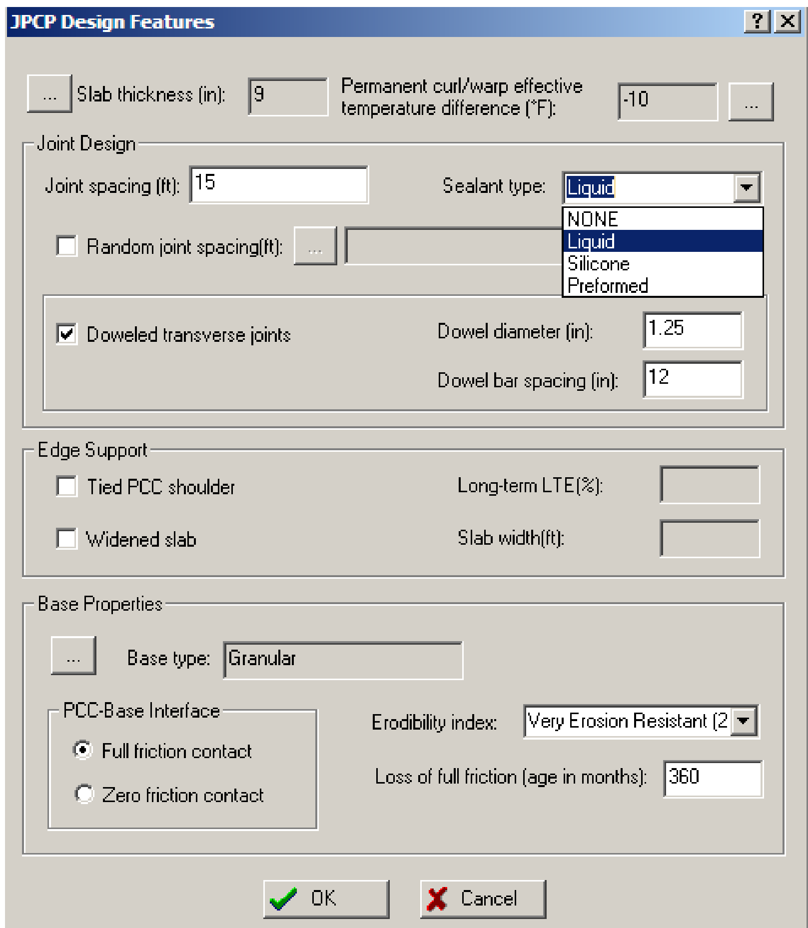

Figure 2. JPCP Design Features input screen in MEPDG software.

Spalling Prediction Model

The model used in the MEPDG software to predict spalling is presented in the *M-E Pavement Design Guide* as equation 3.4.43 in Part 3, Chapter 4 (page 3.4.94), as shown here in Equation 1.

$$SPALL = \left[\frac{AGE}{AGE + 0.01}\right]\left[\frac{100}{1 + 1.005^{(-12 * AGE + SCF)}}\right] \tag{1}$$

where:

SPALL	=	percentage of joints spalled (medium and high severities)
AGE	=	pavement age since construction, years
SCF	=	scaling factor based on site-, design-, and climate-related variables

The equation for the scaling factor is given as equation 3.4.44 in Part 3, Chapter 4 (page 3.4.95) as shown here in Equation 2.

$$\begin{aligned} SCF = & -1400 + 350 \bullet AIR\% \ (0.5 + PREFORM) + 3.4 \ f'_c \bullet 0.4 \\ & -0.2\,(FTCYC \bullet AGE) + 43\ h_{PCC} - 536 \quad WC\_Ratio \end{aligned} \tag{2}$$

where:

SCF	=	spalling prediction scaling factor used in SPALL equation
AIR%	=	PCC air content, percent
AGE	=	time since construction, years
PREFORM	=	1 if preformed sealant is present, 0 of not
f'_c	=	PCC compressive strength, psi
FTCYC	=	average annual number of freeze-thaw cycles
h_{PCC}	=	PCC slab thickness, inches
WC_Ratio	=	PCC water/cement ratio

Statistics: R^2 = 78 percent, N = 179, SEE = 6.8 percent of joints

The cited source for the MEPDG spalling model is a report by Hoerner et al. (2000). The model is presented as equation 97, on page 131 of that report, in the exact same way that it appears in the MEPDG text, as shown in this paper in Equation 1. However, the equation for the scaling factor (equation 98 on page 131 of Hoerner et al.'s *Performance-Related Specifications*, or PRS, report), does not match the scaling factor equation presented in the MEPDG:

$$\begin{aligned} SCF = & -1400 + 350 \bullet AIR\% \ (0.5 + PREFORM) + 3.4 \ {f'_c}^{0.4} \\ & -0.2\,(FTCYC \bullet AGE) + 43\ h_{PCC} - 536 \quad WC\_Ratio \end{aligned} \tag{3}$$

The portion of the MEPDG's equation 3.4.44 that is presented as $3.4\, f'_c \bullet 0.4$ is presented in the PRS report's equation 98 as $43.4\, {f'_c}^{0.4}$. Personal communication with the MEPDG software developer confirms that that this term appears in the software code as it does in the PRS report.

Examination of the scaling factor model clearly shows that the spalling equation in the MEPDG report and software does not differentiate among no sealant, liquid sealant, and silicone sealant in the prediction of joint spalling. It only differentiates between preformed sealant and the other three possibilities. Joints with no sealant, liquid sealant, and silicone sealant are all predicted by the model in the MEPDG report and software to develop the exact same amount of spalling.

The data on which this model is based are summarized in the PRS report (Table 32, page 129, shown here as Table 1). Field data from 88 LTPP GPS-3 sections were supplemented with data from laboratory tests on specimens subjected to accelerated freeze-thaw testing. The GPS-3 field data spans an age range from 2.0 to 27.4 years (average 13.7 years). The laboratory data spans an estimated age range from 3.3 to 28.1 years (average 11.7 years), based on the number of freeze-thaw cycles applied.

Table 1. Summary of GPS-3 JPCP data and CTL laboratory data used in spalling model development, from PRS report.

