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Guide for Mechanistic-Empirical Design
OF NEW AND REHABILITATED PAVEMENT STRUCTURES

FINAL DOCUMENT

APPENDIX PP:
SMOOTHNESS PREDICTION FOR RIGID PAVEMENTS

NCHRP

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Foreword

The appendix describes models developed to predict rigid pavement smoothness (the performance indicator used to characterize overall pavement condition in the Design Guide). Specifically, the models developed and described are for predicting JPCP and CRCP smoothness and are suitable for new JPCP and CRCP design along with rehabilitation with JPCP or CRCP design.

The information contained in this appendix serves as a supporting reference to PART 3, Chapters 4 and 7 of the Design Guide.

APPENDIX PP

SMOOTHNESS PREDICTION FOR RIGID PAVEMENTS

1.0 Introduction

Rough roads lead to user discomfort, increased travel times, and higher vehicle operating costs that can lead to millions of dollars in losses to the general economy. Although the structural performance of a pavement is most important to highway designers, the complaints generated by rough roads often contribute to a large part of the rehabilitation decisions that are made by State highway agencies.

Smoothness has been used since the AASHO Road Test as a measure of pavement serviceability and, hence, performance. The present serviceability rating (PSR) concept was adopted as a subjective measure of the ability of a pavement to serve the traveling public. For practical purposes, the present serviceability index (PSI) was developed as an objective means of determining performance from physical measurements on the pavement.(1) Although the physical measurements used in computing PSI included distresses such as cracking and patching, it was the longitudinal profile or smoothness of the pavement that provided the major correlation variable. Several studies since the AASHO Road Test have confirmed smoothness as a strong indicator of the serviceability of a pavement, and many State highway agencies rely on smoothness measurement to estimate serviceability over time.(2, 3, 4, 5)

Road smoothness can be defined as "the variation in surface elevation that induces vibrations in traversing vehicles."(6) Although there are various methods for measuring the smoothness of pavements, one of the most common indices used today is the International Roughness Index (IRI).(7) IRI is defined simply as the accumulated suspension vertical motion divided by the distance traveled as obtained from a mathematical model of a simulated quarter-car traversing a measured profile at 80 km/h.

As a mathematical index of the longitudinal surface profile of the road in the wheelpaths, IRI represents the typical vibrations induced in a passenger car by the unevenness of the road. It is basically the sum of vertical deviations of the frame of a mathematically defined vehicle over a given distance, measured as meters per kilometer.

IRI was adopted as a standard measure of smoothness for the following reasons:

- It is time stable and can be reproduced easily from longitudinal profile elevation data, since it is just a computed statistic of the road profile.
- It gives consistently high correlations with the outputs of other roughness measuring devices at different speeds.
- It has been shown to correlate well with user serviceability rating.

Following a World Bank study that recommended IRI as a reliable measure of smoothness, the FHWA adopted IRI as a standard for measuring smoothness.(8, 9, 10) Since 1989, FHWA has been requiring all States to report pavement smoothness in terms of IRI units for paved rural arterials and urban freeways, including Interstates.(7)

2.0 Definition of Problem

The AASHTO design procedure has used pavement serviceability as its sole performance design criterion for nearly 40 years. This situation has had both positive and negative implications on design adequacy. On the positive side, the serviceability concept has ensured that the Nation's pavements are designed to provide the traveling public with a smooth highway. It is also used as a basis for triggering rehabilitation when serviceability is no longer adequate. This contributes to the satisfaction of the public, as well as minimizing highway vehicle operating costs such as fuel and vehicle maintenance costs.

On the negative side, pavement designs based only on serviceability do not directly address prevention of distresses such as fatigue cracking, rutting, joint faulting, and punchouts. Such distresses eventually lead to a decrease in smoothness, making pavements unable to meet the traveling public's need for good ride quality and often leading to the early failure of the pavement. Thus, many pavements designed and constructed based on serviceability have failed early due to a lack of consideration of specific design features and material properties that would have prevented the early failures.

The 2002 mechanistic-empirical (M-E) design procedures to be developed under this contract will result in M-E models for key distress types for flexible and rigid pavements. While such models will be invaluable, they lack the direct consideration of pavement serviceability, which is the most important indicator of the traveling public's satisfaction with the highway.(11) Thus, it is highly desirable to also predict pavement smoothness over time so that all performance criteria can be met for a proposed pavement design.

3.0 Alternative Approaches for Including Rigid Pavement Smoothness in the 2002 Design Procedure

There are basically three approaches for including smoothness as a key performance indicator in the 2002 design procedure:

1. Predict the longitudinal wheelpath profile over time using M-E principles. While some work has been performed, current technology and material properties are not available to predict profile over time or axle load applications using the M-E approach. This would involve the prediction of the longitudinal profile (point by point) in a wheelpath over time. It is obvious that this approach cannot be implemented at this time, but it may be possible in the future.
2. Predict smoothness over time as a function of initial smoothness, design features, and site conditions (subgrade, traffic, and climate). This may be possible using an M-E approach; however, it is not believed to be the best approach.
3. Predict smoothness over time as a function of key distress types that can be predicted by M-E or empirical procedures. There are several available models using this approach, which is described in detail.

Following a comprehensive review of past research and smoothness model development efforts, approach 3 was adopted. The distress and maintenance variables included in the final smoothness prediction model were drawn from a large pool of independent distress variables in the LTPP database. The model development process was as follows:

1. Conduct a literature review of past research studies to identify distress types that influence smoothness.
2. Assemble databases for JPCP and CRCP model development. The databases must include the distress variables identified in step 1.
3. Evaluate the quality of databases and identify missing/erroneous data items.
4. Develop methods and procedures for estimating important missing data elements and clean data by resolving anomalies.
5. Select the appropriate smoothness model form (should be capable of estimating smoothness loss incrementally).
6. Develop tentative smoothness prediction models for JPCP and CRCP.
7. Perform sensitivity analysis (model verification) on tentative models.
8. Select final smoothness models.

The steps outlined for model development are summarized in the flow chart shown in figure 1. This approach has been used in previous studies and has been improved to provide practical prediction models.

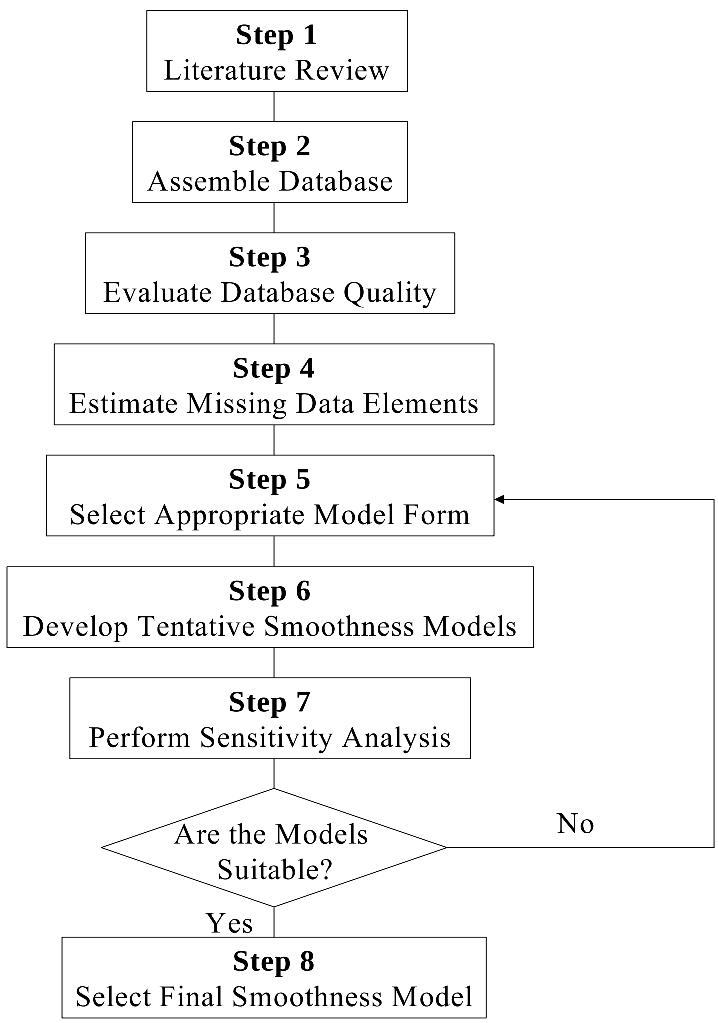


Figure 1. Flow chart for developing distress-based smoothness models.

4.0 Overview of Distress Based Rigid Pavement Smoothness/Serviceability Models Developed from Previous Research

Several research studies have successfully modeled smoothness or serviceability (which is highly correlated to smoothness) using key pavement distress types for both JPCP and CRCP.[1, 4, 12] The results from some of these studies are discussed in the next few sections.

Distress Variables that Influence JPCP Smoothness

AASHO Serviceability Equation

The first relationship between user-defined serviceability and distress was developed by Carey and Irick:[1]

$$PSR = C + A_1R_1 + B_1D_1 + B_2D_2 \quad (1)$$

where

C, A_1, B_1, B_2 = regression coefficients
R_1 = function of longitudinal profile
D_1 = function of transverse profile
D_2 = function of surface distress

This model form was used to develop the serviceability equations of the AASHO Road Test for both rigid and flexible pavements. The rigid pavement model was as follows:[1]

$$PSR = 5.41 - 1.78 \log (1 + SV) - 0.09 (C + P)^{0.5} \quad (2)$$

where

PSI = present serviceability rating (panel mean rating)
SV = slope variance
C = major cracking in ft per 1000 sq ft area
P = bituminous patching in sq ft per 1000 sq ft area

Slope variance is defined as follows:[1]

$$SV = \frac{\sum Y^2 - \frac{1}{n}(\sum Y)^2}{n-1} \quad (3)$$

where

Y = difference between two elevations 9 in apart
n = number of elevation readings

The accuracy of the model can be judged by the following statistics:
R^2 = 92 percent, SEE = 0.32 PSR points

The statistics show that PSR is well correlated with smoothness and distress for rigid pavements.[1] However, smoothness alone accounted for most of the variation observed in serviceability. This is reasonable because the occurrence of distress (medium to high severity, in most cases) on a pavement surface distorts the longitudinal profile of the pavement, which directly affects smoothness. It would therefore be logical to attempt to predict smoothness using only independent distress variables. Results from several studies reporting the relationships between serviceability/smoothness and distress are presented in the next section.

FHWA Zero-Maintenance Pavements Study[11]

The following JPCP model was developed using data from the AASHO Road Test to relate serviceability to distress for rigid pavements:

$$PSR = 4.5 - 0.0364F - 0.0396S - 0.0149P - 0.087(C + S)^{0.5} - 0.7814(1 + F + C) \quad (4)$$

$R^2 = 0.86$, SEE = 0.41 points, N = 65

where

- F = faulting in the wheelpath, in/1000ft
- S = spalling for areas greater than 3-in diameter, $ft^2/1000ft^2$
- C = class 3 and 4 cracking, $ft^2/1000ft^2$
- P = patching, $ft^2/1000ft^2$

The model has an R^2 value comparable to the AASHTO serviceability equation for rigid pavements (equation 2). The SEE reported was slightly larger than that of the AASHTO equation. However, it is clear from these models that user-defined serviceability can be predicted effectively using distress. Actually, these models would have had lower SEE values had the initial PSR of the pavements been known and included in the model.

FHWA Performance of Concrete Pavements (RPPR)[12]

The FHWA RPPR study investigated the effect of distress on both serviceability (PSR) and smoothness (IRI). The models developed as part of the RPPR study are as follows:

JPCP PSR Model

$$PSR = 3.95 - 0.010276*FaulTT - 0.001014*T\text{-}crack - 0.009421*Spall - 0.003911*L\text{-}crack^{0.5} \quad (5)$$

where

- PSR = present serviceability rating (0 to 5 scale)
- FaulTT = total accumulated joint faulting, in/mile
- T-crack = number of transverse cracks per mile
- Spall = percentage of joints spalled
- L-crack = amount of longitudinal cracking, ft/mile

$R^2 = 0.51$, SEE = 0.30 points, N = 186

JRCP PSR Model

$$PSR = 4.165 - 0.06694*FaulTT - 0.00003228*T\text{-}crack - 0.1447*Spall \quad (6)$$

where

PSR = present serviceability rating
FaulTT = total accumulated joint faulting, in/mile
T-crack = number of deteriorated transverse cracks per mile
Spall = percentage of joints spalled

R^2 = 0.66, SEE = 0.28 points, N = 90

Both the R^2 and the standard error of the estimate values are lower than those of the previous models.

IRI Model

$$IRI^2 = 99.59 + 2.6098*FaulTT + 2.2802*T\text{-}crack^3 + 1.8407*Spall \quad (7)$$

where

IRI = International Roughness Index, in/mile
FaulTT = total accumulated joint faulting, in/mile
T-crack = amount of transverse cracking, number of cracks per mile
Spall = percentage of joints spalled

R^2 = 0.61, SEE = 64.11 in/mile, N = 144

For both the serviceability and IRI models, the significant variables were total joint faulting, transverse cracking, and transverse joint spalling. These distresses are therefore strong candidates for model development.

FHWA/Illinois Department of Transportation Study[4]

The following models were developed using "manufactured" profile data. The IRI was computed from the profile, and PSR was computed using equation 9.

$$PSR = 4.115 - 0.0108S - 0.00949TC - 0.2266F \quad (8)$$

R^2 = 0.91, SEE = 0.183 points, N = 27

where

S = high-severity spalling (percentage of joints)
TC = high-severity transverse cracking (percentage of slabs cracked)
F = average joint faulting, mm

$$PSR = 5e^{-0.26IRI}$$

(9)

IRI is the International Roughness Index measured in m/km.

Zero Maintenance and Illinois Studies

Al-Omari and Darter and Darter and Barenberg investigated the effect of individual distress and a combination of distresses on pavement smoothness. The following is a summary of their findings for rigid pavements.[4, 11]

Joint Faulting

The analysis showed a correlation between IRI and faulting. The following linear model was developed to predict IRI from faulting using a limited set of LTPP data:[4]

$$IRI = 1.471 + 0.2794*F \quad (10)$$

(R^2 = 0.50, SEE = 0.34 m/km, N = 29)

where
IRI = smoothness, m/km
F = transverse joint faulting, mm

For this study, the correlation between IRI and faulting was reported as 0.5. The R^2 value was not very high because the pavement sections used in the analysis had other distresses that also contributed to the change in smoothness. Therefore, faulting was not expected to account for the total change in smoothness. Al-Omari and Darter also reported the effect of faulting on estimated PSR. Table 1 presents the results of the analysis and shows a significant decrease in smoothness as mean joint faulting for a given pavement section increases from 1 to 10 mm.

