

Restoration of Concrete Pavement Using the NCHRP 1-37A Design Guide

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Abstract

Concrete pavement restoration (CPR) of jointed plain concrete pavement (JPCP) has evolved over the past 40 years into a major preservation treatment. These projects often involve several different types of activities such as replacement and/or repair of cracked slabs, spall repair, joint load transfer restoration, joint resealing, subdrainage improvement, diamond grinding, and shoulder replacement. These projects have usually been successful in extending the service life of the pavement for many years into the future. However, these projects have been developed based on practical experience and guidelines, as there has not been a formal design procedure available. The new NCHRP 1-37A Mechanistic-Empirical (ME) Pavement Design Guide includes a formal design procedure for CPR that can be used to assist highway agencies in the evaluation of feasible applications of CPR and the design of more reliable restoration projects. This paper provides an overview of this design procedure by means of a case study.

Introduction

Restoration of jointed plain concrete pavement (JPCP) was first attempted in 1965 and has evolved into a major preservation treatment over the past 40 years. These projects have been generally successful in extending the service life of the pavement for many years into the future at approximately one-half the cost of an overlay. However, these projects have all been developed based on experience and guidelines as there has not been a formal design procedure available. The 1993 AASHTO Design Guide (AASHTO, 1993) addressed concrete pavement restoration and provided useful guidelines but did not provide a design procedure. As a consequence, some of these projects did not last their expected life and thus hindered the further development of the procedure. The new NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide (ARA, 2004) now includes a formal design procedure that provides the highway community with a state-of-the-practice tool for the design of concrete pavement restoration (CPR) projects, based on mechanistic-empirical principles. This procedure will assist highway agencies in the design of more reliable restoration designs in the future. The procedure provides

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direct feedback to the designer on the performance of the CPR project and, thus, poor applications of CPR will be quickly identified.

This paper presents an overview of the M-E design of restoration of existing JPCP through use of a case study. It describes an iterative process used to achieve a feasible design beginning with (1) a trial design, (2) evaluation of the trial design, (3) design modification if needed, and (4) selection of a final design. The design of CPR for the first time includes M-E based procedures used to evaluate the performance of existing JPCP subjected to commonly applied CPR techniques such as diamond grinding, full-depth patching, joint repair, and load transfer restoration (LTR).

Design Approach

Mechanistic empirical rehabilitation design with portland cement concrete (PCC) is divided into three major stages.

1. Stage 1 consists of a comprehensive evaluation of the existing pavement, assessing overall pavement condition. If the existing pavement does not have a significant load carrying capacity problem or material durability problem, CPR will normally be the most cost effective solution.
2. Stage 2 of the rehabilitation process is the trial design of each rehabilitation alternative selected in stage 1. Trial design for CPR is an iterative process beginning with the definition of the trial design structure, determination of layer properties, characterization of traffic and climate properties, selecting CPR treatments, and ending with distress and smoothness prediction. The predicted distress/smoothness is then compared with user defined threshold values. Trial designs determined to be inadequate (i.e., experiencing excessive distress or smoothness loss over its design life) must be modified and reanalyzed.
3. Stage 3 of the rehabilitation process includes activities such as life cycle cost analysis (LCCA) of the rehabilitation alternatives designed to determine the preferred rehabilitation design (i.e., the most cost-effective design).

Only stages 1 and 2 of the design procedure will be illustrated in this paper and they are explained using a specific design example.

Step-By-Step CPR Design Example

The new CPR design procedure is closely tied to the new design methodology. A summary of most inputs to the CPR design example is given in table 1 and are discussed throughout the paper. The desired design life is 15-years with a 90 percent reliability.

Table 1. Summary of key inputs used in design analysis of CPR project.