Data Source	Variable	Min	Max	Mean	Standard Deviation
LTPP (146 records)	Medium- and high-severity spalling, percent joints	0.0	26.1	1.3	3.8
	Age, years	2.0	27.4	13.7	5.2
	PCC thickness, in	7.0	14.3	9.8	1.3
	Water cement ratio	0.27	0.72	0.45	0.09
	Air content, percent	3.8	9.8	5.7	1.1
	Compressive strength, psi	3,840	12,488	6,335	1,937
	Air freeze-thaw cycles	15	3102	1101	653
	Sealant type	33 records had preformed sealantss			
CTL (33 records)	Medium- and high-severity spalling, percent joints[a]	0.0	84.0	28.7	27.5
	Age, years[b]	3.3	28.1	11.7	8.1
	PCC thickness, in	6.0	6.0	6.0	0
	Water cement ratio	0.42	0.50	0.45	0.04
	Air content, percent	2.5	4.8	3.7	0.9
	Compressive strength, psi	2,720	7,150	4,984	1,595
	Total air freeze-thaw cycles[c]	262	2,250	942	653
	Sealant type	No records had a preformed sealant			

Notes:

(a) CTL data were measured as average length of spalling per joint, percent. This was converted to percent joint spalled using the assumption that average length of spalling per joint (in percent) is approximately equal to percentage of spalled joints.

(b) An average air freeze-thaw cycle of 80 per year was assumed and used to estimate age for the CTL data.

(c) The CTL laboratory study measured the total in-pavement freeze thaw cycles at a depth of 76 mm (3 in) from the slab surface. The cumulative number of in-pavement freeze-thaw cycles was converted to tatal air freeze-thaw cycles by multiplying the measured in-pavement cycles by a factor of 7.5. The 7.5 multiplying factor was obtained by determining the ratio of air and pavement base freeze-thaw cycles in Illinois.

Spalling Prediction Examples

The MEPDG report's spalling model and the PRS report's spalling model are compared with the output from the MEPDG software using a series of examples. The trial design is a 254-mm [10-inch] JPCP on a 152-mm [6-inch] granular base (identified in the input file as "fairly erodible"), over a gravel subbase and fine-grained subgrade (73.5 percent fines). The concrete mix has a water/cement ratio of 0.5, air content of 5 percent, and 28-day flexural strength of 4.48 MPa [650 psi]. The joints are spaced at 4.6 m [15 feet] and have dowels 32 mm [1.25 inch] in diameter spaced 305 mm [12 inches] apart. The shoulders are asphalt concrete.

The first site considered is Columbus, Ohio. The MEPDG software's climatic data file for the Port Columbus International Airport gives the Freezing Index as 247.37°C-days [445.26°F-days], with an average of 51 freeze-thaw cycles per year. The initial ADTT was set at 2,000, and other truck traffic distribution and growth rate inputs were set such that the accumulated rigid pavement equivalent single-axle loads (ESALs) over a 60-year analysis period are computed to be 112.94 million. (Note that for rigid pavements, computed ESALs are not reported in the output summary from the MEPDG software, but the total rigid ESALs over the analysis period are reported in an accompanying output file called ESALs.txt.) The initial IRI was set at 63 inches per mile.

This example was first run using the above inputs and with no transverse joint sealant. The spalling prediction results are shown in Figure 3. Note that the air content input to the PRS and MEPDG equations was 5 percent.

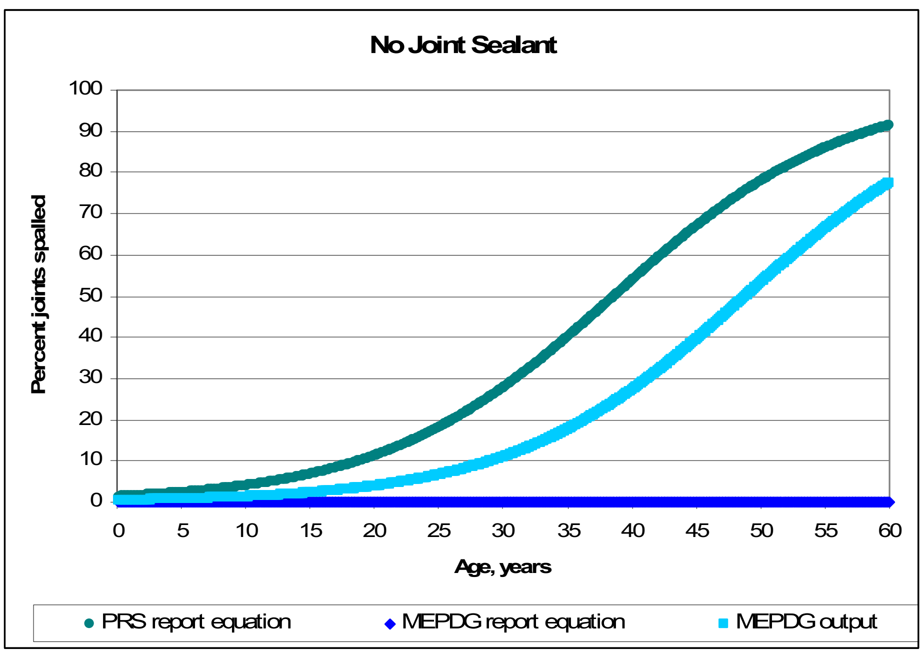

Figure 3. Predicted spalling for no joint sealant, equations (at air content = 5 percent) versus MEPDG software.

The spalling predicted by the model as it appears in the MEPDG report yields only zero or near-zero values, which are not at all similar to the spalling values predicted by either the PRS report equation or the MEPDG software output. This is attributable to the previously mentioned typographical error in the scaling factor model as it appears in the MEPDG report (Equation 2).

Examination of the MEPDG software input screens reveals that there is no place to input an air content for the concrete mix. Personal communication with the MEPDG software developer confirms that the air content of the concrete mix is fixed in the software, at a value of 6 percent.

Figure 4 shows the spalling predicted by the MEPDG software and the PRS equation, for a range of air contents, and with compressive strength estimated from the correlation $f'_c = (MR/9.5)^2$, where MR is the 28-day modulus of rupture in psi (see page 2.2.36 of the MEPDG report). The spalling prediction output from the MEPDG software agrees with the spalling predicted by the PRS equation when the air content entered into the PRS equation is 6 percent.

Effect of Fixed Air Content on Prediction Quality

The plots in Figure 4 suggest that the spalling predicted by this model is fairly sensitive to air content. For the Columbus, Ohio example described, each 1-percent difference in the air content corresponds to about an 8-year difference in the number of years to 50 percent joint spalling.

Both the MEPDG and the PRS report give the coefficient of determination (R^2) of the joint spalling model as 78 percent and the standard error of the estimate (SEE) as 6.8 percent. Neither report gives the partial R^2 associated with the concrete air content, that is, how much of the model's R^2 of 78 percent is contributed by how much the total variation in observed spalling can be explained by variation in air content.