Table 1. Effect of mean joint faulting on pavement smoothness (IRI and PSR).[4]

Mean Joint Faulting* (mm)	IRI (m/km)	PSR**
1	0.358	4.50
2	0.716	4.15
4	1.433	3.45
6	2.149	2.86
8	2.865	2.37
10	3.582	1.97

* Joint spacing = 5 m
** Equation 9

Transverse Cracking

Al-Omari and Darter used only high-severity (faulted and spalled) transverse cracks to determine the effect of transverse cracking on rigid pavement smoothness. Table 2 clearly shows a significant increase in IRI as the number of slabs with transverse cracking increases from 0 to 50 percent. Also, the results show that the specific dimensions of the cracking had a major effect on IRI. Darter and Barenberg also reported that the critical limit of PCC transverse cracking (number below which there is no significant effect on smoothness) is 1 to 3 medium- to high-severity cracks every 30 meters.[11] A higher number of cracks will significantly reduce serviceability.

Table 2. Effect of transverse cracking on pavement smoothness (IRI).[4]

Transverse Cracking (percent slabs)	IRI (m/km)
0	0.406
20	0.800
50	1.345

Transverse Joint Spalling

Table 3 shows the effect of transverse joint spalling on IRI, determined using IRI values calculated for different percentages of joints spalled. The spalling width across the joint was 100 mm and its depth was 37.5 mm. The analysis showed that IRI increases approximately linearly as the percentage of joints spalled increases. The specific dimensions of the joint spalling also have a major effect on IRI. The dimensions used in the analysis are typical of spalled joints that would be rated as high severity.

Table 3. Effect of transverse joint spalling on pavement smoothness (IRI).[4]

Transverse Joint Spalling (percent joints)	IRI (m/km)
0	0.406
20	0.758
50	1.285

<u>Distress Variables that Influence CRCP Smoothness</u>

Few models are available for predicting CRCP deterioration. The available models do not directly predict user-defined serviceability or smoothness but rather CRCP failure (which is based on the presence of medium- and high-severity distress).[13, 14] Two examples of models used to define CRCP failure are presented in the following sections.

Illinois CRCP Study

$$FAIL = 8.8PATCH + PUNCH + MHPOT + HTCRK \tag{11}$$

where

FAIL	=	CRCP failure per mile
PATCH	=	all severities of permanent patching
PUNCH	=	all severities of punchouts, number per mile
MHPOT	=	medium- and high-severity of potholes and localized distress
HTCRK	=	high-severity transverse cracking, numbers per mile

Texas Pavement Study

$$\text{FAIL} = \text{PUNCH} + \text{PATCHES} \quad (12)$$

where

FAIL	=	CRCP failure per mile
PATCH	=	total number (all severities) of permanent patching
PUNCH	=	total number (all severities) of punchouts

The definitions of CRCP failure presented indicate that high-severity transverse cracking, potholes, and punchouts are the main distresses that cause CRCP failure. Maintenance events, such as patching, also indicate CRCP failure. It is obvious that smoothness will decrease as the CRCP fails. The distress types identified will be used for model development.

Summary

The various JPCP and CRCP models identify the distress types that affect both user panel serviceability and smoothness. A summary of distress variables that have been shown to significantly influence JPCP user-rated serviceability or smoothness and CRCP failure is presented in tables 4 and 5.

Table 4. Distress variables affecting JPCP smoothness/serviceability.

Distress	Al-Omari & Darter[4]	Bustos et al. [15]	Yu et al.*[12]	AASHO Serviceability Equation[1]	Darter and Barenberg[11]	Yu et al. +[12]
Joint faulting	✓	✓	✓		✓	✓[1,2]
Transverse cracking	✓	✓	✓	✓	✓	✓[1,2]
Joint spalling	✓	✓	✓		✓	✓[1,2]
Patching				✓	✓	
Longitudinal cracking						✓[1]

1 = JPCP, 2 = JRCP
* = JPCP roughness model
\+ = Serviceability model

Table 5. Distress variables affecting CRCP smoothness/serviceability.

Distress	Illinois Study[13]	Texas Study[14]
Transverse cracking	✓	
Joint spalling	✓	
Patching	✓	✓
Punchouts	✓	✓
Potholes	✓	

The review of past research and existing models for JPCP and CRCP shows clearly that there is no one fundamental mechanism that can be attributed to the loss of smoothness on pavements. Rather, the different distresses and maintenance events combine to contribute to the loss of smoothness on pavements. The significance of each distress may vary depending on its severity.

Another key factor for predicting future smoothness is the smoothness of the pavement when it is newly constructed.[5, 16] Results from the recent NCHRP 1-31 project showed that future smoothness is significantly related to initial smoothness for all pavement types and AC overlays.[5, 16] For PCC pavements, the study found that the initial smoothness was significant to the future smoothness for over 80 percent of the projects evaluated. This suggests that pavements that are constructed smoother will typically stay smoother over time, and pavements that are constructed less smooth initially will tend to remain that way. Other more recent studies have confirmed these results.[17, 18]

For a pavement with a given initial smoothness, several factors combine to contribute to the loss of smoothness over time. Chief among these factors is the occurrence and progression of visible distress. Increasing quantities and severities of JPCP and CRCP distress such as faulting, transverse cracking, joint spalling, crack or joint deterioration, and punchouts will contribute to a loss of pavement smoothness. The occurrence and progression of the distresses are directly related to increased application of traffic and environmental loads, loss of support provided by the foundation, and the effects of aging on paving materials. As part of the NCHRP 1-37 study, the interactions of traffic, site, and environmental factors will be used in M-E analysis to develop prediction models for estimating distress, which will serve as input data for the smoothness models developed.

5.0 Preparation of Data for Rigid Pavement Smoothness Model Development

Data preparation and assembly for JPCP and CRCP was subdivided into the following tasks:

1. Assemble database for each model based on pavement type.
2. Identify missing/erroneous data items.
3. Explore and clean data.

These steps are described in the following sections.

Assemble Database for JPCP and CRCP Models

The data used for model development are from the LTPP GPS-3 and GPS-5 databases for JPCP and CRCP, respectively. The GPS pavements are generally existing pavement sections nominated by State and provincial departments of transportation (DOT) and selected by SHRP and the FHWA's Pavement Performance Division for inclusion into the LTPP data collection program. To meet the experimental criteria, pavement section materials and structural designs must reflect standard engineering practices in the United States and Canada.[19, 20, 21]

For the data collected and recorded in the LTPP Information Management System (IMS), clear procedures and standards were established and are observed. These procedures help guarantee the consistency and the quality of the data collected. Extensive data quality checks are performed during the entire process. Information is also available showing the data reliability for a set of data. Throughout the selection, gathering, and recording process, the basic philosophy of the LTPP program has been to provide high-quality data collected in a statistically correct and consistent manner.[19, 20, 21]

The data sets from the LTPP IMS used in model development are automated/manual distress and longitudinal profile. Automated and manual distress data provide a measure of pavement condition, primarily on the surface. The data evaluate the frequency and severity of distresses such as cracking (e.g., longitudinal, transverse, durability), pumping, faulting, joint damage, surface deformation, and surface defects. Maintenance activities such as patching are also recorded.[19, 20, 21] The primary means used to obtain the surface distress data stored in the LTPP IMS is visual inspection of the pavement surface or visual interpretation of high-resolution 35-mm photographic images of the pavement surface.[19, 21] The guidelines for distress data collection are contained in the *Distress Identification Manual for the Long-Term Pavement Performance Project*.[22] The surface distress data are collected every 1 to 2 years.[20, 21]

Longitudinal profile data show the relative elevation of the pavement along the wheel path. The IRI, Mays Index, Root Mean Square Vertical Acceleration (RMSVA), and an approximation of slope variance are also computed from the data. The raw data include the X-Y profile data for at least five repeat runs for each wheel path. It is stored separately from the statistics.[19, 20, 21] LTPP regional offices are responsible for collecting longitudinal profile data using profilometers or dipsticks.[22] The *Manual for Profile Measurement: Operational Field Guidelines* contains details on the process. The longitudinal profile of each LTPP test section is measured approximately once per year. Sections for the detailed study of seasonal effects are tested quarterly every other year.[21]

The data used in model development were from the following LTPP GPS-3 and GPS-5 databases:

- Smoothness (IRI)—MON_PROFILE_MASTER.
- Faulting—MON_DIS_JPCC_FAULT.
- JPCP Distress—MON_DIS_JPCC_REV/MON_DIS_PADIAS42_JCP.
- CRCP Distress—MON_DIS_CRCP_REV/ MON_DIS_PADIAS42_CRCP.

The distress data assembled included all the data elements listed in table 6. Data assembly was done using SAS©, Microsoft Access©, and Microsoft Excel©. The next step was to merge the LTPP data into two datasets with profile and corresponding distress values for JPCP and CRCP.

Merging LTPP Datasets and Identification of Missing/Erroneous Data Elements

The data sets were examined thoroughly for missing and erroneous data before merging. The following were observed:

- The distress and profile surveys dates did not match up (i.e., surveys were not conducted at the same time).
- The LTPP profile database contained no information on initial smoothness of pavements.
- The profile data had only minimal errors since it had recently been cleaned as part of the ongoing LTPP data analysis project.
- The faulting data had minimal errors since it had recently been cleaned as part of the ongoing LTPP data analysis project.
- Distress data had some erroneous data, depending on which data set was used (manual or automated). The best data sets were MON_DIS_JPCC_REV for JPCP distress and MON_DIS_PADIAS42_CRCP for CRCP distress, and these were used for model development.

Table 6. Summary of LTPP GPS-3 and GPS-5 data used in model development.

Distress Variable	JPCP	CRCP
Durability cracking	✓(L, M, H)	✓(L, M, H)
Longitudinal cracking	✓(L, M, H)	✓(L, M, H)
Transverse cracking	✓(L, M, H)	✓(L, M, H)
Corner breaks	✓(L, M, H)	
Transverse joint seal damage	✓(L, M, H)	
Longitudinal joint seal damage	✓	✓
Spalling (longitudinal joint)	✓(L, M, H)	✓(L, M, H)
Spalling (transverse joint)	✓(L, M, H)	
Map cracking	✓	✓
Scaling	✓	✓
Polished aggregates	✓	✓
Popouts	✓	✓
Blowups	✓	✓
Transverse joint faulting	✓	
Patch/patch deterioration	✓(L, M, H)	✓(L, M, H)
Water bleeding and pumping	✓	✓
Tranverse construction joint deterioration		✓
Punchouts		✓

L = low-severity distress
M = medium-severity distress
H = High-severity distress

Two issues had to be resolved before merging the data sets: obtaining reasonable estimates of initial smoothness and resolving the discrepancies in survey and profile data dates. Two methods were proposed for resolving these issues:

- Based on the assumption that that there are no significant changes in measured profile or distress within 120 days of data collection, profile and distress data collected during this period can be merged with minimal error.
- Models could be developed based on the pavement age and measured smoothness for each pavement section with time-series smoothness data, then used to estimate smoothness corresponding to distress survey dates by interpolation or extrapolation. The models developed may also be used for obtaining estimates of initial smoothness by extrapolating to age = 0 years.

The second method was adopted for use in estimating initial smoothness and smoothness at the time of distress surveys.

Backcasting Initial Smoothness Values

As noted, the LTPP database did not contain initial smoothness values. Therefore, initial smoothness had to be backcasted. The process for backcasting initial smoothness values was as follows:

1. Determine suitable model form for backcasting initial smoothness.
2. Backcast initial smoothness values for each pavement section using available time-series IRI data.
3. Evaluate reasonableness of backcasted initial IRI values by reviewing trends and slopes of time-series data, comparing backcasted values with measured initial IRI from LTPP-SPS pavement sections, and reviewing diagonstic statistics from the fitted model.
4. Compare the distribution (mean and variance) of backcasted initial IRI to typical initial IRI values measured from newly constructed LTPP-SPS pavements.

Various model forms (e.g., linear, exponential, logarithmic, and polynomial) were evaluated for backcasting initial smoothness with pavement age as the independent variable and measured smoothness as the dependent variable. The functional form was thus:

$$IRI = f(age) \tag{13}$$

Initial smoothness was therefore the smoothness at age = 0 years. The typical pavement section used in the analysis was more than 10 years old and had 3 or more sets of time-series data. Using a linear model for backcasting initial smoothness was found to be the most practical since there was no data close to the construction date (less than 3 years) available. The linear model form used for interpolating and extrapolating smoothness values was as follows:

$$IRI = \alpha AGE + \beta \tag{14}$$

where

α = slope
AGE = pavement age in years
β = regression constant equivalent to initial smoothness

Figure 2 is a sketch of a linear model fitted to time-series data and used in backcasting. Using this method of curve fitting, initial smoothness was determined for the pavement sections in the LTPP-GPS database with time-series smoothness data.

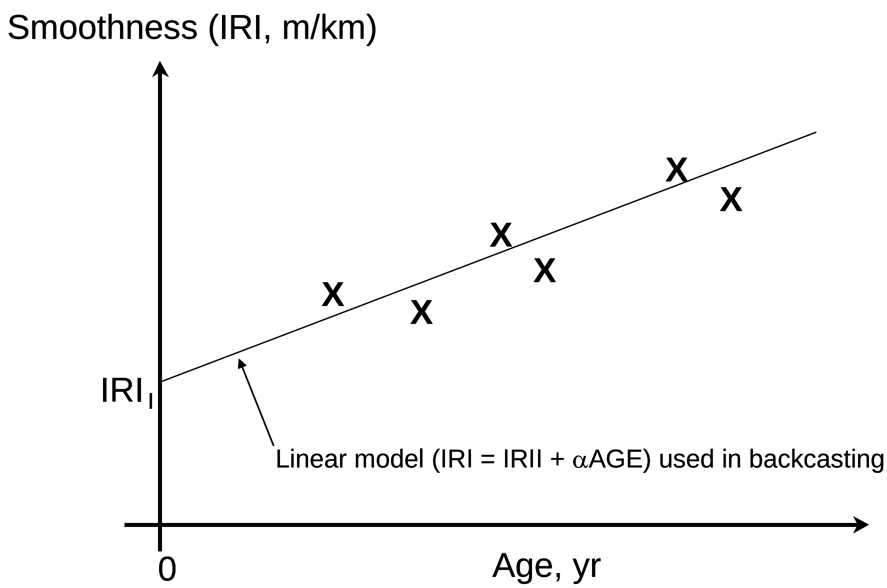


Figure 2. Sketch of linear model for backcasting initial IRI.