Data category	Input variable	Input value
General information	Design life	15 years
	Pavement (original) construction	April
	Traffic (original) open	September
Performance criteria	Initial IRI (in/mi)	73
	Terminal IRI (in/mi)	172
	Transverse cracking (percent slabs cracked)	15
	Mean joint faulting (in)	0.12
	Reliability (percent)	90
Traffic	Initial two-way average annual daily truck traffic	2222
	Number of lanes in design direction	2
	Percent of trucks in design direction (percent)	50
	Percent of trucks in outer design lane (percent)	90
	Traffic growth rate (percent)	6
	Mean wheel location (inches from the lane marking)	18
	Design lane width (ft):	12
	Axle load distribution (default distribution in software)	Typical rural Interstate
	Truck class distribution (default distribution in software)	Typical rural Interstate
Climate	Latitude (degrees-minutes)	40.47
	Longitude (degrees-minutes)	-111.6
	Elevation (ft)	4221
	Depth of water table (ft)	20
Design features	Permanent curl/warp effective temperature difference (°F)	-10
	Transverse joint spacing (ft)	15
	Transverse joint sealant type	Liquid
	Transverse joint dowel diameter (in)	None
	Transverse joint dowel bar spacing (in)	None
	Slab to shoulder joint long-term LTE(percent)	No tied shoulders
	Widened Slab (ft)	No
Base design parameter	Base type	Cement treated aggregate
	Elastic modulus, psi	1,000,000
	Erodibility index	Erosion resistant (3)
	Base/slab friction coefficient	0.65
	PCC-Base Interface	Bonded
	Loss of bond age (months)	60

Table 1. Summary of key inputs used in design analysis of CPR project, continued.

Data category	Input variable	Input value
Structure (PCC layer)	Layer thickness (in)	10
	Coefficient of thermal expansion (per F° x 10 ⁻⁶)	5.5
	Cement type	Type I
	Cementitious material content (lb/yd ³)	600
	Water/cement ratio	0.42
	Aggregate type	Limestone
	Curing method	Curing compound
	28-day PCC modulus of rupture (psi)	690
Structure (crushed gravel)	Thickness(in)	10
	Modulus (input) (psi)	35,000
	Plasticity Index, PI	1
	Passing no. 200 sieve (percent)	13.8
	Passing no. 4 sieve (percent)	43
	D60 (mm)	9.5
Structure (subgrade)	Thickness(in)	Semi-infinite
	Dynamic modulus of subgrade reaction (backcalculated) (psi/in)	232
	Plasticity Index, PI	7
	Passing no. 200 sieve (percent)	35.7
	Passing no. 4 sieve (percent)	71
	D60 (mm)	1.2

Step 1—Evaluate Existing Pavement

The existing pavement is an Interstate JPCP located in a dry-freeze climatic zone. The existing pavement design consists of a 10-in PCC slab with 15-ft joint spacing without dowel bars, HMA shoulder, a 4-in cement treated base, and a 4-in crushed stone subbase, over a fine grained subgrade. The pavement is 10 years old and experiencing the following distress:

- Joint faulting: 0.10-in.
- Slab cracking: 5 percent.
- International Roughness Index (IRI): 150 in/mi.
- No PCC durability problem.
- HMA shoulder in poor condition, needs replacement.

Step 2—Select Trial Design

This involves the selection of the appropriate combination of CPR techniques. The initial trial design will be designated CPR #1.

- All cracked slabs will be replaced during CPR.

- Dowels will not be retrofit unless required to control future faulting.
- Tied concrete shoulders will not be added unless necessary to control future faulting and/or cracking.
- Retrofit longitudinal edge drains will be added.
- Joints will be filled and a few existing spalls repaired.
- Diamond grinding will be performed in both traffic lanes.

Step 3— Select Performance Criteria

Both limiting distress and smoothness criteria and design reliability that these levels will not be exceeded must be specified. Typical values are recommended.

- Limiting mean joint faulting will be 0.15-in at 90 percent reliability.
- Limiting slab cracking will be 15 percent at 90 percent reliability.
- Limiting smoothness will be an IRI of 172 in/mile at 90 percent reliability.

Step 4—Determine Design Inputs

- Traffic – The initial two-way truck volume is 2222 vehicles, and this is expected to grow at compounded rate of 6 percent annually. The single, tandem, and tridem axle load distributions and the vehicle classification distribution are that of a typical rural Interstate highway. Defaults for these traffic inputs are in the software and represent the means of many weigh-in-motion (WIM) sites across the U.S.
- Materials – PCC strength, elastic modulus, and other properties were determined from project records and shown in table 1. In addition, the cement treated base elastic modulus and the aggregate subbase resilient modulus were estimated from material descriptions. All of these values could be measured from specimens cut from the existing pavement if resources permit.
- Subgrade – The required input is either a resilient modulus of the soil or a backcalculated k-value. For this project, a falling weight deflectometer (FWD) backcalculated (dynamic) value was obtained for the project with an average of 232 psi/in for the month of July.
- Climate – a virtual weather station was established given the project site as specified in table 1.
- Cross-section – thicknesses of all layers were determined from coring and are given in table 1.