To whatever degree the model is sensitive to air content – however much air content contributes to the total R^2 and SEE associated with the model – the actual R^2 of the model as it is implemented in the MEPDG software is less than 78 percent, if air content is fixed in the software rather than allowed to vary. Correspondingly, the actual standard error of the estimate of the model as it is implemented in the MEPDG software is greater than 6.8 percent. Since the variance (the square of the standard error of the estimate, $(6.8)^2 = 46.24$ percent) associated with the spalling model is a direct input into the calculation of the predicted IRI at the user-input desired reliability level (see MEPDG report page 3.4.96), the practical consequence of fixing the concrete air content in the MEPDG software is that the actual IRI at the user-input reliability level is greater than the IRI reported by the MEPDG software for that reliability level.

Effect of Joint Sealant Type and Climate on Predicted Spalling

The example described above was run four times for the Columbus, Ohio climate, to examine the spalling predictions for each of the four joint sealing options displayed in the MEPDG software: no sealant, liquid sealant, silicone sealant, and preformed sealant. The results obtained matched exactly for the no sealant, liquid sealant, and silicone sealant options. The preformed sealant option, however, yielded a prediction of essentially no spalling, over a 60-year analysis period.

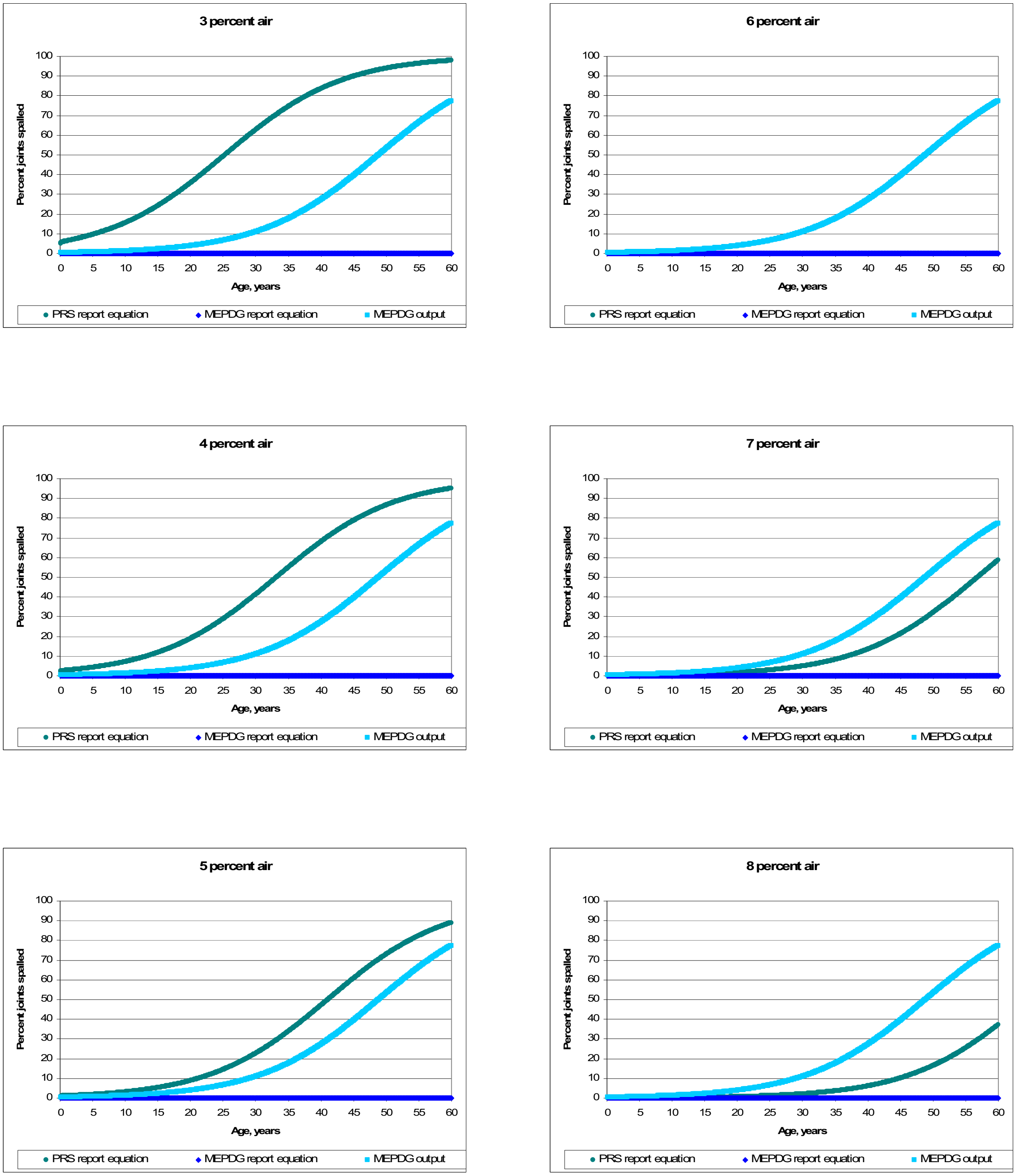

Figure 4. Spalling prediction for various air contents, PRS equation versus MEPDG software output, no joint sealant.

$$IRI = IRI_I + 0.013\,\%CRACKED + 0.007\,\%SPALL + 0.001\,TFAULT + 0.03\,SITE \qquad (8)$$

where:

IRI_I	=	initial smoothness measured as IRI, m/km
%CRACKED	=	percent slabs with transverse cracking and corner cracks (all severities)
%SPALL	=	percentage of joints with spalling (medium and high severities)
PATCH	=	percent surface area with flexible and rigid patching (all severities)
TFAULT	=	total joint faulting accumulated per km, mm
SITE	=	site factor $= AGE\left(1+FI\right)^{1.5}\left(1+P200\right)*10^{-6}$ (9)
AGE	=	pavement age, years
FI	=	freezing index, °C-days
P200	=	percent subgrade material passing the 0.075-mm (#200) sieve
Statistics:		R^2 = 70 percent, N = 183, SEE = 0.35 m/km

The data on which this model is based are summarized in the PRS report (Table 37, page 153) as shown here in Table 4. Note that Tables 3 and 4 report the same ranges and means for measured IRI, initial estimated IRI, transverse cracking, joint spalling, total faulting, and corner breaks.