The backcasted initial IRI values for JPCP and CRCP pavements used in analysis were evaluated to determine their reasonableness by determining the following:

1. If there was a significant difference in mean initial IRI values for the backcasted JPCP and CRCP data and reference-measured initial IRI data.
2. If there was a significant difference in variance in the backcasted and measured data sets.
3. If the diagnostic statistics of the linear models used in interpolating or extrapolating IRI values are reasonable.

The reference-measured initial smoothness values used for comparison were obtained from the LTPP SPS database (smoothness values measured within the first 12 months of pavement construction were used). Analysis of variance (ANOVA) and t-test comparisons were used in determining if there were significant differences in the means and variance from the measured and backcasted initial smoothness values. The results are presented in tables 7 and 8 for JPCP and CRCP, respectively.

Table 7. Summary of t-test results for the comparison of measured and backcasted initial IRI for JPCP.

Data set	N	Mean IRI	Std Dev IRI	Std Error IRI	Min IRI	Max IRI
JPCP (backcasted)	73	1.22698	0.3973	0.0465	0.389	2.246
SPS (measured)	97	1.25219	0.2837	0.0288	0.758	2.094

Variances	T	DF	Prob>|T|
Unequal	-0.4608	124.2	0.6457
Equal	-0.4826	168.0	0.6300

For H_0: variances are equal, F' = 1.96 DF = (72,96) Prob>F' = 0.0021

Table 8. Summary of t-test results for the comparison of measured and backcasted initial IRI for CRCP.

Data set	N	Mean IRI	Std Dev IRI	Std Error IRI	Min IRI	Max IRI
CRCP (backcasted)	49	1.2236	0.2781	0.0397	0.751	1.710
SPS (measured)	97	1.2521	0.2837	0.0288	0.758	2.094

Variances	T	DF	Prob>|T|
Unequal	-0.5817	98.2	0.5621
Equal	-0.5778	144.0	0.5643

For H_0: variances are equal, F' = 1.04 DF = (96,48) Prob>F' = 0.8964

The t-test results for comparison of the mean initial IRI and variance values show that there are no significant differences between measured initial smoothness (from SPS pavements) and backcasted initial smoothness for JPCP and CRCP. There was also no significant difference in the variance observed for the measured and backcasted initial smoothness for CRCP. Backcasted initial smoothness showed a significantly higher variance than that of the measured SPS data; however, the variance was not excessive (as shown in figure 3).

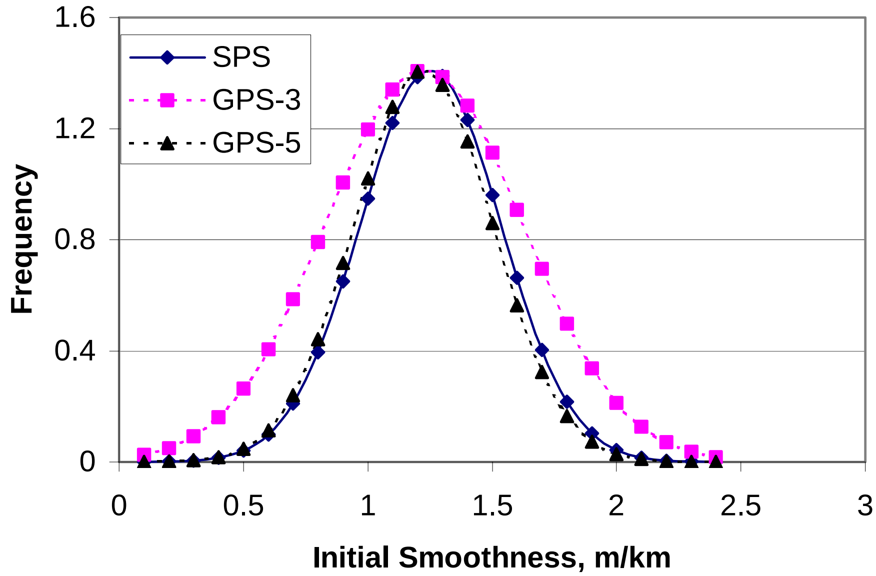


Figure 3. Initial smoothness distribution for measured (SPS) and backcasted (JPCP and CRCP) data.

Measured initial IRI for SPS sections ranged from 0.5 to 2 m/km. This range of values was adopted as the reasonable range for backcasted values, and values out of this range were assumed to be outliers.

The final step in evaluating the quality of the backcasted initial smoothness values was to determine if there was any correlation between the backcasted initial IRI values and the pavement age. This was to ensure that older pavements did not necessarily have lower initial IRI values since, for the same rate of smoothness loss (rate of increase in IRI values), an older pavement will have a lower backcasted initial smoothness value. Older pavements should not have lower IRI values for the following reasons:

- Most of the JPCP and CRCP pavements in the GPS LTPP database were constructed 15 to 30 years ago.
- There was no significant change in initial smoothness specifications for pavement construction within that time period.
- It is only within the past 5 to 15 years that the importance of initial smoothness was established and smoothness-related specifications have been promoted and encouraged to increase pavement life and performance.

Bivariate plots of initial smoothness versus age were developed for both JPCP and CRCP to determine if there is any correlation. Figures 4 and 5 show no significant trends between initial smoothness and age. The backcasted data were therefore suitable for model development.

With the missing data (initial smoothness) backcasted, the data sets were merged with the LTPP section identification number and construction number as the reference. An example of the merged datasets is shown in table 9.

Table 9. Example of combined LTPP distress and profile parameter datasets.

SHRP ID	**State Code**	**Construction Date**	**α (IRI Model Slope)**	**β = Initial Smoothness**	**Distress Survey Date**	**Age**	**Smoothness IRI = αAGE + β**	**Distress Variables**
XXX1	Z1							
XXX2	Z1							
XXX1	Z2							
XXX4	Z3							

The assembled data were thoroughly evaluated to identify possible problem spots in the database, such as time-series data with a significant increase in smoothness with time. Attempts were made to obtain replacements for missing data where possible. The data set was also checked and cleaned for anomalies and gross data error. A summary of the data, its inference space, and other statistical characteristics is presented in tables 10 and 11 for JPCP and CRCP, respectively.

6.0 Rigid Pavement Smoothness Model Development

The model development procedure was divided into the following tasks:

- Selecting suitable model form.
- Selecting appropriate statistical tools for regression and optimization.
- Tentative models development.
- Sensitivity analysis and model selection.

The tasks are described in greater detail in the following sections.

Smoothness Prediction Model Form

Clearly, several pavement distresses have a significant effect on smoothness and should be used in modeling and predicting smoothness over time. The general hypothesis to be used in the proposed smoothness model is that the various distresses resulting in significant changes in smoothness should be represented by separate components within the model. The smoothness model could be structured as follows:

$$S(t) = S_0 + a_1 D(t)_1 + a_2 D(t)_2 + \ldots\ldots\ldots\ldots + a_n D(t)_n + b_j M_j \quad (15)$$

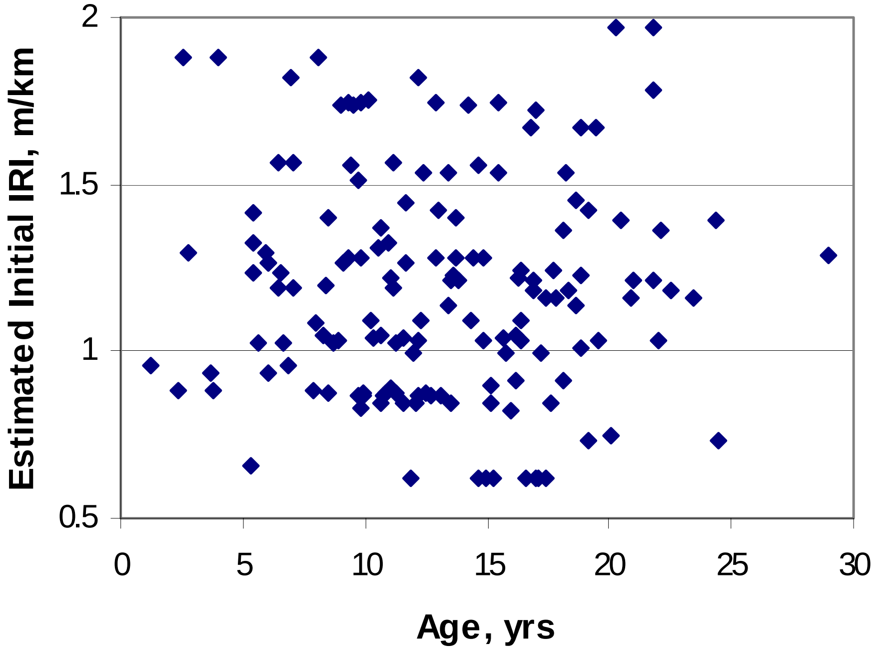


Figure 4. Plot of estimated initial (backcasted) IRI versus age for JPCP.

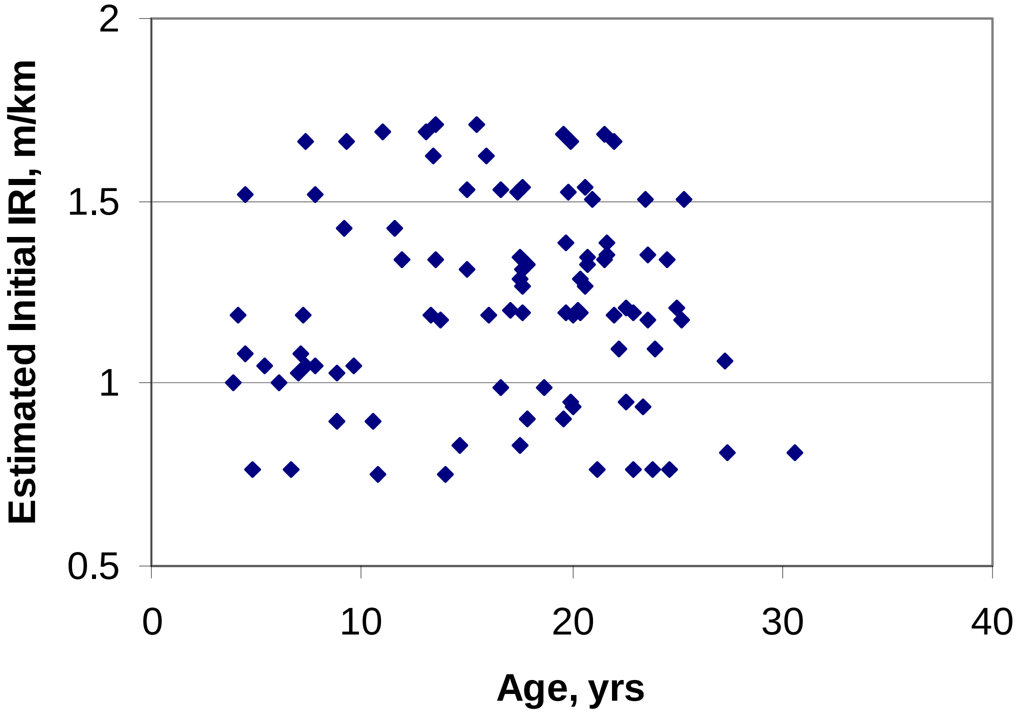


Figure 5. Plot of estimated initial (backcasted) IRI versus age for CRCP.

Table 10. Summary of GPS-3 JPCP data used in model development and calibration.

Distress Variable*	Range		Mean
	Min.	Max.	
Durability cracking (number per km of pavement)	0	231	2.5
Longitudinal cracking (m per km of pavement)	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
IRI (estimated initial), m/km	0.4	1.78	1.22
IRI (measured overtime), m/km	0.76	3.6	1.71

* All severities, unless otherwise stated.

Table 11. Summary of GPS-5 CRCP data used in model development and calibration.

Distress Variable*	Range		Mean
	Min.	Max.	
Longitudinal cracking, m per km of pavement	0	826	60.7
Transverse cracking, number per km of pavement	0	303	39.4
Longitudinal joint spalling, m per km of pavement	0	862	37.5
Patching, percent pavement surface area	0	5	1
Punchouts, number M-H severity per km of pavement	0	20	1
IRI (estimated initial), m/km	0.75	1.71	1.22
IRI (measured overtime), m/km	0.78	2.60	1.44

* All severities, unless otherwise stated.

where

$S(t)$ = pavement smoothness over time (IRI, m/km)
S_0 = initial smoothness (IRI, m/km)
a_i, b_j = regression constants
$D(t)_i$ = i^{th} distress at a given time
M_j = maintenance activities that significantly influence smoothness (e.g., patching)

The general model form proposed is based on existing smoothness models that show an additive combination of initial smoothness, initial distress, change in distress, and the effect of maintenance on smoothness. The model also is in agreement with the proposed pavement design philosophy of the NCHRP 1-37 study, which is to estimate increased distress and smoothness loss incrementally overtime. The proposed model will be suitable for both JPCP and CRCP. Distress variables used in predicting smoothness for JPCP and CRCP will, however, likely vary.

Statistical Tools for Regression and Optimization

The SAS nonlinear procedure (NLIN) was selected as the appropriate nonlinear regression tool to be used in final model calibration because the procedure is versatile and allows for constraining model coefficients where required (e.g., initial smoothness should always have a coefficient of 1.0).[23] Other SAS procedures, such as STEPWISE, REG, RSQUARE, and RSREG, were used in preliminary model development for determining and selecting the most suitable variables for incorporation into the final model.

The SAS NLIN procedure can use five different iterative methods for optimization:

- Steepest-Descent or Gradient.
- Newton.
- Modified Gauss-Newton.
- Marquardt.
- Multivariate Secant.