Step 5—Determine Past Fatigue Damage

Figure 1 shows a schematic of the relationship between transverse (fatigue) cracking and fatigue damage. This relationship was calibrated using data from LTPP and is used to estimate past fatigue damage (prior to restoration) for any given JPCP once the amount of transverse cracking (percent slabs cracked including previously repaired cracks or replaced slab panels) prior to restoration is known (by conducting a

distress survey). For this case study, past a project survey was performed and 5 percent of the slabs exhibited cracking in the outer traffic lane. No slabs in the inner lane were cracked. None had been replaced. The past damage is estimated using figure 1, which is the calibrated relationship between slab cracking and computed fatigue damage.

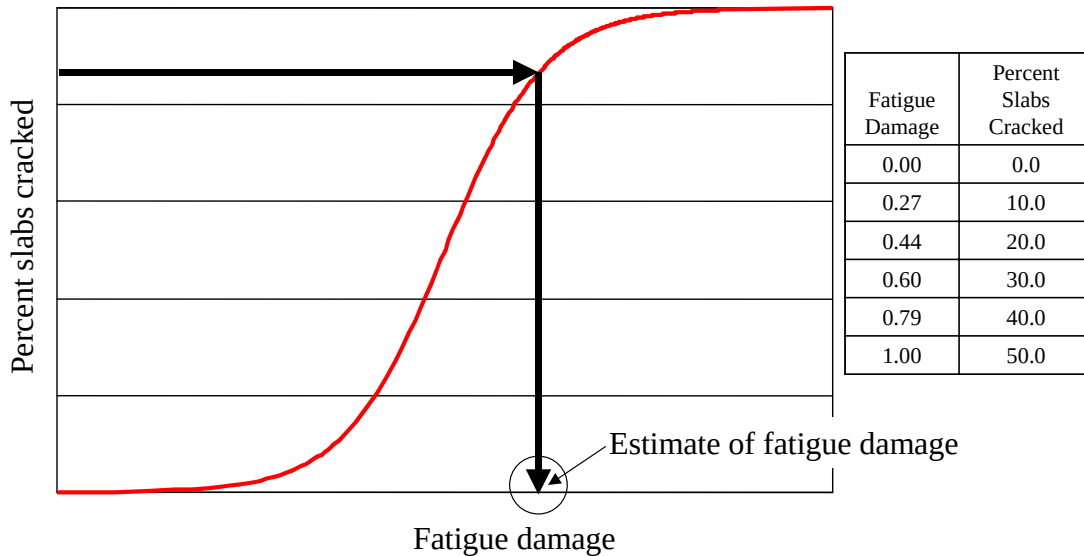


Figure 1. Determining past damage to existing JPCP based on calibrated damage/cracking relationship (ARA, 2004)

Step 6—Process Input Data

After all inputs have been obtained as summarized in table 1, the program computes iteratively on a monthly basis over the entire design analysis period all of the parameters needed to calculate key distresses and smoothness. The actual increment of damage accumulation is hourly which differentiates day time and night time so that the proper thermal gradients through the PCC slab and truck loadings are considered. The traffic loadings are distributed over the design period on an hourly basis as are temperature and moisture profiles through the pavement structure. The materials properties over time (e.g., PCC strength and modulus, other layer moduli) are then computed. Various other parameters, such as transverse joint load transfer, are also calculated on a monthly basis over the design life.

Step 7—Compute Critical Structural Responses

The program calculates critical stresses and deflections in the slab given the applied traffic loads and temperature and moisture gradients in the slab. Critical locations are a function of distress type. The stresses are based on neural network models imbedded in the software that are based on the ISLAB2000 finite-element model (FEM). (Khazanovich et al., 2000)

Step 8—Estimate Future Distress

The software includes calibrated distress models for transverse cracking, joint faulting, and smoothness (IRI). Calibration data used to validate the CPR models were obtained from the states shown in figure 2. The cracking model (see figure 3 predicted versus measured results) and IRI model was validated as the same as that used for new design. The faulting model coefficients showed bias and had to be revised for CPR.