Table 4. Summary of GPS-3 JPCP data used in IRI model development, from PRS report.

Distress variable	Minimum	Maximum	Mean
Transverse cracking[1] (percent slabs)	0	42	3
Corner cracks[1] (percent slabs)	0	20	1
Transverse joint spalling[2] (percent joints)	0	100	16
Total transverse joint faulting (mm/km)	0	1367	230
Annual mean temperature (°C)	5.1	21.8	10.2
Freezing index (°C-days)	0	1862	301
Percent subgrade passing 0.075-mm sieve	1	98	39.5
Initial estimated IRI (m/km)	0.4	1.78	1.22
IRI measured over time (m/km)	0.76	3.6	1.71

[1] Transverse cracking and corner cracks (all severities) were combined to estimate total cracking.
[2] Only medium- and high-severity spalling were considered.

The MEPDG's Appendix PP presents a five-page tabulation (Table 16, pages 35 to 39) of these data. There are 68 different LTPP GPS-3 sections in this data set, some with only one observation and some with as many as seven (i.e., IRI measured on the same section at different points in time). There are 184 data points reported in this table, but two of them are repeated, so there are actually 182 different observations. The data summary tables in the MEPDG and PRS report do not report the age range of the observations, but from the tabulation in Appendix PP it can be determined that the range is 2.37 to 33.71 years, with an average of 14.11 years.

Personal communication with the MEPDG software developer confirms that the JPCP IRI model is coded in the software as it appears in Equation 4 above and in equation 3.4.42 in the MEPDG report.

The development of the MEPDG's JPCP IRI model is documented in the MEPDG's Appendix PP, where it appears (as equation 20, on page 22, of that Appendix) in the form shown here as Equation 6 (with a typographical error corrected).

$$IRI = IRI_I + 0.013\,TC + 0.007\,SPALL + 0.005\,PATCH + 0.0015\,TFAULT + 0.4\,SF \quad (6)$$

where:

IRI_I	=	initial smoothness measured as IRI, m/km
CRK	=	percent slabs with transverse cracks (all severities)
SPALL	=	percentage of joints with spalling (all severities)
PATCH	=	percent surface area with flexible and rigid patching (all severities)
TFAULT	=	total joint faulting accumulated per km, mm
SF	=	site factor $= AGE\,(1+FI)(1+P200)/1000000$ (7)
AGE	=	pavement age, years
FI	=	freezing index, °C-days
P200	=	percent subgrade material passing the 0.075-mm sieve

The data on which this model is based are summarized in Appendix PP (Table 10, page 19) as shown here in Table 3.

Table 3. Summary of GPS-3 JPCP data used in IRI model development, from MEPDG Appendix PP.

Distress variable*	Minimum	Maximum	Mean
Durability cracking (number per km)	0	231	2.5
Longitudinal cracking (m per km)	0	1000	53
Transverse cracking (percent slabs)	0	42	3
Corner breaks (percent joints)	0	20	1
Transverse joint spalling (percent joints)	0	100	16
Total transverse joint faulting (mm/km)	0	1367	230
Patching (percent surface area)	0	18	1
Initial estimated IRI (m/km)	0.4	1.78	1.22
IRI measured over time (m/km)	0.76	3.6	1.71

*All severities, unless otherwise noted.

The PRS report (Hoerner et al. 2000) also seems to be the source of the MEPDG's JPCP IRI model, although it is not cited as such in the MEPD nor in its Appendix PP. The model appears in the PRS report (as equation 108 on page 154) as shown here in equation 8.

$$IRI = IRI_I + 0.013\,\%CRACKED + 0.007\,\%SPALL + 0.001\,TFAULT + 0.03\,SITE \quad (8)$$

where:

IRI_I =	initial smoothness measured as IRI, m/km	
%CRACKED =	percent slabs with transverse cracking and corner cracks (all severities)	
%SPALL =	percentage of joints with spalling (medium and high severities)	
PATCH =	percent surface area with flexible and rigid patching (all severities)	
TFAULT =	total joint faulting accumulated per km, mm	
SITE =	site factor $= AGE\,(1 + FI)^{1.5}\,(1 + P200) \times 10^{-6}$	(9)
AGE =	pavement age, years	
FI =	freezing index, °C-days	
P200 =	percent subgrade material passing the 0.075-mm (#200) sieve	
Statistics:	R^2 = 70 percent, N = 183, SEE = 0.35 m/km	

The data on which this model is based are summarized in the PRS report (Table 37, page 153) as shown here in Table 4. Note that Tables 3 and 4 report the same ranges and means for measured IRI, initial estimated IRI, transverse cracking, joint spalling, total faulting, and corner breaks.

Table 4. Summary of GPS-3 JPCP data used in IRI model development, from PRS report.

Distress variable	Minimum	Maximum	Mean
Transverse cracking[1] (percent slabs)	0	42	3
Corner cracks[1] (percent slabs)	0	20	1
Transverse joint spalling[2] (percent joints)	0	100	16
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Initial estimated IRI (m/km)	0.4	1.78	1.22
IRI measured over time (m/km)	0.76	3.6	1.71

[1] Transverse cracking and corner cracks (all severities) were combined to estimate total cracking.
[2] Only medium- and high-severity spalling were considered.

The MEPDG's Appendix PP presents a five-page tabulation (Table 16, pages 35 to 39) of these data. There are 68 different LTPP GPS-3 sections in this data set, some with only one observation and some with as many as seven (i.e., IRI measured on the same section at different points in time). There are 184 data points reported in this table, but two of them are repeated, so there are actually 182 different observations. The data summary tables in the MEPDG and PRS report do not report the age range of the observations, but from the tabulation in Appendix PP it can be determined that the range is 2.37 to 33.71 years, with an average of 14.11 years.

As Table 5 shows, there are several discrepancies between the ranges reported in the data summary tables and the data tabulated in Appendix PP.

Table 5. JPCP IRI model data ranges reported in summary tables and in Appendix PP tabulation.

Data element	Range in summary tables	Range in tabulated data
Measured IRI, m/km	0.76 to 3.6	0.77 to 4.18
Initial estimated IRI, m/km	0.4 to 1.78	0.43 to 2.59
Transverse cracking, percent slabs	0 to 42	0 to 65.1
Spalling, percent joints	0 to 100	0 to 105.4 (see note 1)
Total faulting, mm/km	0 to 1367	0 (see note 2) to 1589.7

Note 1: More than 100 percent joint spalling is reported for three different GPS-3 sections.
Note 2: There are 19 instances of total faulting reported as zero when nonzero total faulting is reported for the same section at one or more younger ages.