The Marquardt algorithm was used in optimization. The first step in the optimization procedure was to set up a series of equations represented by the nonlinear model and based on the data provided. The equations are shown as equation 16.

$$Y = F(\beta_0^*, \beta_1^*, \ldots\ldots\ldots\ldots \beta_r^*, \; Z_1, Z_2, \ldots\ldots\ldots Z_r) + \varepsilon \quad = F(\beta^*) + \varepsilon \qquad (16)$$

where

- Z = matrix of independent variables
- β^* = vector of unknown regression parameters
- ε = the error vector
- F = function of the independent variables

The functions are solved by selecting the most appropriate regression parameters, β^*, to minimize the error vector, ε. The equations are solved as follows:[23]

$$X'F(\beta) = X'e \qquad (17)$$

where

- ε = $Y - F(\beta)$
- X = $\partial F/\partial \beta$
- β = estimate of β^*

A starting (initial) value of β was chosen and continually improved until the error sum of squares was minimized. This was done by an iterative process which used X and Y (note that X varies for each set of β values while Y remains constant) to compute a factor, $\varepsilon\Delta$, such that:[23]

$$L(\beta + \alpha\Delta\Delta < \quad L(\beta_o) \qquad (18)$$

For the Marquardt method used in optimizing the IRI model, Δ was calculated as follows:[10]

$$\Delta \quad = \quad (X'X + \lambda \; \mathrm{diag}(X'X))^{-}X'e \qquad (19)$$

where λ varies from 0 to infinity with an initial value of 0.001 and all other parameters are as already defined. Further details on the Marquardt procedure can be obtained from the SAS/STAT User's Guide.(23)

Tentative JPCP Smoothness Model

The assembled JPCP (GPS-3) data were explored to learn more about the suitability of individual distresses (at different levels of severity) for model development. This was done by performing a comprehensive stepwise regression analysis of the cleaned data to evaluate the preliminary relationships between the measured smoothness, backcasted initial smoothness, and distress. Table 12 presents the strength of the relationships between the potential independent variables and smoothness for JPCP.

The distress variables that show some correlation with smoothness can be categorized as follows:

- Structural.
  - Faulting.
  - Corner breaks.
  - Transverse cracking.

- Nonstructural.
  - Joint spalling.
  - Longitudinal cracking.

- Surface Defects.
  - Initial smoothness.
  - Map cracking.

- Maintenance.
  - Patching (flexible and rigid materials).

- Others.
  - Age (represents time dependent factors affecting longitudinal profile such as settlements, heaves, and swelling soils).

Inputs to the JPCP smoothness model for the NCHRP 1-37 study should be compatible with the other distress models that will be used in design. Therefore, there may be some distress variables that have an influence on smoothness but will not be predicted as part of the M-E design process. Such distress variables may or may not be included in the final smoothness model. However, these distresses will be represented by a pseudo-variable such as age that, although not a distress, could represent the effects of distresses and surface defects that affect smoothness. Also, for the smoothness model to be compatible with the outputs of individual distress models that will serve as inputs, distress severities will be combined.

Table 12. Summary of stepwise regression output for JPCP smoothness.

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 presented 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.

Final JPCP Smoothness Prediction Models

The model developed for predicting smoothness of JPCP pavements is as follows:

$$IRI = IRI_I + 0.013*TC + 0.007*SPALL + 0.005*PATCH + 0.0015*TFAUL + 0.4S*FT \quad (20)$$

where

IRI_I = initial smoothness measured as IRI, m/km
TC = percentage of slabs with transverse cracking (all severities)
SPALL = percentage of joints with spalling (all severities)
PATCH = pavement surface area with flexible and rigid patching (all severities), percent
TFAULT = total joint faulting cumulated per km, mm
SF = site factor = Age*(1+FI)*(1+P200)/1000000
Age = pavement age in years
FI = freezing index, ^oC days
P200 = percent subgrade material passing the 0.075-mm sieve

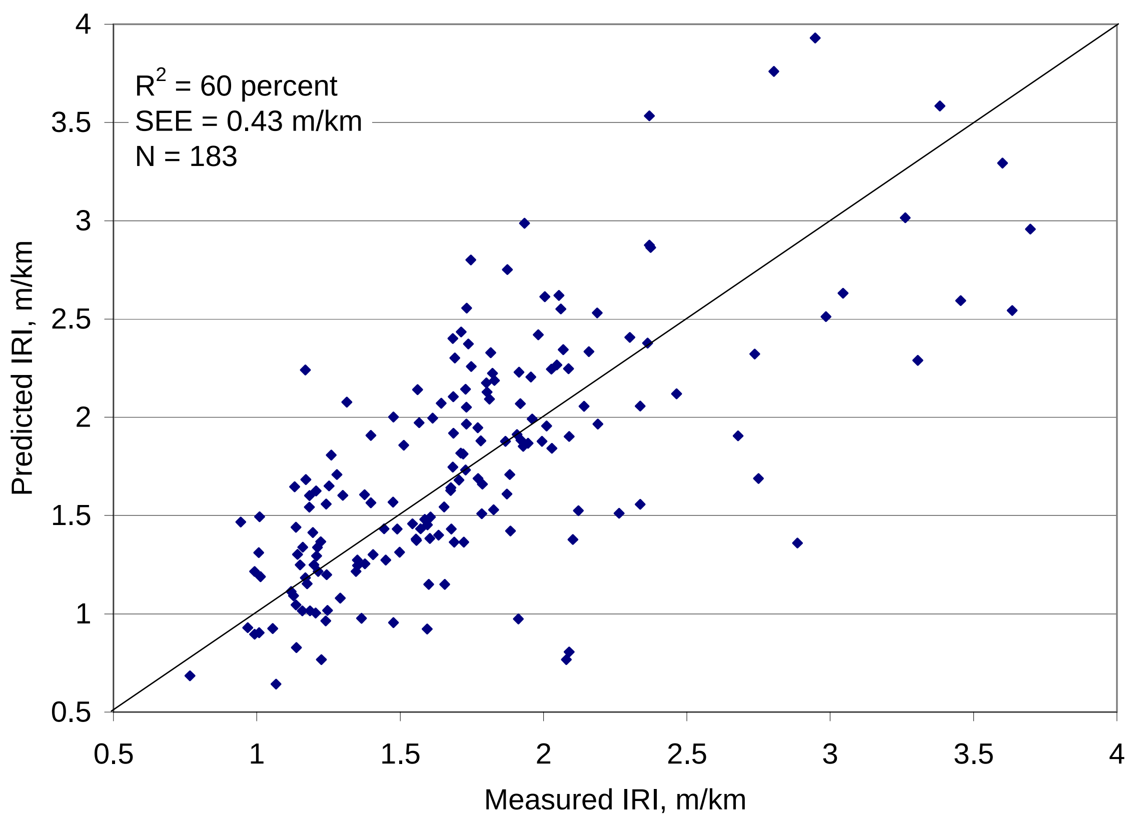
The model had the statistics presented in table 13.

Figures 6 and 7 are plots of the predicted versus the actual smoothness and residual versus predicted smoothness, respectively, for the model. The R^2 and other diagnostic statistics for the model are reasonable and verify that the model provides reasonable predictions of IRI for JPCP.

Table 13. Statistics for JPCP smoothness model.

Distress Variable	Severities	t_{calc} for H_0: Parameter = 0	Probability $t_{calc} > t_{0.05}$	Is Distress Variable Significant?*
Initial IRI	—	4.69	0.0001	Yes
Transverse cracking	(L, M, H)	2.07	0.404	Yes
Transverse joint spalling	(L, M, H)	2.51	0.0132	Yes
Patching	(L, M, H, flexible and rigid)	3.83	0.0002	Yes
Corner breaks	(L, M, H)	2.85	0.0051	Yes
Age	—	2.10	0.0370	Yes
Faulting	Total joint per km	8.85	0.0001	Yes

1. Significance level = 5 percent.
2. N = 183
3. R^2 = 60 percent
4. SEE = 0.43 m/km



Figures 6. Plot of the predicted versus the actual smoothness for JPCP.

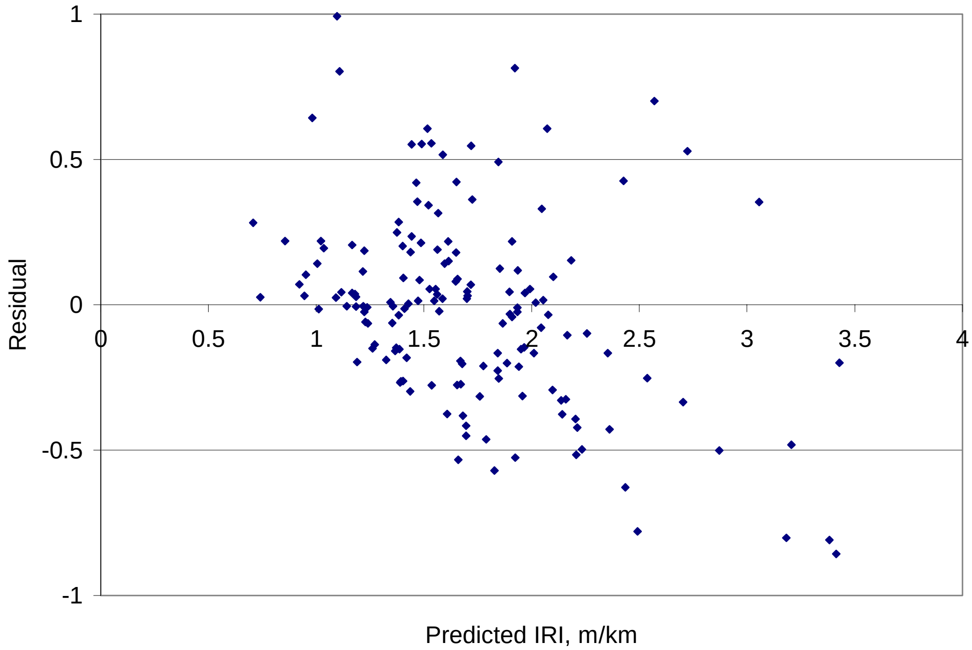


Figure 7. Plot of residual versus predicted smoothness for JPCP.

<u>Tentative CRCP Smoothness Model</u>

The assembled CRCP (GPS-5) data were explored to learn more about the suitability of individual distresses at different levels of severity for model development. This was done by performing a comprehensive stepwise regression analysis of the cleaned data to evaluate the preliminary relationships between the measured smoothness, backcasted initial smoothness, and distress. Table 14 presents the strength of the relationships between the potential independent variables and smoothness for CRCP. The distress variables showing some correlation with smoothness can be categorized as follows:

Table 14. Summary of stepwise regression procedure for CRCP smoothness.

Step	Distress Variable	Partial R^2	R^2	Significance Level (Prob>F)
1	Punchouts	0.252	0.252	0.0010
2	Patching	0.080	0.336	0.0018
3	Scaling	0.035	0.371	0.0150
4	Transverse cracking	0.034	0.405	0.1200
5	Pumping	0.015	0.420	0.1300
6	Map cracking	0.0142	0.434	0.1300

1. All variables presented 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.

- Structural.
  - Punchouts.
  - Transverse cracking.
  - Pumping.

- Surface Defects.
  - Initial IRI.
  - Scaling.
  - Map cracking.

- Maintenance.
  - Patching.

The CRCP smoothness model for the NCHRP 1-37 study should be compatible with the other distress models that will be used in pavement design. Therefore, there may be some distress variables that have an influence on smoothness but will not be predicted as part of the design process and as such may or may not be included in the final smoothness model.

Final CRCP Smoothness Prediction Models

The model developed for predicting smoothness of CRCP pavements is as follows:

$$IRI = IRI_I + 0.003*TC + 0.008*PUNCH + 0.45*SF + 0.2*PATCH \quad (21)$$

where

IRI_I	=	initial IRI, m/km
TC	=	number of medium- and high-transverse cracks/km
PUNCH	=	number of medium- and high-severity punchouts/km
PATCH	=	percentage pavement surface with patching (M-H severity flexible and rigid)
SF	=	site factor = Age*(1+FI)*(1+P200)/1000000
Age	=	pavement age in years
FI	=	freezing index, ^{o}C days
P200	=	percent subgrade material passing the 0.075-mm sieve

The statistics for this model are presented in table 15.

Table 15. Statistics for CRCP smoothness model.

Distress Variable	Severities	t_{calc} for H_0: Parameter = 0	Probability $t_{calc} > t_{0.05}$	Is Distress Variable Significant?
Initial IRI	—	8.98	0.0001	Yes
Transverse cracking	(M, H)	2.42	0.0173	Yes
Punchout	(M, H)	4.87	0.0001	Yes
Patching	(M, H)	2.56	0.0121	Yes
Surface defects	e.g., D-cracking, map cracking (all severities)	2.3	0.0244	Yes
1. Significance level = 5 percent. 2. N = 94 3. R^2 = 60 percent 4. SEE = 0.23 m/km				

Figures 8 and 9 are plots of the predicted versus the actual smoothness and residual versus predicted smoothness, respectively, for the model. The R^2 and other diagnostic statistics for the model are reasonable and verify that the model provides reasonable predictions of smoothness for CRCP.

7. Rigid Pavement Smoothness Models Verification

A sensitivity analysis was conducted on the final smoothness models to determine their reliability for predicting smoothness within and outside of the inference space of the database used to develop them. This was accomplished by studying the effects of the various input distress and maintenance parameters on predicted smoothness. The results obtained were compared with past empirical data and theoretical observations.

Sensitivity Analysis for JPCP

The distress and maintenance factors that were incorporated into the final JPCP smoothness model included initial smoothness, transverse cracking, transverse joint spalling, patching, and corner breaks. Their effects on predicted smoothness are discussed in the following sections.