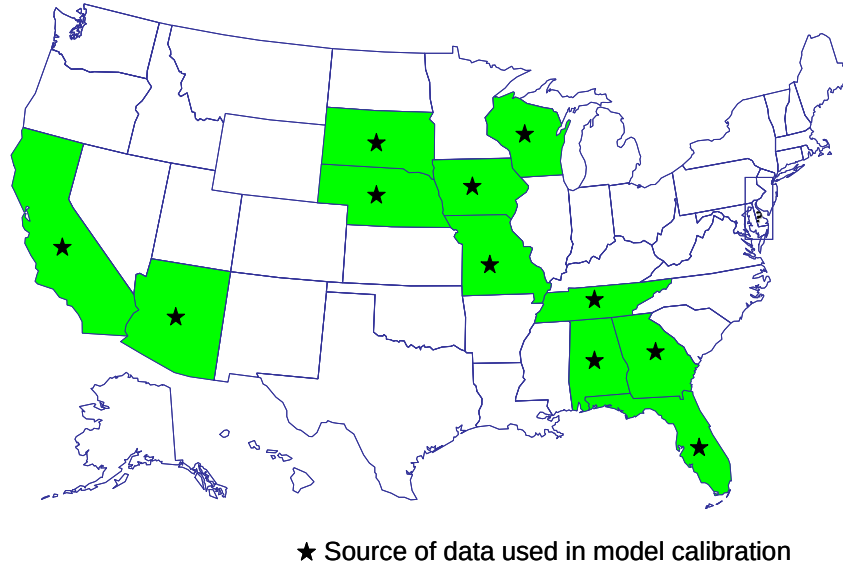


Figure 2. States from which data to validate CPR models were obtained.

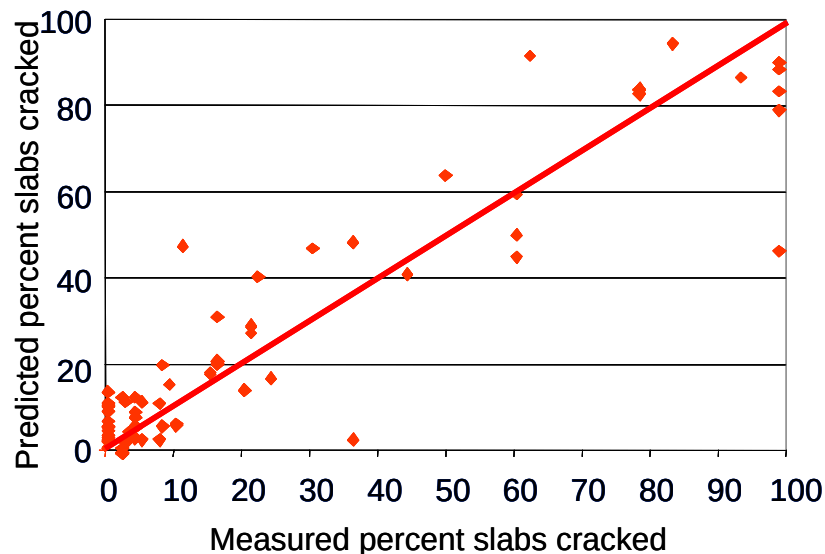


Figure 3. Calibration plot for slab cracking of CPR sections showing reasonable validation of calibrated model.

Step 9—Evaluate Performance (Evaluation of the Trial Design, Design Modification, and Selection of Final Design)

The output results of the first trial design of the CPR project are shown in table 2. Two CPR trial design were considered. CPR #1 included the following treatments:

- All cracked slabs were replaced during CPR.
- Retrofit longitudinal edge drains.
- Joints will be filled and a few existing spalls repaired.
- Diamond grinding will be performed.

Table 2 shows that the performance of this design is not satisfactory as joint faulting, slab cracking, and IRI all do not satisfy the 90 percentile reliability requirements. For example, joint faulting at 90 percent reliability was 0.16-in and the limiting criteria was 0.15-in. Slab cracking was 21 percent and the limiting criteria was 15 percent. The IRI was 185 in/mi and the limiting criteria was 172 in/mi.

The software outputs the joint load transfer efficiency (LTE) as shown in figure 4a for CPR #1. It is noted how low this is for the non-doweled joint which led to erosion and joint faulting. The retrofitting of dowels would bring this up to a much higher level reducing erosion and pumping and faulting as illustrated in figure 4b.