Some subtle but important differences in how the JPCP IRI model appears in the PRS report and how it appears in the MEPDG report and its Appendix PP are summarized below.

Definition of Cracking

For the PRS report's version of the model, the cracking term is defined as "percentage of slabs with transverse cracking and corner cracks (all severities)." For the MEPDG's version of the model, the cracking term is defined in Part 3, Chapter 4 as "percent slabs with transverse cracks (all severities)" and similarly in Appendix PP as "percentage of slabs with transverse cracking (all severities)." The MEPDG design methodology does not include a model for predicting corner cracking, so the cracking term in the MEPDG's JPCP IRI model cannot be based on both transverse and corner cracking, but rather must be based on transverse cracking only. Both the PRS report and the MEPDG's Appendix PP give the cracking coefficient as 0.013 for IRI in meters per kilometer. The MEPDG's Part 3, Chapter 4 gives the cracking coefficient as 0.8203 for IRI in inches/mile (= 0.01295 ≈ 0.013, for IRI in m/km).

According to a summary of the contributions of each of several variables to the coefficient of determination (R^2) of the IRI model, as determined by stepwise regression, corner cracking was found to be the third most important of the variables considered, after faulting and initial IRI. This is shown in Table 12 on page 22 of the MEPDG's Appendix PP, reproduced here as Table 6. Corner cracking was found to contribute 11.62 percent to the total R^2. Transverse cracking, in contrast, was found to contribute only 2.4 percent to the total R^2.

Definition of Spalling

The spalling term of the JPCP IRI model is defined in both the PRS report and the MEPDG's Part 3, Chapter 4 as the "percentage of joints with spalling (medium and high severities)." It is defined in the MEPDG's Appendix PP as the "percentage of joints with spalling (all severities)," and according to the note ("all severities, unless otherwise noted") at the bottom of Table 3, taken from Appendix PP, low-, medium-, and high-severity spalling were considered together in the development of the IRI model as it appears in Appendix PP. The data tabulation in Appendix PP includes a column of data labelled "Percent Joints Spalled," and does not specify whether or not the quantities given include low-severity spalling.

Table 6. Summary of stepwise regression output for the MEPDG's JPCP IRI model, from MEPDG Appendix PP.

Step	Distress Variable	Partial R[2]	R[2]	Significance Level (Prob>F)
1	Wheelpath faulting, mm	0.2896	0.2896	0.001
2	Initial IRI	0.1258	0.4156	0.0001
3	Corner breaks	0.1162	0.5316	0.0001
4	Flexible patching	0.0534	0.5851	0.0001
5	Longitudinal joint damage, m	0.0346	0.6197	0.0012
6	Transverse cracking	0.0240	0.6437	0.0053
7	Transverse crack seal	0.0174	0.6611	0.0148
8	Rigid patching	0.0161	0.6772	0.0166
9	Transverse joint spalling	0.0183	0.6955	0.0092
10	Age	0.0061	0.7016	0.0977
11	Map cracking	0.0065	0.7082	0.1077
12	Longitudinal joint spalling	0.0081	0.7163	0.0676

[1] All variables presente are significant at the 0.1500 level. Variables left out did not meet the 0.1500 significance level for entry into the model.
[2] R^2 is the coefficient of determination.
[3] The distress variables listed may not include all severities.

And yet, the spalling term's regression coefficient of 0.4417 given in the MEPDG's Part 3, Chapter 4 for IRI in inches per mile, divided by 63.357, yields a value of 0.00697 (≈ 0.007) for IRI in meters per kilometer. Furthermore, both the data summary table in the Appendix PP (see Table 3) and the data summary table in the PRS report (see Table 4) report the same average, 16 percent, for the joint spalling data used in the IRI model regression. It remains unclear whether or not low-severity spalling quantities were used in the development of the IRI model as it appears in the MEPDG report and software.

Patching Term

The JPCP IRI model as it appears in Appendix PP includes a term for patching, which is not present in the IRI model as it appears in either the PRS report or Part 3, Chapter 4 of the MEPDG. The inclusion of this term suggests that regression was done to determine the coefficient of this term, but that seems inconsistent with the fact that the coefficients of the cracking and spalling terms are the same in the PRS report as in the MEPDG's Appendix PP. It is conceivable that the average patching area was so small that the inclusion or exclusion of patching in the regression would not change the coefficients of the other variables beyond the three significant digits shown.

Coefficient and Exponent on Freezing Index Term

In the PRS report, the Freezing Index term in the site factor equation appears as $(1 + FI)^{1.5}$, where FI is in °C-days. The 1.5 exponent on the Freezing Index term of the site factor equation in the PRS report does not appear in either the MEPDG or its Appendix PP. Personal communication with the MEPDG software developer confirms that in the code the exponent on the (1 + FI) term is 1.0 rather than 1.5.

Comparisons of IRI Predictions

The consequences of these differences in the various presentations of the JPCP IRI model were examined using the data tabulated in the MEPDG's Appendix PP. Figure 5 shows how IRI predicted from the PRS report's model (Equation 8) compares to IRI predicted from Appendix PP's model (Equation 6). Figure 6 shows how IRI predicted from the PRS report's model (Equation 8) compares to IRI predicted from Part 3, Chapter 4's model (Equation 6).

Figure 7 illustrates how the predictions from the three IRI models compare to the measured IRI data on which they are based. The closer the *x* coefficient of the linear trendline equation is to 1.0, the closer the constant of the equation is to 0, and the closer the R^2 of predicted to actual IRI is to 1.0, the better the prediction is. As Figure 7 shows, the best prediction is given by the PRS model (Equation 8), followed closely by the Appendix PP model (Equation 6) and then the Part 3, Chapter 4 model (Equation 6). That the *x* coefficient of the linear trendline is less than 1.0 for all three models means that all three are more likely to underpredict IRI than to overpredict it.

Contribution of Spalling to IRI

Examination of the IRI model shows that the contributions of cracking, spalling, and faulting to predicted IRI are linear, and not interactive. Regardless of the amounts of cracking and faulting present, the contribution of medium- and high-severity joint spalling to the predicted IRI in inches per mile is roughly 0.44 times the percent of joints spalled.

Recall that faulting, initial IRI, and corner breaks were by far the most significant variables in the IRI model regression, and also that transverse joint spalling contributed only 1.83 percent to improvement in the R^2 of the IRI model. This apparent insensitivity of the IRI model to spalling seems to be at odds with the sensitivity implied by the spalling coefficient in the model. A range of 0 to 100 percent joints with medium- and high-severity spalling corresponds to a contribution of 44 inches/mile to the predicted IRI.