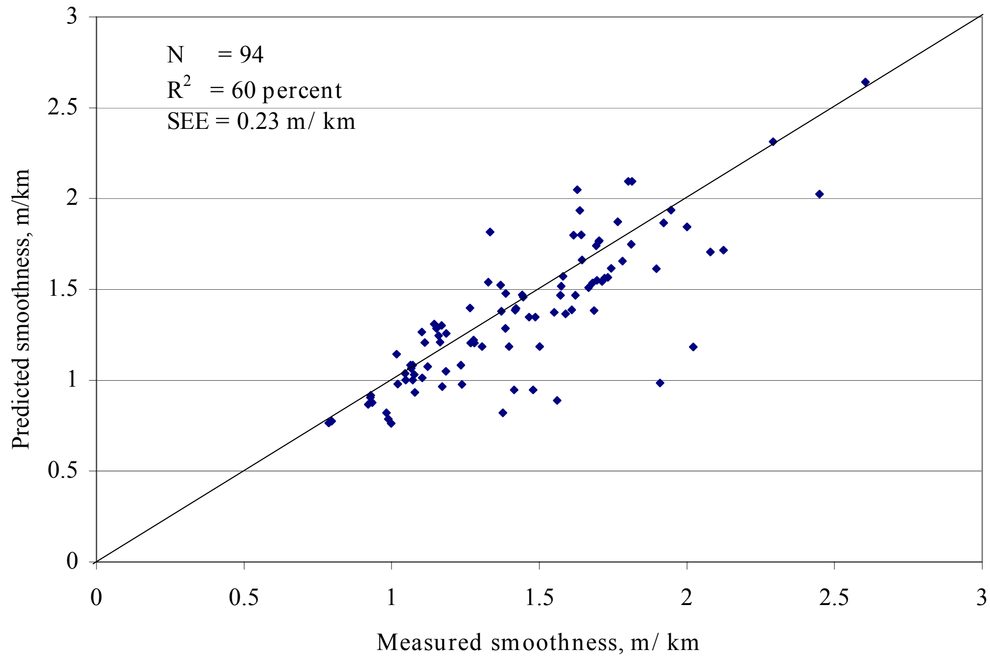


Figure 8. Plot of the predicted versus the actual smoothness for CRCP.

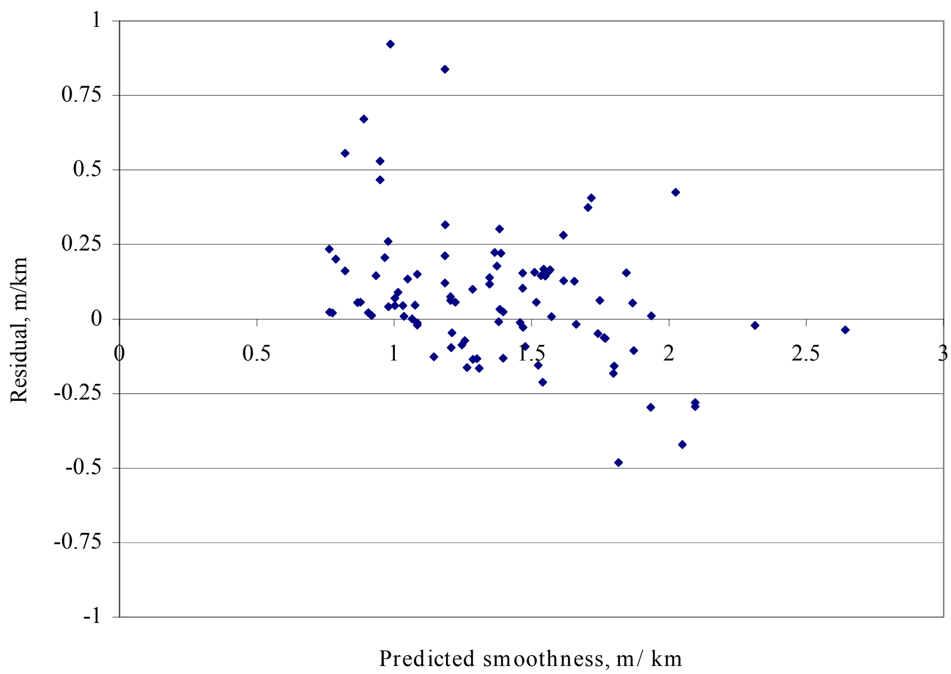


Figure 9. Plot of residual versus predicted smoothness for CRCP.

Effect of Initial Smoothness

Initial smoothness is not only an indicator of overall quality of construction, but all other things being equal, new pavements constructed with a smoother profile will last longer than rougher ones. Initial smoothness typically ranges from 0.5 to 2.0 m/km.[18] Figure 10 shows the effect of differences in initial smoothness for pavements with the same amount of distress (e.g., total faulting for 150-m section = 200 mm). The figure shows that pavements constructed rough (higher IRI) will stay rougher than pavements with an initial smoother surface throughout the pavement's life.

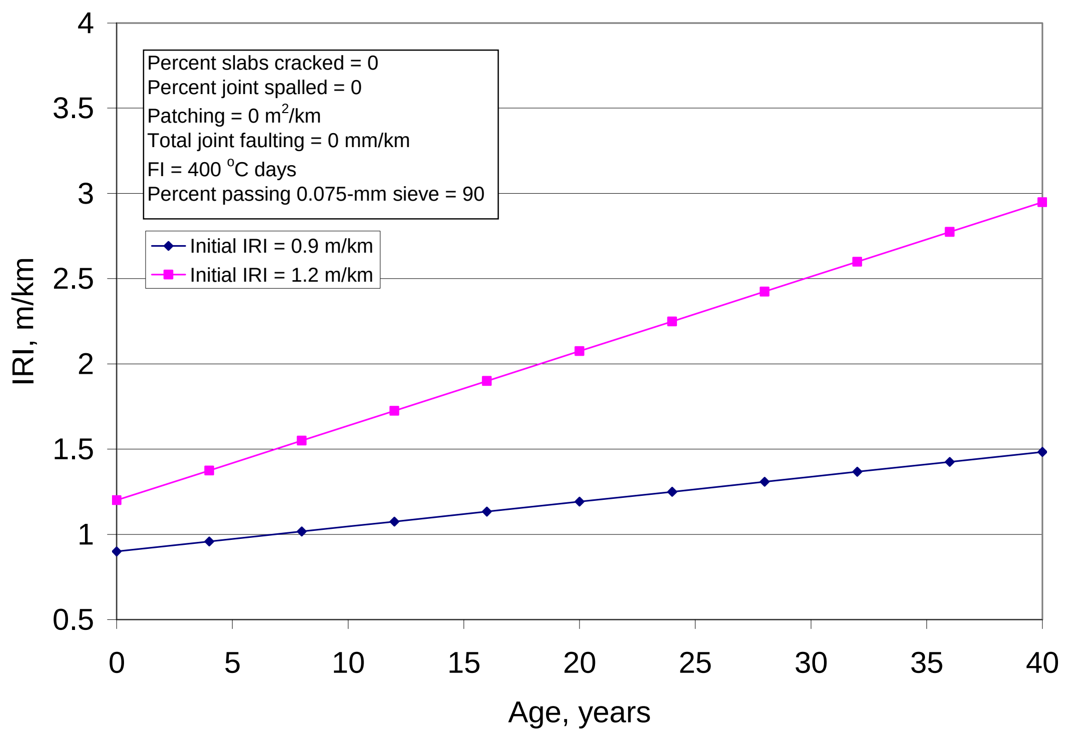


Figure 10. Effect of initial smoothness on long-term JPCP IRI.

Effect of Transverse Cracking

Transverse cracks can occur at the midslab of JPCP slabs parallel to the joint. Typically, midslab cracks begin as a single crack at the edge of the slab that propagates through the entire slab as traffic is applied to the pavement.[24, 25] Transverse cracks increase pavement roughness as the cracks fault and spall and there is a general breakup of the pavement.[24, 25] This decreases serviceability and results in costly rehabilitation. Transverse cracks, especially when they are badly spalled, also cause surface runoff from rainfall to infiltrate the pavement structure, which normally results in erosion of the base and faulting, increasing deflections and resulting in an additional decrease in smoothness.[25]

Figure 11 shows the effect of an increasing number of transverse cracks on pavement smoothness. The plot shows that there is a decrease in smoothness as the percentage of slabs with transverse cracking increases. The plot confirms the trends and observations from previous research.

Effect of Transverse Joint Spalling

Spalling is the breakdown or disintegration of a PCC slab's edges at transverse joints, usually resulting in the removal of sound concrete.(16, 24) Several field studies have observed that joint spalling may be due to the deterioration of the concrete material from environmental factors on infiltration of incompressibles. Spalling caused by a sudden force is usually of low severity and does not progress or deteriorate with time. Spalling from fatigue and concrete deterioration is more significant. Spalling eventually causes a decrease in the smoothness of the pavement, resulting in a need for costly rehabilitation. Figure 12 shows the effect of an increasing percentage of joints spalled on pavement smoothness.

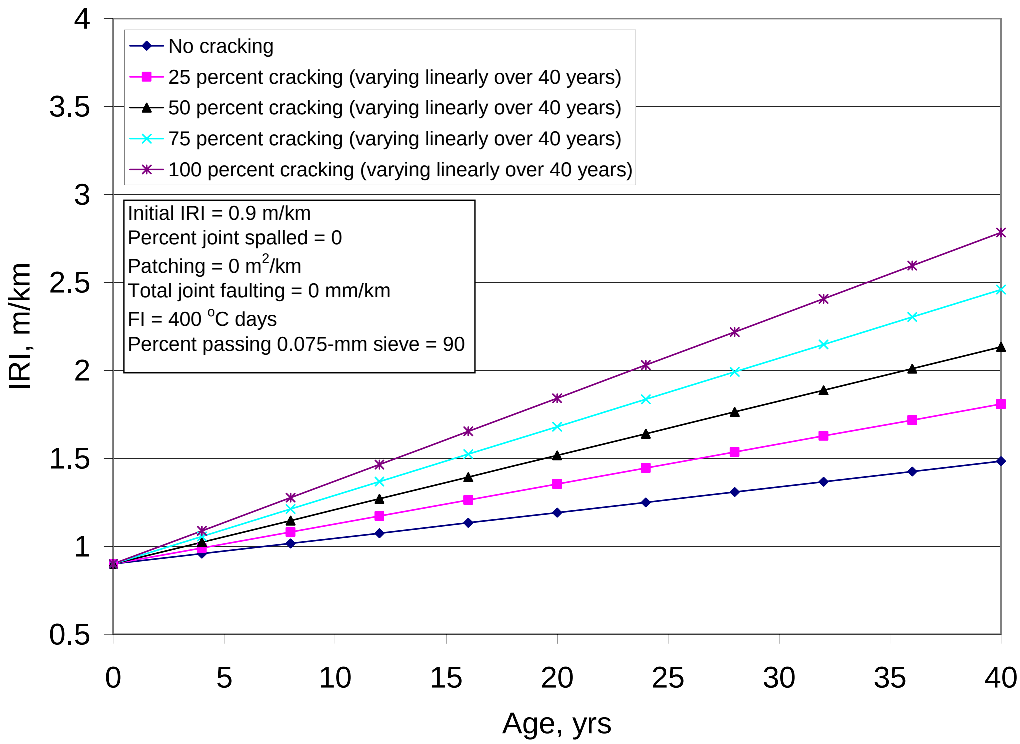


Figure 11. Effect of transverse cracking on JPCP IRI.

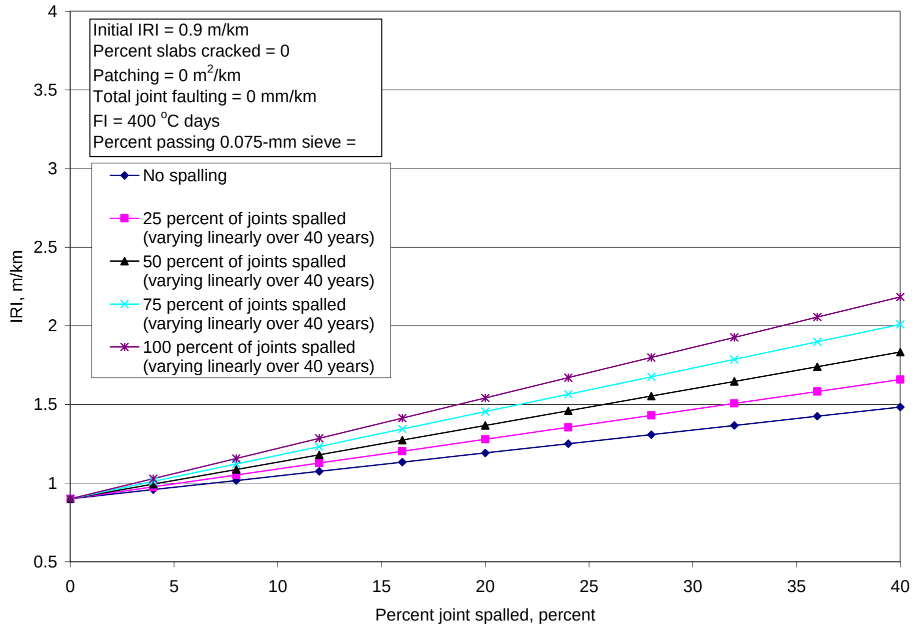


Figure 12. Effect of transverse joint spalling on JPCP IRI.

Effect of Joint Faulting

Faulting is the result of a combination of poor load transfer across a joint or crack, heavy axle loads, free moisture beneath the pavement, and pumping of the supporting base, subbase, or subgrade material from underneath the slab.[24, 27] It is primarily caused by the erosion of the supporting material from underneath the leave slab or treated base and a buildup of the loose material under the approach slab at a joint or crack. Faulting is a major distress that occurs in jointed concrete pavements (JCP). It is the difference in elevation between the adjacent slabs across a transverse joint or crack. Excessive faulting will greatly reduce the smoothness of a JCP and will appreciably increase user discomfort. The influence of pavement joint faulting on smoothness of JPCP, as depicted by the model, is shown in figure 13.

Effect of Site Conditions

The effect of site conditions on long-term IRI development is estimated using freezing index and the percentage of subgrade material passing the 0.075-mm sieve. These two parameters are empirically related to the potential for soil movements due to frost heaving and settlement which has a negative influence on IRI. The effect on IRI of these parameters are presented in figures 14 and 15.

<u>Sensitivity Analysis for CRCP</u>

The distress and maintenance factors that were incorporated into the final CRCP smoothness model included initial smoothness, transverse cracking, punchouts, presence of surface defects, and presence of patching. Their effects on predicted smoothness are discussed in the following sections.