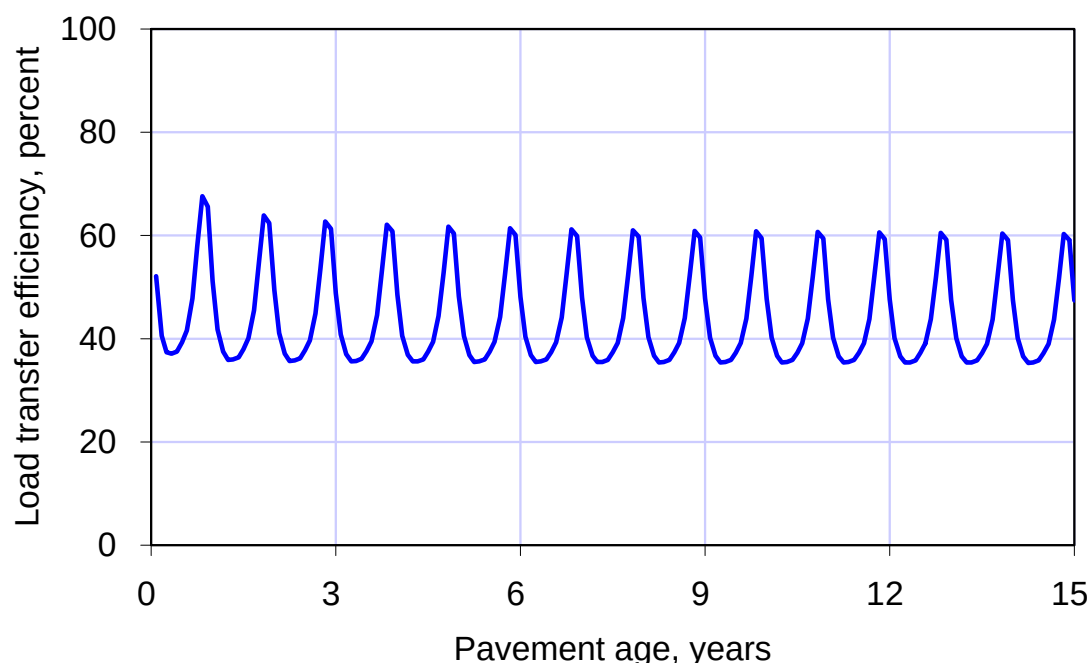


Figure 4a. Transverse joint load transfer for CPR #1 design without retrofit dowels.

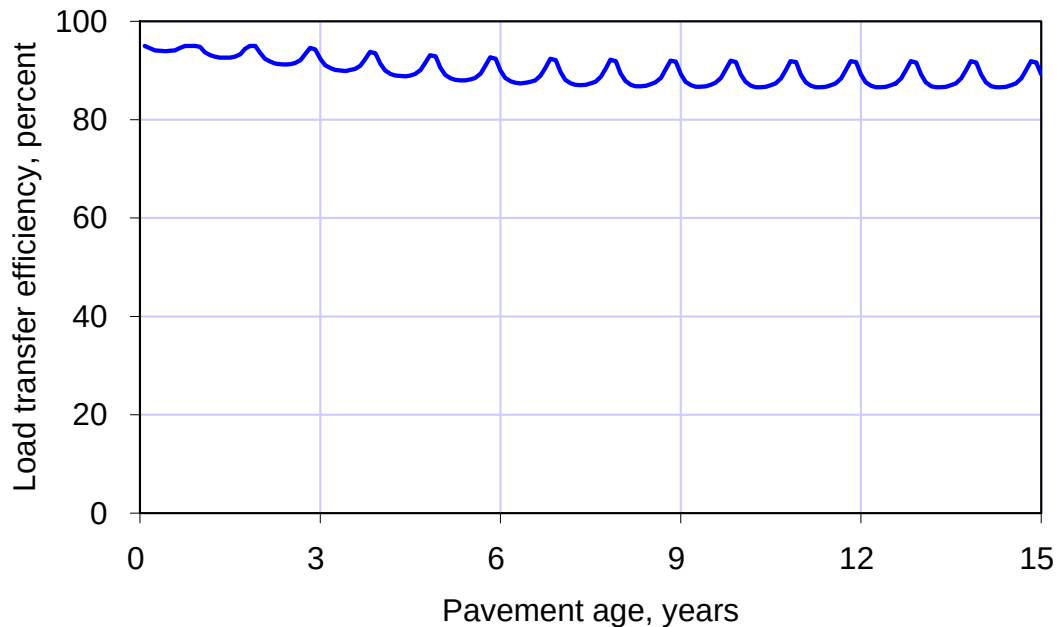


Figure 4b. Transverse joint load transfer for CPR #2 design with retrofit dowels.

Table 2. Design and analysis of CPR project.