The sensitivity of the JPCP IRI model to spalling can also be examined by comparing the results from the example described earlier, run with doweled joints, for three different climates: Columbus, Fargo, and El Paso. For each of the three locations, as reported earlier in this paper, the preformed sealant option results in zero or near-zero predicted spalling, and the other three sealant options (none, liquid, and silicone) all result in the exact same predicted spalling.

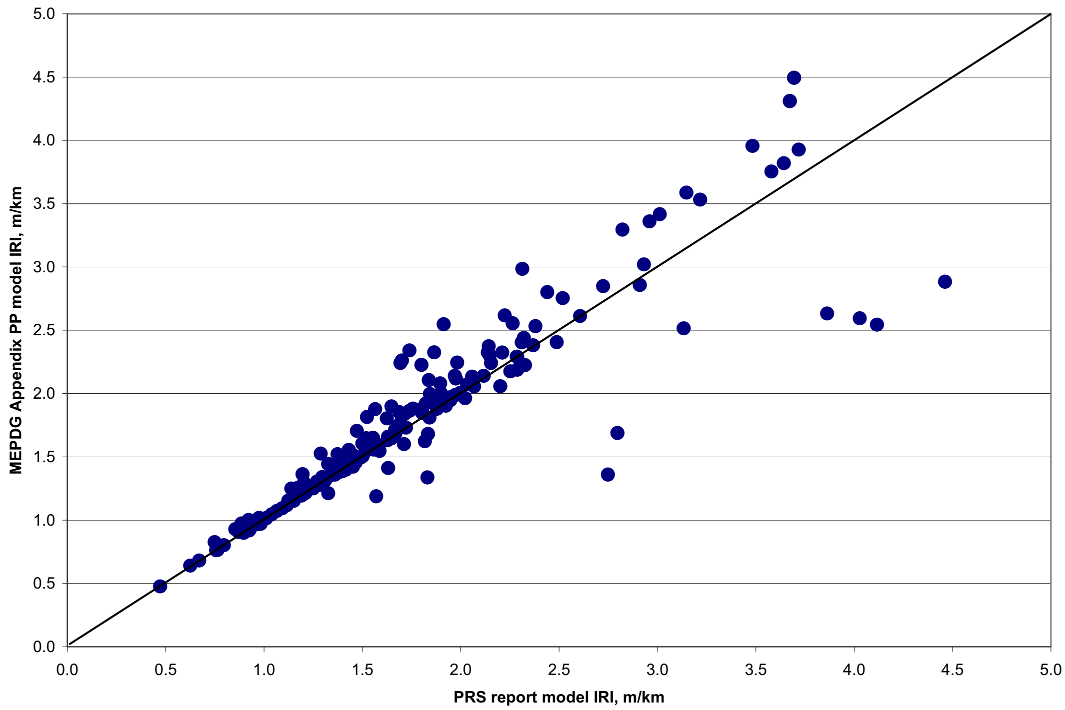

Figure 5. JPCP IRI from PRS model versus MEPDG Appendix PP model.

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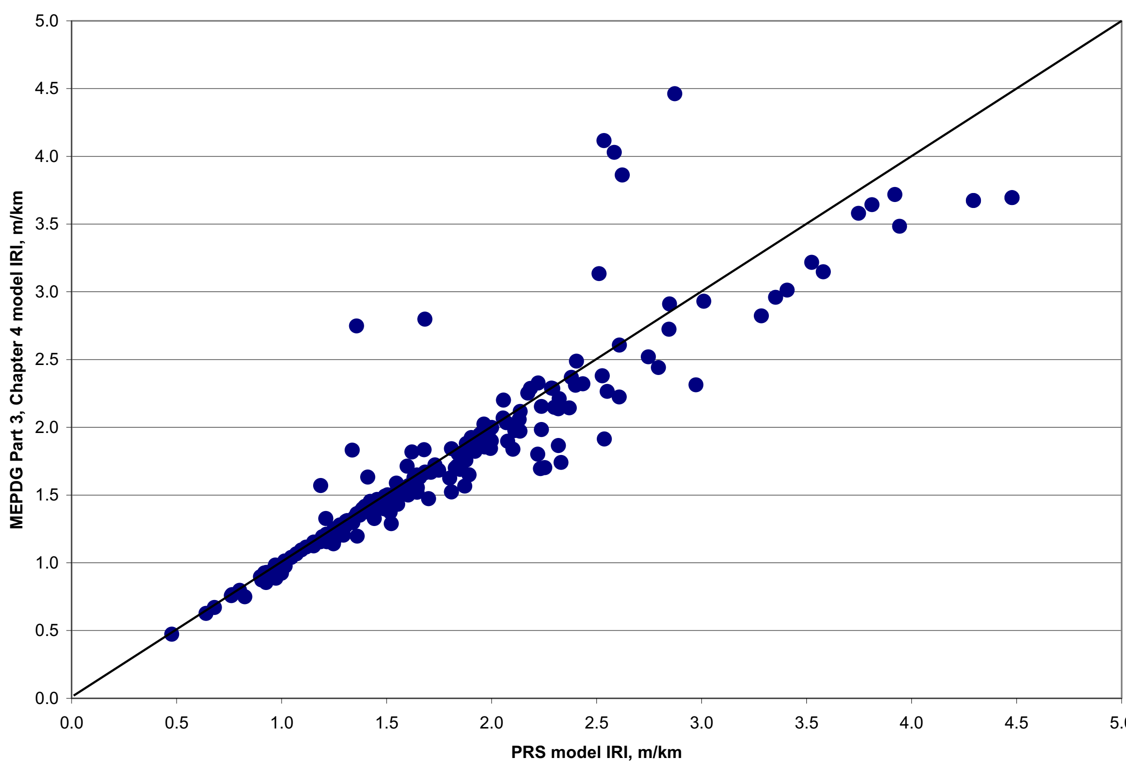

Figure 6. JPCP IRI from PRS model versus MEPDG Part 3, Chapter 4 model.