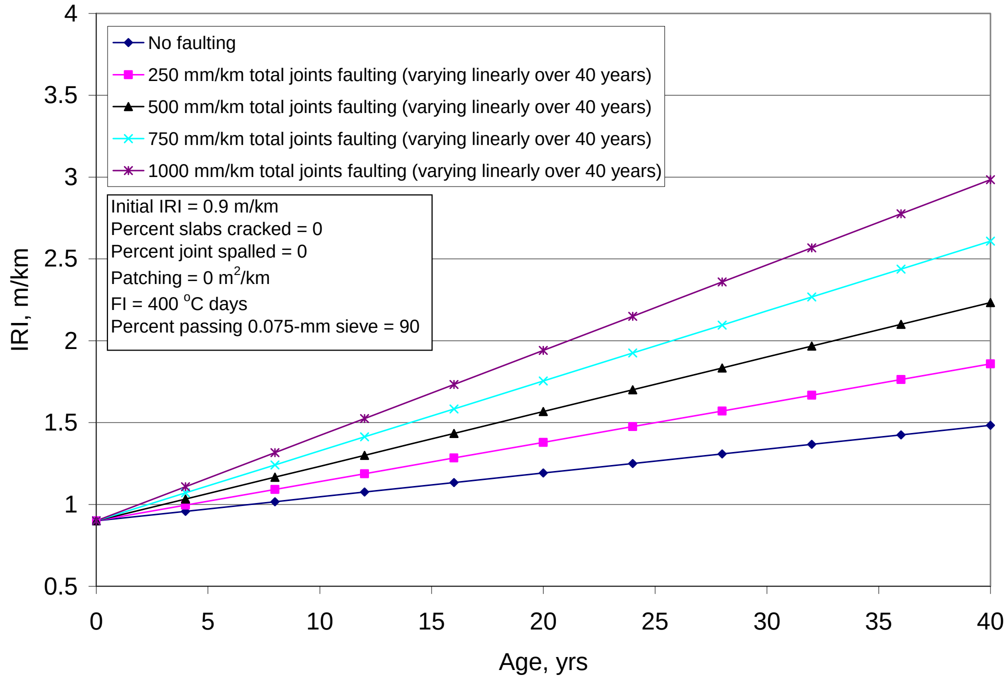


Figure 13. Effect of total joint faulting on JPCP IRI.

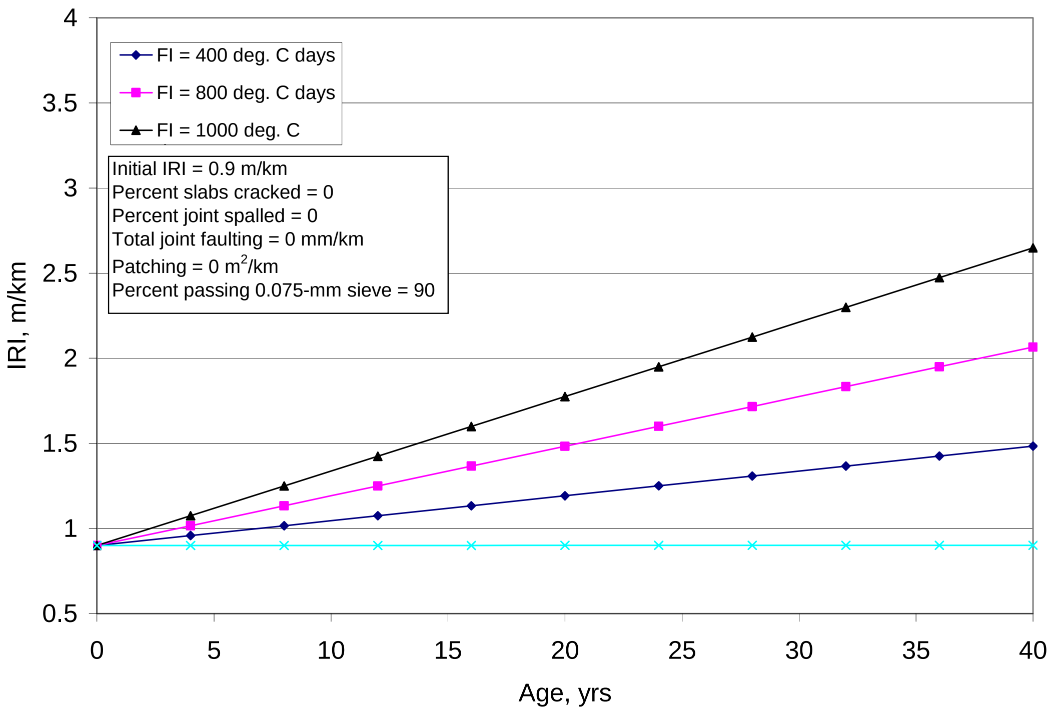


Figure 14. Effect of freezing index on JPCP IRI.

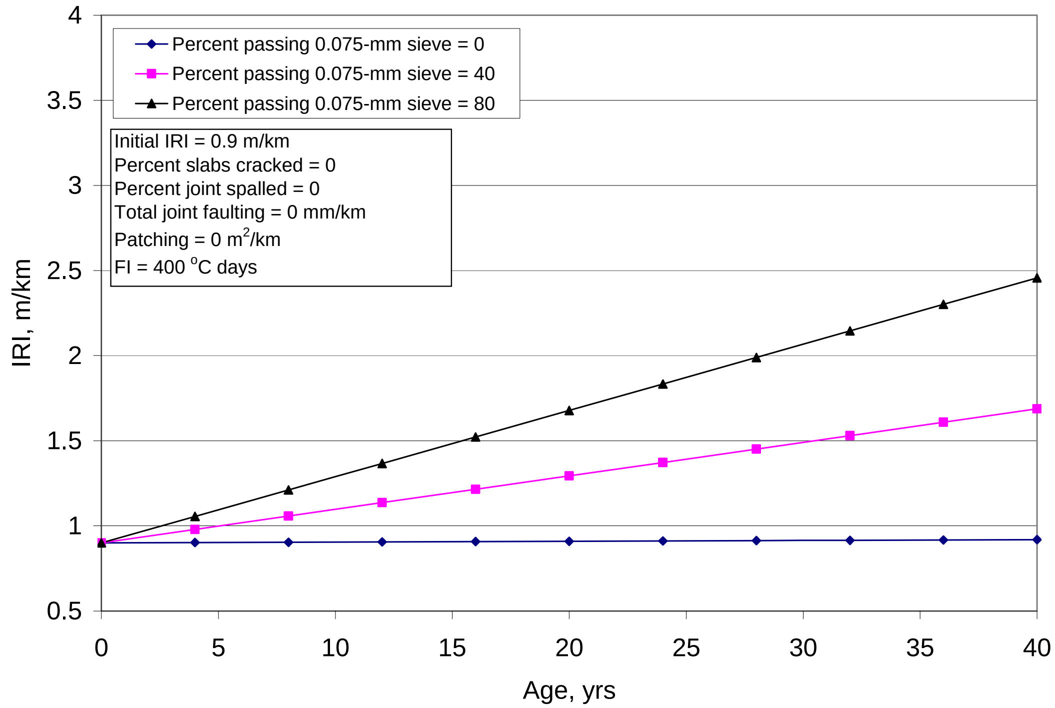


Figure 15. Effect of percentage of subgrade material passing the 0.075-mm sieve on JPCP IRI.

Effect of Initial Smoothness

Initial smoothness indicates overall quality of longitudinal profile. All other things being equal, new CRCP constructed with a smoother profile will last longer than rougher ones.[(18)] Figure 14 shows the effect of differences in initial smoothness for CRCP with the same amount of distress (e.g., 25 M-H severity punchouts per km). The figure shows that pavements constructed rough (higher IRI) will stay rougher than pavements with an initial smoother surface.

Effect of Transverse Cracking

CRCP are designed to have low-severity transverse cracks typically spaced 0.5 to 1.0 m apart. These cracks do not significantly affect smoothness. However, with the application of traffic and climatic load cycles, they can deteriorate into medium- and high-severity cracks. Medium- and high-severity transverse cracks are spalled and contribute significantly to pavement deterioration by allowing surface runoff from rainfall to infiltrate the pavement structure, resulting in the weakening of the pavement foundation, pumping, and the deterioration of reinforcing steel bars within the PCC. All these have the combined effect of decreasing smoothness. Highly deteriorated transverse cracks also lead to punchouts. Figure 15 shows the effect of an increasing number of medium- and high-severity transverse cracks on pavement smoothness.

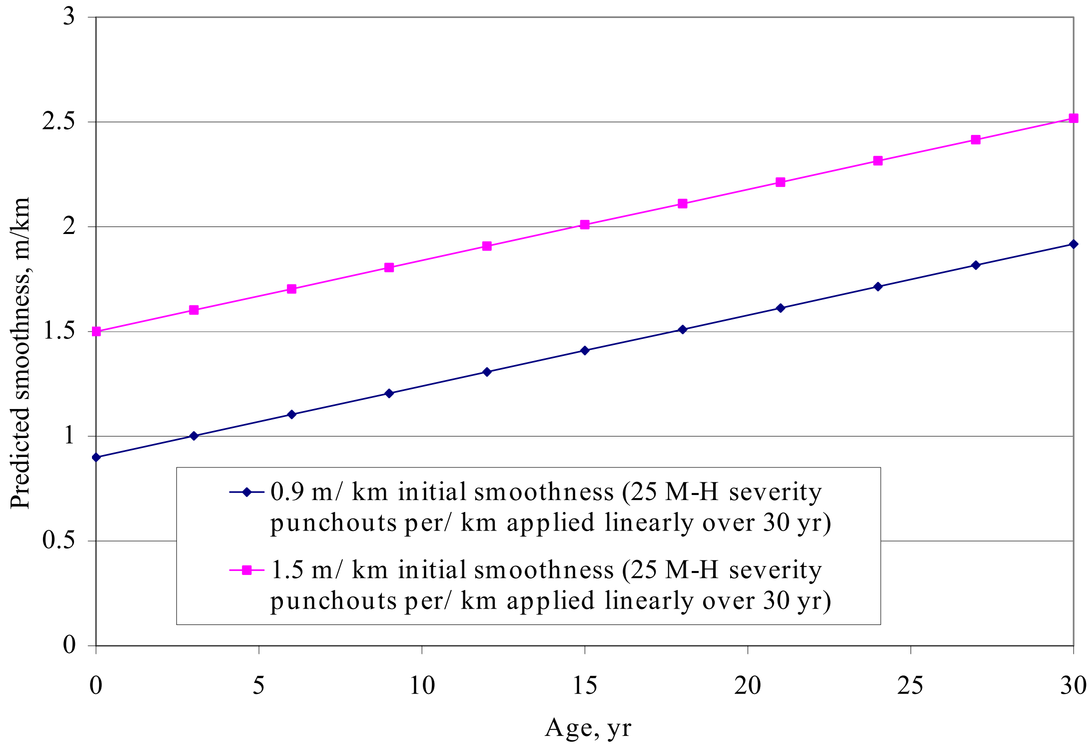


Figure 14. Effect of initial smoothness on long-term CRCP IRI.

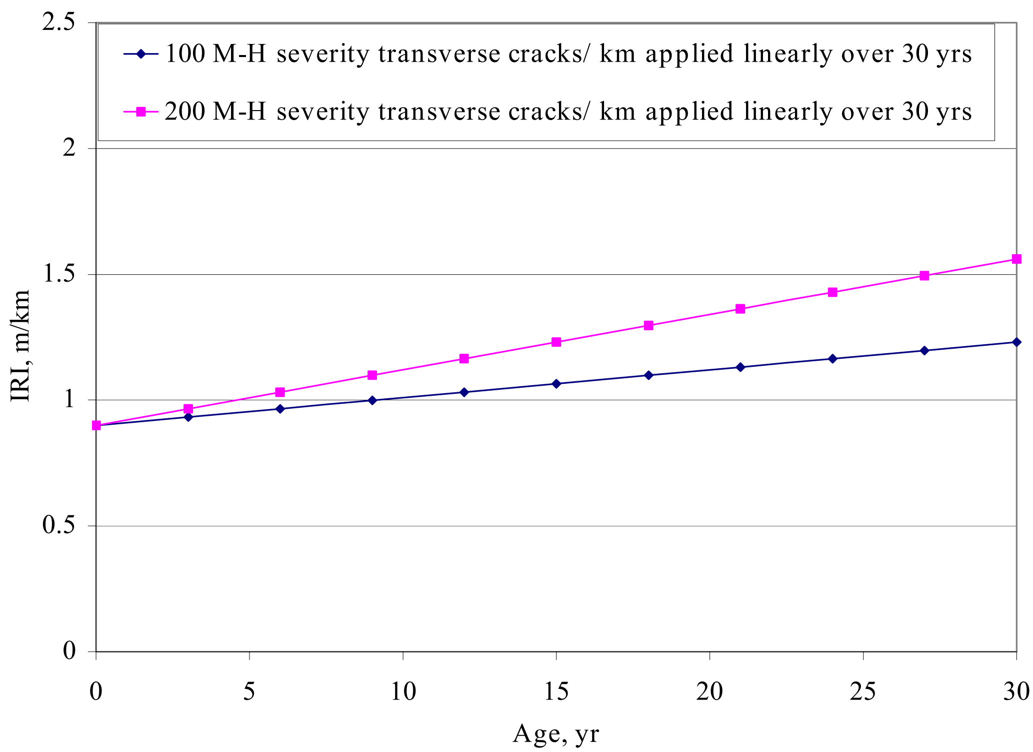


Figure 15. Effect of M-H transverse cracks on CRCP IRI.

Effect of Punchouts

Punchouts are described as the area enclosed by two closely spaced (usually less than 0.6 m) transverse cracks, a short longitudinal crack, and the edge of the pavement or a longitudinal joint. Y cracks that exhibit spalling, breakup, and faulting are also described as punchouts. Medium- and high-severity punchouts are heavily spalled and faulted, and the concrete within the punchout is punched down or broken up in pieces. This leads to very rough sections of pavement and, hence, a decrease in smoothness. Figure 16 shows the effect of an increasing number of medium- and high-severity punchouts on pavement smoothness. Punchouts are often patched before reaching high severity.