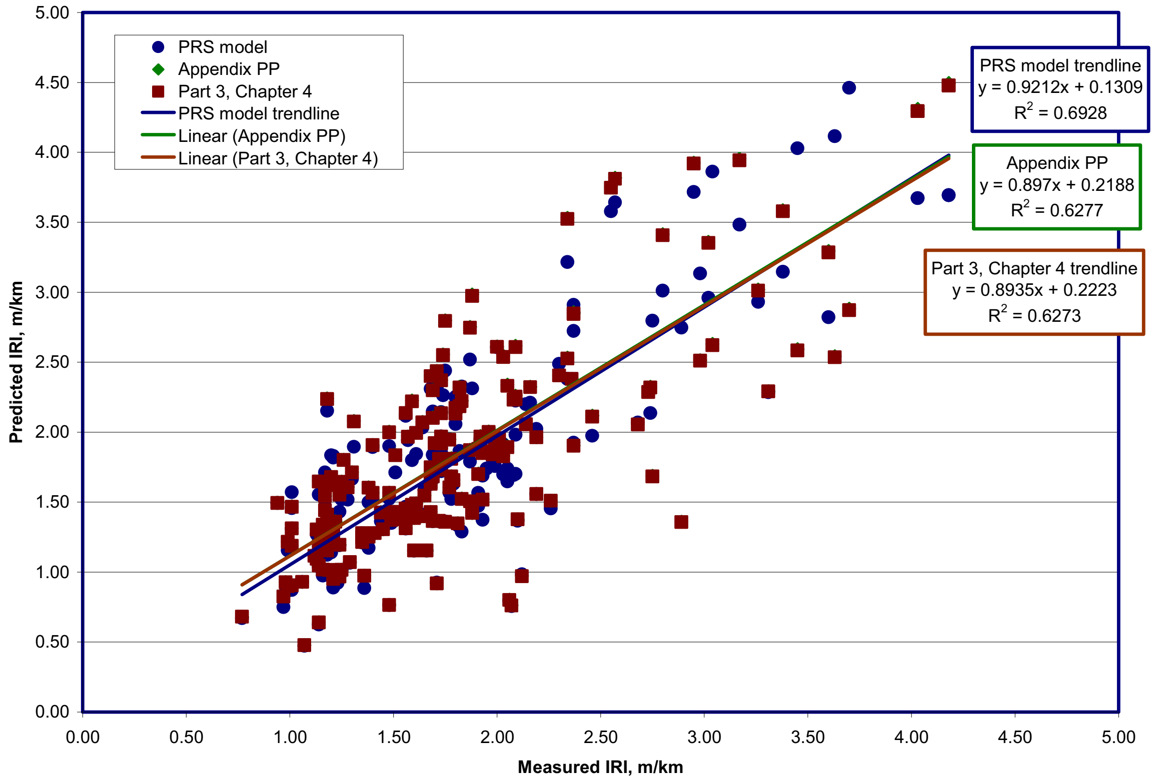

Figure 7. Prediction quality of IRI models with respected to measured values.

The differences in predicted spalling among the three locations are not direct indicators of the magnitudes of the differences in predicted IRI, since Freezing Index is a variable in both the spalling and IRI models.

Figure 8 indicates that the spalling predicted by the MEPDG software is not very sensitive to differences in climate for the first 25 or so years of service life, but becomes increasingly sensitive to climate at greater ages. The confidence one should associate with the spalling quantities predicted for 30 years or more is limited, considering that the spalling model was developed using data from a set of pavement sections that were all less than 28 years old. This, together with the previously highlighted sensitivity of the spalling model to the concrete air content are notable, and worthy of further examination by comparison with field data.

The MEPDG spalling model suggests that joints that are unsealed, hot-pour sealed, or silicone sealed will all develop exactly the same amount of spalling, for any length of analysis period, any climate, any traffic level, any concrete air content – indeed, any combination of design inputs. Joints with preformed sealants, on the other hand, are predicted to develop essentially no spalling, for any length of analysis period, any climate, any traffic level, any concrete air content – any combination of design inputs.

Figure 9 illustrates the notable sensitivity of JPCP IRI predicted by the MEPDG software to the combination of climate and joint spalling (which in turn is notably sensitive to climate, according to the MEPDG software). The predicted IRI becomes increasingly sensitive to whether or not preformed sealants are used as the Freezing Index increases.

Note that both Figure 8 and Figure 9 show the results of MEPDG software runs for a trial design with dowelled joints. When the same runs are conducted assuming the joints are undowelled, the predicted IRI values are substantially larger. For example, for the Columbus, Ohio site, for preformed sealant and no dowels, the predicted IRI at 60 years is 411 inches per mile, or 6.49 m/km. For any other sealant option and no dowels, the predicted IRI at 60 years is 445 inches per mile, or 7.02 m/km.

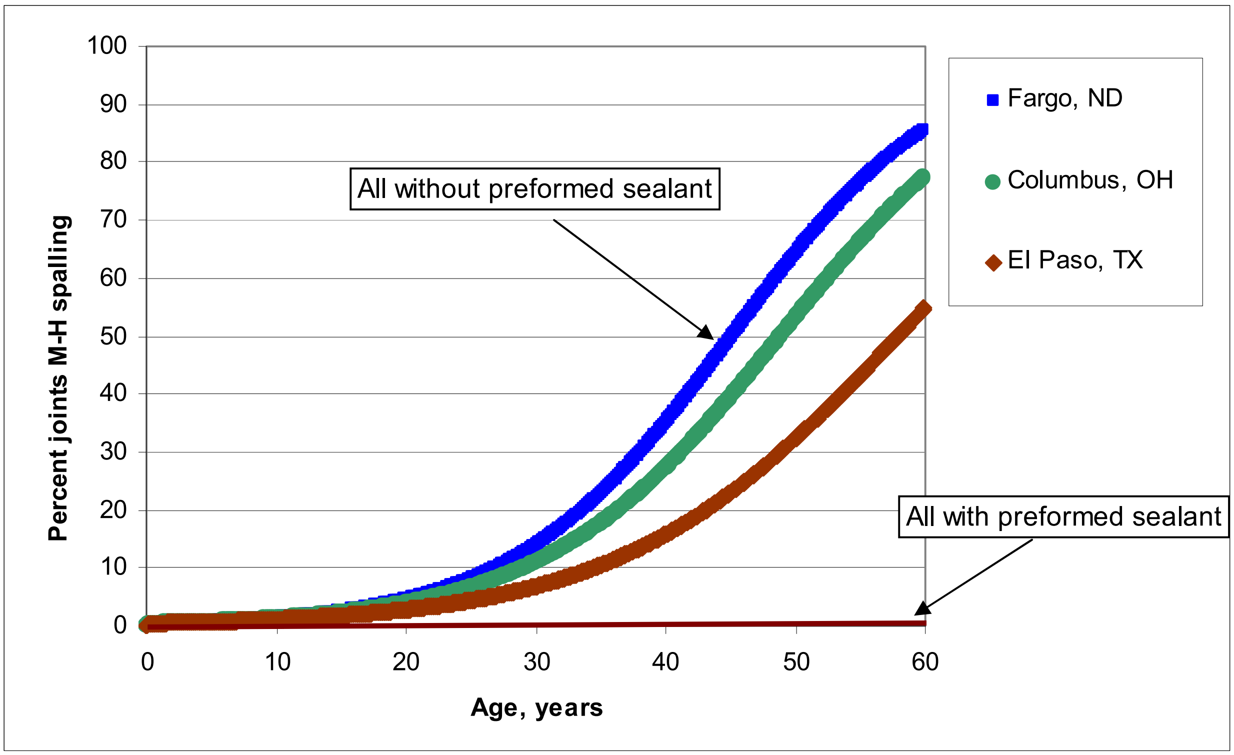

Figure 8. Predicted spalling for Fargo, Columbus, and El Paso examples.

Conclusions

Examination of the scaling factor model (Equation 2) clearly shows that the spalling equation in the MEPDG report and software does not differentiate among no sealant, liquid sealant, and silicone sealant, in the prediction of joint spalling. It only differentiates between preformed sealant and the other three possibilities. Joints with no sealant, liquid sealant, and silicone sealant are all predicted by the model in the MEPDG report and software to develop the exact same amount of spalling.

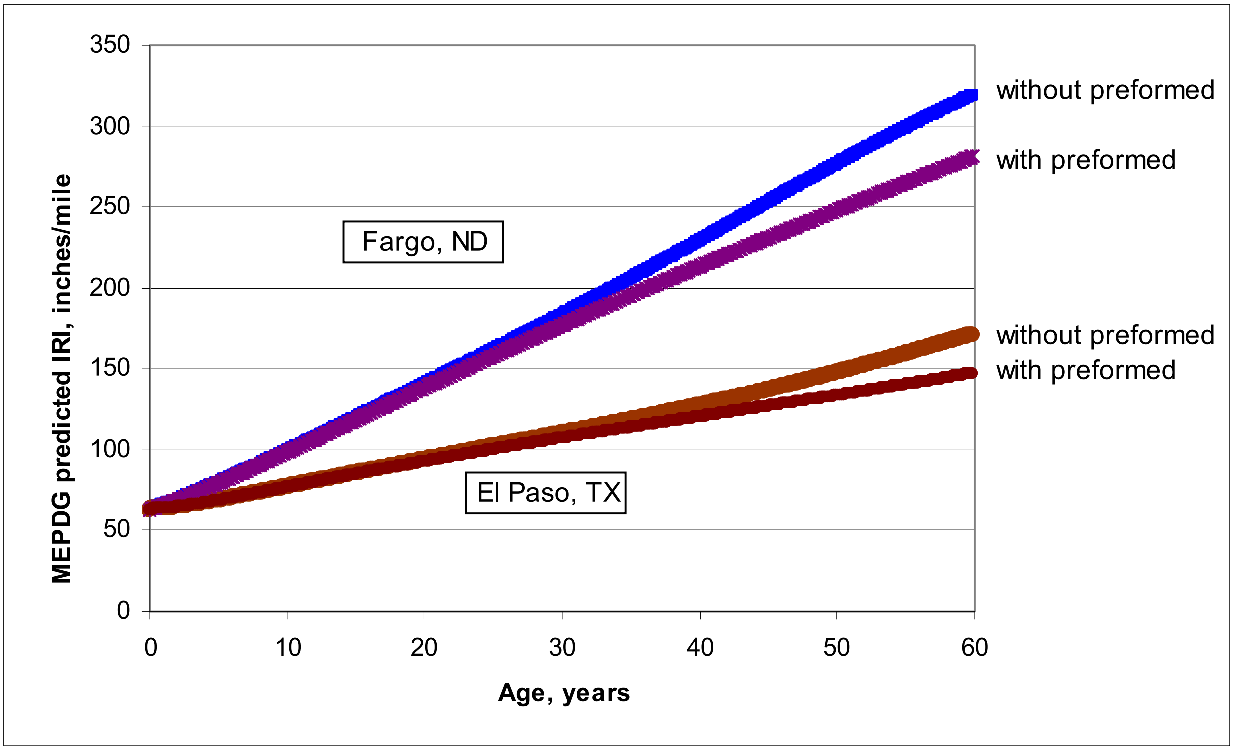

Figure 9. Predicted IRI for Fargo and El Paso examples.

The MEPDG's spalling and scaling factor models (Equations 1 and 2 in this paper; Equations 3.4.43 and 3.4.44 in the MEPDG report) indicate that concrete air content is an input to prediction of JPCP joint spalling. In fact, the MEPDG software does not allow the user to enter concrete air content as an input, and concrete air content is set to a fixed value of 6 percent in the software. Users of the MEPDG aoftware should be aware of this, given the spalling model's sensitivity to air content.

The quality of the prediction of joint spalling in the MEPDG software is not as good as the MEPDG report indicates, because concrete air content is set to a fixed value rather than treated as a variable in the joint spalling model. As a result, the margin of error around the prediction of JPCP IRI in the MEPDG software is greater than the user-input reliability level for IRI would suggest. This is a practical concern due to the evident sensitivity of the joint spalling model to concrete air content.

The MEPDG software predicts essentially no joint spalling for joints with preformed sealant, but substantial amounts of spalling – and exactly the same amounts of spalling – for unsealed joints, hot-pour-sealed joints, and silicone-sealed joints, especially at ages in excess of about 25 years.

The spalling model in the MEPDG report and software was based on data from pavements ranging in age from about 2 to 28 years. Prediction of spalling for design lives greater than 28 years is an extrapolation beyond the inference space of the model.

The MEPDG software's prediction of JPCP IRI suggests a notable sensitivity to climate itself and climate's effect on joint spalling. Considering that the partial R^2 contribution of joint spalling to the regression for IRI was only 1.83 percent, the sensitivity of IRI to spalling warrants further examination using field data. The sensitivity of IRI to climate (specifically Freezing Index) should also be examined further.

The JPCP IRI model in the MEPDG report and software was based on data from pavements ranging in age from about 2 to 34 years. Prediction of IRI for design lives greater than 34 years is an extrapolation beyond the inference space of the model.

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