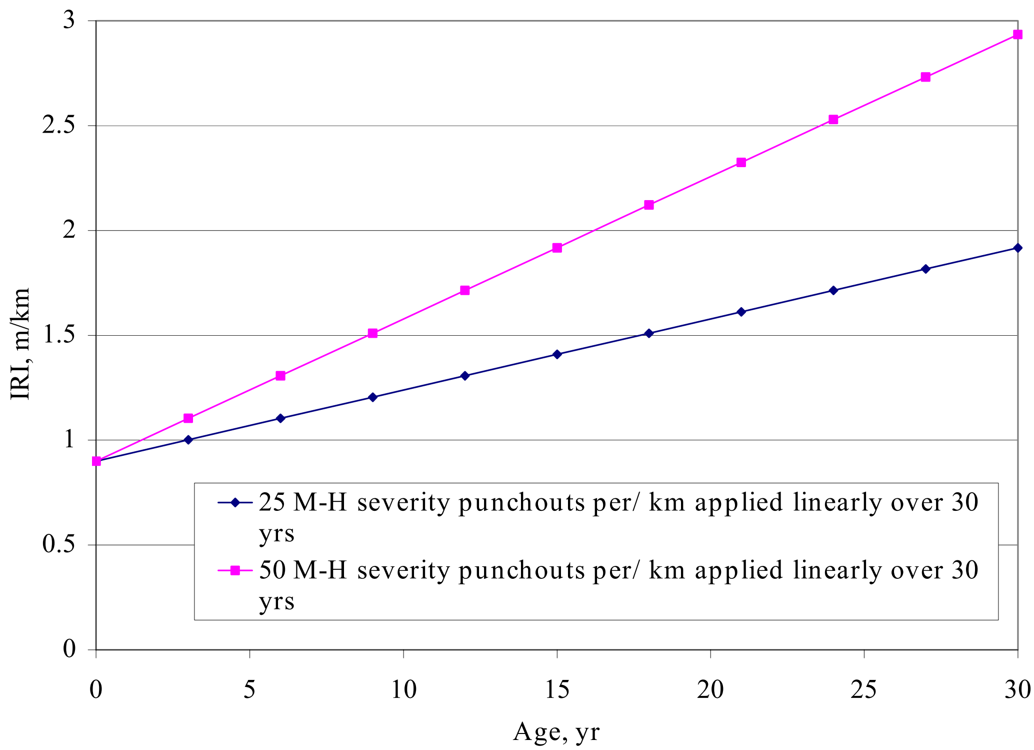


Figure 16. Effect of punchouts on CRCP IRI.

8.0 Summary

A major objective of this study was to use the LTPP database to develop improved prediction models for JPCP and CRCP smoothness. None of the existing models were acceptable. An important goal was to use innovative analytical techniques and mechanistic principles to develop state-of-the-art prediction models that are practical for application in the 2002 Design Guide. They also may be useful to State highway agencies for pavement management purposes.

Two distress-based empirical models have been developed for predicting JPCP and CRCP smoothness. They can be used to check the adequacy of designs from a smoothness standpoint, and they provide information on the distress types that influence the long-term smoothness of pavements. For both models, initial pavement smoothness strongly influences predicted smoothness over time.

Because the models include initial smoothness values, they can be used to predict smoothness loss incrementally over time. Each of the models was evaluated and verified using statistical techniques and by performing comprehensive sensitivity analyses to ensure the ability of each model to predict smoothness within reasonable accuracy and within the limits of the LTPP database. The sensitivity analyses also confirmed that the smoothness models are in agreement with sound engineering principles and judgment.

9.0 Summary of Data used in Model Development and Calibration

Table 16. Summary of LTPP GPS-3 (JPCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Percent Slabs with Transverse Cracking	Percent Joints Spalled	Flexible and Rigid Patching, Area (m^2)	Total Joint Faulting, mm/km	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
1	3028	20.32	2.28	3.31	0	0	0	0.0	32.0	44.7
1	3028	21.84	2.28	3.38	0	0	0	861.8	32.0	44.7
4	7614	13.56	0.85	1.16	0	6	0	83.8	2.4	18.7
5	3011	8.95	1.03	1.14	0	0	0	0.0	52.1	84.3
5	3011	12.17	1.03	1.18	0	6	0	39.9	52.1	84.3
5	3011	14.86	1.03	1.21	0	0	0	159.4	52.1	84.3
6	3010	13.65	1.23	1.30	3.1	43.4	0	93.0	0.0	24.2
6	3010	18.84	1.23	1.28	0	15.5	0	179.1	0.0	24.2
6	3013	9.40	1.56	1.64	2.7	51.3	0	78.9	0.0	26.3
6	3013	14.63	1.56	1.69	5.4	29.7	0	309.5	0.0	26.3
6	3017	13.41	1.14	1.48	9.3	24.8	0	88.9	0.0	13.9
6	3017	18.64	1.14	1.61	0	9.3	0	191.6	0.0	13.9
6	3019	11.98	1.00	1.48	0	99.2	0	205.6	1.0	46.2
6	3019	17.18	1.00	1.69	3.1	37.2	0	537.1	1.0	46.2
6	3024	11.06	1.22	1.57	3.1	89.9	0	53.1	0.8	28.2
6	3024	16.30	1.22	1.73	0	58.9	0	338.3	0.8	28.2
6	3030	19.19	0.73	1.29	24.8	0	0.7	12.9	0.7	51.0
6	3030	24.48	0.73	1.44	37.2	3.1	0	128.6	0.7	51.0
6	3042	12.56	0.77	1.01	6.2	83.7	0	19.9	7.6	64.5
6	3042	17.07	0.77	1.01	3.1	71.3	0	0.0	7.6	64.5
6	3042	17.16	0.77	1.01	3.1	0	0	61.5	7.6	64.5
6	3042	17.25	0.77	0.94	15.5	74.4	0	0.0	7.6	64.5
6	7456	20.48	1.39	2.34	6.2	86.8	0	302.2	0.2	47.8
6	7456	24.32	1.39	2.19	6.2	12.4	0	0.0	0.2	47.8
6	7493	8.48	1.40	1.40	10.8	45.9	0	32.2	0.0	11.4
6	7493	13.68	1.40	1.40	0	2.7	0	98.7	0.0	11.4
12	3804	6.25	1.31	1.68	62.4	0	0	188.9	3.5	2.9

Table 16. Summary of LTPP GPS-3 (JPCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Percent Slabs with Transverse Cracking	Percent Joints Spalled	Flexible and Rigid Patching, Area (m^2)	Total Joint Faulting, mm/km	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
12	3811	15.68	1.22	1.77	56	0	0	0.0	0.7	31.1
12	3811	18.59	1.22	1.87	64	0	0	467.1	0.7	31.1
12	4057	5.33	0.65	0.77	0	0	0	20.6	0.2	2.5
12	4059	2.37	0.89	0.99	0	0	0	6.6	3.4	1.0
12	4059	3.78	0.89	1.06	0	5.6	0	0.0	3.4	1.0
12	4059	7.88	0.89	1.24	0	11.2	0	0.0	3.4	1.0
12	4109	2.60	1.88	1.92	0	0	0	19.5	0.0	2.8
12	4109	4.03	1.88	1.91	0	0	0	0.0	0.0	2.8
12	4109	8.14	1.88	1.96	0	8.4	0	32.7	0.0	2.8
12	4138	16.94	1.84	2.80	28	0	337.5	807.4	0.1	14.7
12	4138	18.36	1.84	2.73	28	12	293.4	0.0	0.1	14.7
12	4138	22.48	1.84	3.02	16	16	559.2	799.7	0.1	14.7
13	3007	9.37	1.50	1.78	0	20	0	26.3	24.8	50.5
13	3007	9.82	1.50	1.87	0	0	0	0.0	24.8	50.5
13	3007	12.90	1.50	1.77	0	0	0	65.8	24.8	50.5
13	3007	15.46	1.50	1.95	0	0	0	236.8	24.8	50.5
13	3011	16.41	1.06	1.12	0	8	0	0.0	4.6	27.7
13	3011	19.51	1.06	1.14	4	36	0	189.8	4.6	27.7
13	3011	21.99	1.06	1.13	0	20	0	69.6	4.6	27.7
13	3015	11.61	0.68	1.23	0	12	0	157.9	25.2	1.4
13	3015	12.07	0.68	1.48	0	12	0	0.0	25.2	1.4
13	3015	15.17	0.68	1.36	0	4	0	177.6	25.2	1.4
13	3015	17.65	0.68	1.21	0	12	0	125.0	25.2	1.4
13	3016	13.82	1.21	1.35	0	0	0	0.0	19.7	37.9
13	3016	16.91	1.21	1.38	0	12	0	203.9	19.7	37.9
13	3017	17.37	1.19	1.24	0	0	0	240.0	17.5	35.3
13	3017	17.82	1.19	1.24	0	0	0	0.0	17.5	35.3
13	3017	20.91	1.19	1.25	0	11.7	0	246.6	17.5	35.3
13	3017	23.47	1.19	1.26	0	11.7	0	350.4	17.5	35.3
13	3018	17.79	0.47	0.98	0	35.1	0	136.3	23.5	43.2
13	3018	18.24	0.47	1.07	0	0	0	0.0	23.5	43.2
13	3018	21.33	0.47	1.14	3.9	11.7	0	19.4	23.5	43.2
13	3018	23.88	0.47	0.97	3.9	11.7	0	142.7	23.5	43.2
13	3019	9.36	1.31	1.50	0	0	0	78.9	11.1	59.9
13	3019	9.82	1.31	1.56	0	0	0	0.0	11.1	59.9
13	3019	12.91	1.31	1.49	0	0	0	39.5	11.1	59.9
13	3019	13.67	1.31	1.57	0	0	0	78.9	11.1	59.9
13	3019	14.41	1.31	1.59	0	4	0	92.1	11.1	59.9
13	3019	14.88	1.31	1.59	0	0	0	92.1	11.1	59.9
13	3020	6.02	1.25	1.35	0	4	0	0.0	3.7	21.4

Table 16. Summary of LTPP GPS-3 (JPCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Percent Slabs with Transverse Cracking	Percent Joints Spalled	Flexible and Rigid Patching, Area (m^2)	Total Joint Faulting, mm/km	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
13	3020	6.07	1.25	1.35	0	0	0	0.0	3.7	21.4
13	3020	9.15	1.25	1.45	0	8	0	0.0	3.7	21.4
13	3020	11.65	1.25	1.41	0	4	0	0.0	3.7	21.4
16	3017	5.40	1.33	1.60	0	0	0	6.6	308.5	68.0
16	3017	10.91	1.33	1.88	0	0	0	0.0	308.5	68.0
18	3002	16.79	1.63	1.80	9.3	9.3	0	99.5	456.1	67.4
18	3002	18.88	1.63	1.83	0	34.1	0	79.6	456.1	67.4
18	3002	19.50	1.63	1.82	3.1	18.6	0	95.9	456.1	67.4
18	3003	16.34	1.38	1.65	0	12	0	0.0	389.0	31.7
18	3003	17.72	1.38	1.68	4	0	0	82.2	389.0	31.7
18	3030	13.56	1.19	1.63	0	9.3	0	26.5	300.0	62.4
19	3006	18.85	1.19	3.26	36	8	0	677.6	618.1	60.9
19	3009	17.82	2.13	2.30	8	8	0	0.0	515.0	30.6
19	3028	9.77	1.60	1.72	0	0	0	69.6	470.7	56.3
20	3013	10.69	1.35	1.61	0	0	0	358.8	270.4	93.3
20	3060	9.85	0.81	1.38	0	0	0	225.7	296.4	89.6
21	3016	7.36	1.43	1.51	0	0	4.6	251.5	191.0	52.3
23	3013	21.81	1.79	2.19	0	4	0.7	31.6	546.0	19.7
23	3014	20.96	1.23	1.56	0	16	0	44.2	516.3	9.9
23	3014	21.81	1.23	1.54	0	0	0	65.8	516.3	9.9
28	3018	6.42	1.36	1.69	0	0	0	0.0	77.4	26.3
28	3018	7.09	1.36	1.72	0	0	0	0.0	77.4	26.3
28	3018	11.13	1.36	1.93	0	0	0	322.4	77.4	26.3
28	3019	6.42	1.07	1.60	4	4	0	0.0	48.2	29.4
28	3019	7.09	1.07	1.66	4	4	0	0.0	48.2	29.4
28	3019	11.17	1.07	1.99	8	48	0	243.4	48.2	29.4
31	3018	8.52	0.91	1.71	0	0	0	0.0	472.9	4.7
31	3018	9.97	0.91	1.78	0	0	0	595.5	472.9	4.7
31	3018	10.85	0.91	1.91	0	0	0	636.7	472.9	4.7
31	3018	11.28	0.91	1.82	0	0	0	935.1	472.9	4.7
31	3018	12.52	0.91	1.59	0	0	0	868.2	472.9	4.7
31	3023	9.14	1.11	1.16	6.2	0	0	95.9	483.8	2.4
31	3023	10.89	1.11	1.18	65.1	0	0	185.7	483.8	2.4
31	3023	13.21	1.11	1.17	24.8	0	0	68.5	483.8	2.4
31	3028	10.20	1.11	1.20	0	49.6	0	6.4	530.4	97.9
31	3028	12.33	1.11	1.17	0	0	0	154.3	530.4	97.9
31	3028	14.35	1.11	1.18	0	0	0	0.0	530.4	97.9
31	3028	16.38	1.11	1.21	0	0	0	112.7	530.4	97.9
32	3010	9.03	1.74	2.68	15.5	12.4	0	0.0	374.1	19.5
32	3010	9.52	1.74	2.34	3.1	105.4	0	656.6	374.1	19.5

Table 16. Summary of LTPP GPS-3 (JPCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Percent Slabs with Transverse Cracking	Percent Joints Spalled	Flexible and Rigid Patching, Area (m^2)	Total Joint Faulting, mm/km	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
32	3010	14.20	1.74	2.37	9.3	0	0	0.0	374.1	19.5
32	3013	10.52	1.31	1.87	21.7	0	0.7	179.1	338.1	8.4
37	3008	11.67	1.55	1.79	0	4.26	0	46.9	48.2	33.9
37	3011	18.64	1.47	1.68	0	12	0	123.4	41.0	31.8
37	3044	28.98	1.30	2.03	12	0	2.0	219.3	47.3	79.1
37	3807	17.04	1.77	1.80	8.52	4.26	0	141.6	51.8	28.2
38	3005	8.25	1.05	1.21	0	0	0	13.6	1460.0	54.5
38	3006	6.01	0.98	1.01	0	0	0	0.0	1434.9	59.2
39	3801	12.03	1.88	2.00	0	76	0	78.9	355.3	46.8
40	4157	5.61	1.09	1.13	0	0	0	0.0	107.1	17.9
40	4157	6.68	1.09	1.17	0	0	0	232.2	107.1	17.9
40	4157	8.68	1.09	1.15	0	0	0	103.3	107.1	17.9
40	4157	11.23	1.09	1.14	0	0	0	58.1	107.1	17.9
40	4160	12.38	1.69	1.73	0	3	0	0.0	49.7	80.3
40	4160	13.43	1.69	1.74	0	0	0	562.1	49.7	80.3
40	4160	15.43	1.69	1.73	0	0	0	438.6	49.7	80.3
40	4160	18.23	1.69	1.75	0	6	0	692.1	49.7	80.3
40	4162	6.37	1.62	1.68	0	0	0	0.0	97.9	41.6
40	4162	7.44	1.62	1.70	0	0	0	193.4	97.9	41.6
40	4162	9.43	1.62	1.69	0	0	0	32.2	97.9	41.6
40	4162	12.23	1.62	1.73	0	0	0	219.3	97.9	41.6
45	3012	11.61	1.01	1.19	0	0	0	0.0	17.8	54.9
45	3012	15.65	1.01	1.25	0	0	0	0.0	17.8	54.9
46	3009	18.05	1.76	2.98	0	43.4	0	0.0	1000.0	61.4
46	3010	10.12	1.85	2.14	0	9	0	0.0	703.2	49.8
46	3012	12.10	2.59	2.95	3	0	0	737.7	600.8	64.5
46	3053	8.02	1.08	1.21	0	0	0	0.0	622.2	65.1
46	6600	18.13	0.86	2.37	0	70.3	4.6	711.2	664.0	89.8
48	3003	18.13	1.36	2.10	0	0	0	0.0	26.4	88.1
48	3003	22.08	1.36	2.26	0	0	0	86.4	26.4	88.1
48	3589	30.82	2.25	2.36	3	9	0	0.0	54.8	41.3
48	3589	33.71	2.25	2.37	15	6	3.9	219.3	54.8	41.3
49	3010	19.19	1.43	1.71	42	0	0	265.8	268.3	30.2
49	3011	14.64	0.62	1.91	21	3	0	490.1	259.7	35.8
49	3011	14.99	0.62	2.12	21	3	0	0.0	259.7	35.8
49	3011	15.24	0.62	1.88	18	3	0	1367.3	259.7	35.8
49	3011	16.64	0.62	2.09	0	102	0	812.7	259.7	35.8
49	3011	17.02	0.62	2.09	3	99	0	551.5	259.7	35.8
49	3011	17.05	0.62	2.05	0	60	0	529.0	259.7	35.8
49	3011	17.43	0.62	1.93	27	0	0	322.6	259.7	35.8

Table 16. Summary of LTPP GPS-3 (JPCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Percent Slabs with Transverse Cracking	Percent Joints Spalled	Flexible and Rigid Patching, Area (m^2)	Total Joint Faulting, mm/km	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
49	3015	6.92	1.82	2.01	0	12.5	0	26.3	214.5	18.1
49	3015	12.19	1.82	2.16	0	20	2.6	229.5	214.5	18.1
49	7082	6.88	0.96	0.99	0	2.5	0	145.5	408.5	18.0
49	7085	5.40	1.29	1.56	52.5	2.5	0	81.1	480.1	25.9
49	7086	5.95	1.29	1.68	0	0	0	81.1	191.8	38.4
53	3011	20.03	0.74	1.83	0	11.5	0	463.1	49.3	25.4
53	3019	11.05	0.89	1.20	0	0	0	206.2	137.1	80.2
53	3813	28.98	0.43	2.08	12	3	0	1083.6	25.7	26.8
53	3813	29.32	0.43	2.09	9	6	0	1109.4	25.7	26.8
53	3813	29.58	0.43	2.03	9	15	0	1257.7	25.7	26.8
53	3813	29.73	0.43	2.05	9	0	0	1189.5	25.7	26.8
53	3813	29.92	0.43	2.07	12	24	0	0.0	25.7	26.8
53	3813	30.10	0.43	2.06	15	24	0	0.0	25.7	26.8
53	7409	15.97	0.82	1.22	2.3	0	0	333.8	196.8	8.5
55	3009	10.10	1.01	4.18	0	64.26	0	1902.3	595.8	74.2
55	3009	10.10	1.01	4.18	0	64.26	0	1902.3	595.8	74.2
55	3009	10.59	1.01	4.03	3.06	97.92	2.0	1589.7	595.8	74.2
55	3009	10.59	1.01	4.03	3.06	97.92	2.0	1589.7	595.8	74.2
55	3010	16.12	0.49	2.46	0	77.48	0	590.8	549.1	55.4
55	3016	8.43	1.24	1.31	0	31	0	404.5	806.9	5.0
56	3027	10.69	1.05	2.74	3.1	21.7	0	636.7	731.8	39.6
56	3027	16.16	1.05	3.60	3.1	0	0	1341.9	731.8	39.6
83	3802	8.46	0.51	2.75	0	0	0	396.1	1862.8	91.6
83	3802	8.98	0.51	2.89	0	33	0	0.0	1862.8	91.6
83	3802	9.58	0.51	3.04	3	96	0	499.6	1862.8	91.6
83	3802	11.13	0.51	3.45	0	66	0	568.9	1862.8	91.6
83	3802	11.81	0.51	3.63	0	66	0	504.4	1862.8	91.6
83	3802	12.05	0.51	3.70	0	99	15.1	564.9	1862.8	91.6
84	3803	15.18	1.13	3.17	5.8	92.8	11.2	1302.9	881.0	26.3
89	3001	19.29	2.18	2.57	3.1	65.1	58.6	683.2	1020.0	14.0
89	3001	20.13	2.18	2.55	3.1	52.7	52.0	694.6	1020.0	14.0
89	3015	9.72	1.00	1.92	7.88	102.44	15.1	89.8	1227.7	2.9
89	3015	9.95	1.00	1.96	11.82	102.44	50.0	77.1	1227.7	2.9
89	3015	10.79	1.00	1.73	0	98.5	33.6	141.3	1227.7	2.9
89	3015	12.22	1.00	1.81	0	23.64	143.4	106.9	1227.7	2.9
89	3015	12.72	1.00	1.75	0	31.52	168.4	76.5	1227.7	2.9
89	3015	13.07	1.00	1.98	0	82.74	114.5	160.3	1227.7	2.9

Table 16. Summary of LTPP GPS-5 (CRCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Number of Transverse Cracking (M-H severities)	Number of Punchouts (all severities)	Number of Patches (all severities)	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
5008	1	17.9	0.91	0.93	0	0	0	35.2	47.9
5008	1	19.6	0.91	0.93	6.6	0	0	35.2	47.9
7079	4	3.9	1.00	1.05	0	0	0	0.0	51.0
7079	4	6.1	1.00	1.07	0	0	0	0.0	51.0
5803	5	19.9	0.95	1.41	0	0	0	49.6	45.0
5803	5	22.6	0.95	1.48	0	0	0	49.6	45.0
7455	6	22.2	1.09	1.16	66	0	0	0.4	53.7
7455	6	24.0	1.09	1.17	118.8	0	0	0.4	53.7
5023	13	19.8	1.39	1.42	0	0	0	13.3	1.7
5023	13	21.7	1.39	1.42	6.6	0	0	13.3	1.7
5843	17	10.8	0.75	1.38	39.6	0	0	512.6	68.6
5843	17	13.9	0.75	1.56	79.2	0	0	512.6	68.6
9267	17	27.3	1.06	1.12	6.6	0	0	473.1	9.9
5849	17	25.2	1.17	1.39	66	0	0	428.8	80.7
5849	17	23.6	1.17	1.37	13.2	0	1	428.8	80.7
5869	17	15.0	1.53	1.71	6.6	0	0	305.4	66.0
5869	17	16.7	1.53	1.73	19.8	0	0	305.4	66.0
5908	17	23.5	1.51	2.08	0	0	0	228.6	91.4
5908	17	25.3	1.51	2.12	6.6	0	0	228.6	91.4
5854	17	11.9	1.34	2.45	132	6.6	0	468.5	79.8
5854	17	13.6	1.34	2.60	231	13.2	1	468.5	79.8
5046	19	17.6	1.27	1.57	6.6	0	1	664.4	32.9
5042	19	17.6	1.54	1.69	6.6	0	0	807.3	45.7
5042	19	20.6	1.54	1.72	13.2	0	0	807.3	45.7
5046	19	20.6	1.27	1.62	6.6	0	4	664.4	32.9
5807	24	4.1	1.19	1.31	0	0	0	337.4	89.9
5807	24	7.2	1.19	1.40	0	0	0	337.4	89.9
5363	26	16.6	0.99	1.91	0	0	0	643.7	12.7
5363	26	18.6	0.99	2.02	6.6	0	2	643.7	12.7
5025	28	14.7	0.83	1.17	79.2	0	0	62.3	19.2
5025	28	17.5	0.83	1.24	85.8	0	0	62.3	19.2
5006	28	13.7	1.17	1.50	6.6	0	0	23.1	79.7
5803	28	13.3	1.19	1.67	79.2	0	1	19.3	12.0
5805	28	17.6	1.29	1.33	145.2	0	0	14.2	2.8
5805	28	20.4	1.29	1.33	303.6	0	0	14.2	2.8
5803	28	16.0	1.19	1.77	138.6	6.6	1	19.3	12.0
5047	29	21.5	1.34	1.55	19.8	0	0	369.3	96.2
5047	29	24.5	1.34	1.58	19.8	0	0	369.3	96.2

Table 16. Summary of LTPP GPS-5 (CRCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Number of Transverse Cracking (M-H severities)	Number of Punchouts (all severities)	Number of Patches (all severities)	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
5037	37	20.0	0.93	1.08	0	0	0	91.9	36.4
5037	37	23.3	0.93	1.10	46.2	0	0	91.9	36.4
5827	37	24.6	0.76	1.00	0	0	0	658.0	39.5
5827	37	23.0	0.76	0.98	33	0	0	658.0	39.5
5003	39	4.4	1.08	1.07	0	0	0	441.7	75.6
5003	39	7.0	1.08	1.06	0	0	0	441.7	75.6
5021	40	27.4	0.81	0.92	33	0	0	70.3	20.4
5021	40	30.6	0.81	0.93	39.6	0	0	70.3	20.4
7081	41	4.8	0.76	0.79	0	0	0	350.7	13.6
7081	41	6.7	0.76	0.80	6.6	0	0	350.7	13.6
5022	41	8.8	0.90	1.02	46.2	0	0	16.8	50.7
5022	41	10.6	0.90	1.05	79.2	0	0	16.8	50.7
5005	41	7.8	1.05	1.16	0	0	0	127.6	35.4
5005	41	9.6	1.05	1.19	6.6	0	0	127.7	35.4
5006	41	22.0	1.19	1.39	52.8	0	0	193.0	41.0
5006	41	20.1	1.19	1.37	79.2	0	0	193.0	41.0
1598	42	17.9	1.33	1.69	33	0	0	398.4	29.4
5020	42	15.0	1.32	1.90	171.6	0	0	250.7	54.4
5020	42	17.7	1.32	2.00	303.6	0	0	250.7	54.4
1598	42	20.8	1.33	1.74	59.4	0	2	398.4	29.4
5035	45	17.1	1.20	1.26	0	0	0	12.7	29.8
5035	45	20.3	1.20	1.28	13.2	0	0	12.7	29.8
5034	45	17.5	1.35	1.46	0	0	0	11.9	24.1
5034	45	20.8	1.35	1.49	0	0	0	11.9	24.1
5020	46	21.2	0.76	0.99	13.2	0	0	615.7	21.0
5020	46	23.9	0.76	1.02	217.8	0	0	615.7	21.0
5283	48	5.3	1.05	1.18	0	0	0	26.7	63.6
5283	48	7.3	1.05	1.23	19.8	0	0	26.7	63.6
5334	48	22.5	1.21	1.11	0	0	0	121.4	69.8
5334	48	25.0	1.21	1.10	33	0	0	121.4	69.8
5154	48	21.7	1.35	1.59	6.6	0	0	6.3	45.2
5154	48	23.7	1.35	1.61	19.8	0	0	6.3	45.2
5336	48	11.6	1.42	1.45	19.8	0	0	97.5	75.3
5336	48	9.2	1.42	1.44	26.4	0	0	97.5	75.3
5278	48	17.4	1.52	1.68	6.6	0	0	28.3	26.9
5278	48	19.8	1.52	1.70	26.4	0	0	28.3	26.9
5323	48	13.5	1.62	1.78	19.8	0	0	129.1	71.5
5274	48	20.0	1.66	1.64	0	0	0	30.2	88.9
5026	48	7.3	1.66	1.69	46.2	0	0	3.7	96.1
5026	48	9.3	1.66	1.70	59.4	0	0	3.7	96.1

Table 16. Summary of LTPP GPS-5 (CRCP) distress and smoothness data used in model development and calibration.

LTPP State Code	SHRP_ID	Age, years	Estimated Initial IRI, m/km	IRI, m/km	Number of Transverse Cracking (M-H severities)	Number of Punchouts (all severities)	Number of Patches (all severities)	Freezing Index, °C days	Percent Subgrade Passing the 0.075-mm Sieve
5323	48	15.9	1.62	1.81	72.6	0	0	129.1	71.5
5274	48	22.0	1.66	1.64	79.2	0	0	30.2	88.9
5287	48	19.5	1.68	1.92	0	0	1	31.3	57.5
5035	48	13.5	1.71	1.80	0	0	1	25.1	61.7
5035	48	15.5	1.71	1.81	0	0	1	25.1	61.7
5301	48	11.0	1.69	1.64	33	0	1	33.2	63.2
5287	48	21.6	1.68	1.95	39.6	0	1	31.3	57.5
5301	48	13.0	1.69	1.63	99	0	1	33.2	63.2
5010	51	4.4	1.52	1.57	0	0	0	66.5	97.3
5010	51	7.8	1.52	1.62	13.2	6.6	0	66.5	97.3
5037	55	19.7	1.19	1.15	52.8	0	0	1095.9	1.9
5037	55	22.9	1.19	1.14	66	0	0	1095.9	1.9

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