Trial CPR Design	Traffic Loadings, Number Trucks	Joint Load Transfer Mechanism	Tied PCC Shoulder	Slab Thick (in)	Joint Faulting (in)	Slab Cracking (percent)	IRI (in/mi)	Reliability (percent)
#1	8.5 million Outer Lane	No Dowels	No	10	0.09	10.6	133	50
					0.16*	21.0*	185*	90
	0.94 million Inner Lane	No Dowels	No	10	0.03	1.0	90	50
					0.06**	7.4**	131**	90
#2	8.5 million Outer Lane	1.25-in Dowels	Yes	10	0.02	5.3	89	50
					0.05**	13.6**	128**	90
	0.94 million Inner Lane	No Dowels	No	10	Same	Same	Same	50
					Same	Same	Same	90

*None of these distresses and IRI meet the 90 percent reliability level at 15 years.

**All of these distress and IRI meet the 90 percent reliability level at 15 years.

Plots of results for CPR #1 are shown for faulting (figure 5a), slab cracking (figure 6a), and IRI (figure 7a). These show both the mean predictions and the 90 percentile predictions which all exceed the 90 percentile. Therefore, another trial CPR design was required.

The CPR #2 trial design was developed (modification of CPR#1) to limit joint faulting and slab cracking by adding retrofit dowels in the outer truck lane and replacing the deteriorated HMA shoulder with a tied PCC shoulder. These features

will both reduce faulting and slab cracking.

The CPR #2 trial design is as follows:

- All cracked slabs were replaced during CPR.
- Retrofit subdrainage will be added and longitudinal edge drains.
- Joints will be filled and a few existing spalls repaired.
- Retrofit dowels will be placed in the truck lane (4 dowels per wheel path, 1.25-in diameter)
- Tied PCC shoulder will be placed against the outer truck lane. This will increase the longitudinal joint load transfer and decrease corner deflections and bending stresses.
- Diamond grinding will be performed.

Results for CPR #2 design are shown in table 2 for the truck lane. In this case, all of the design criteria are met at the 90 percent reliability level as shown in table 2 and it is an acceptable design at 15-years.

- Joint faulting 0.05-in < 0.15-in (see figure 5b)
- Slab cracking 13.6 percent < 15 percent (see figure 6b)
- IRI 128 in/mi < 172-in/mi (see figure 7b)

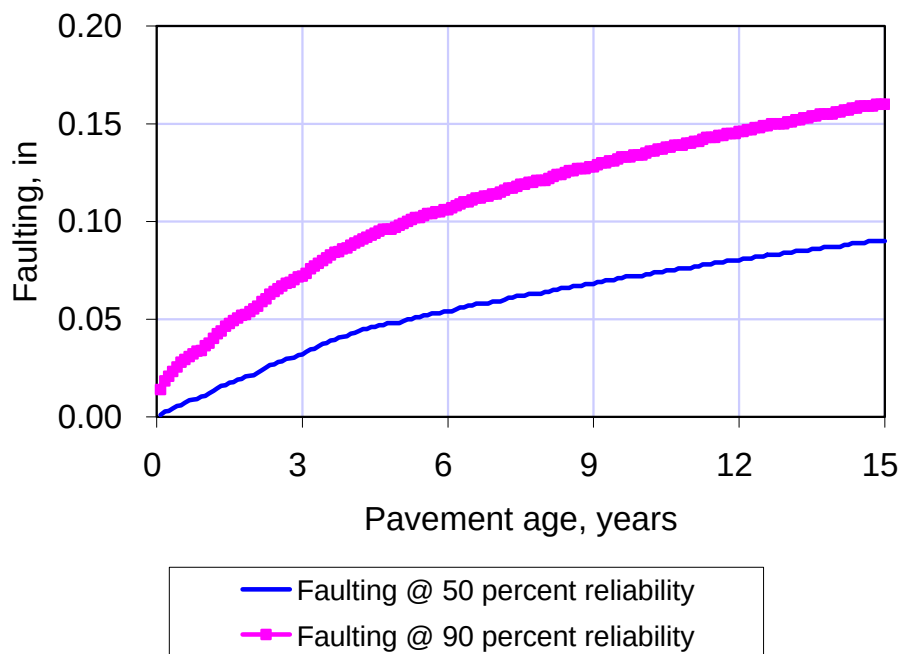


Figure 5a. Predicted joint faulting for CPR #1 trial design.

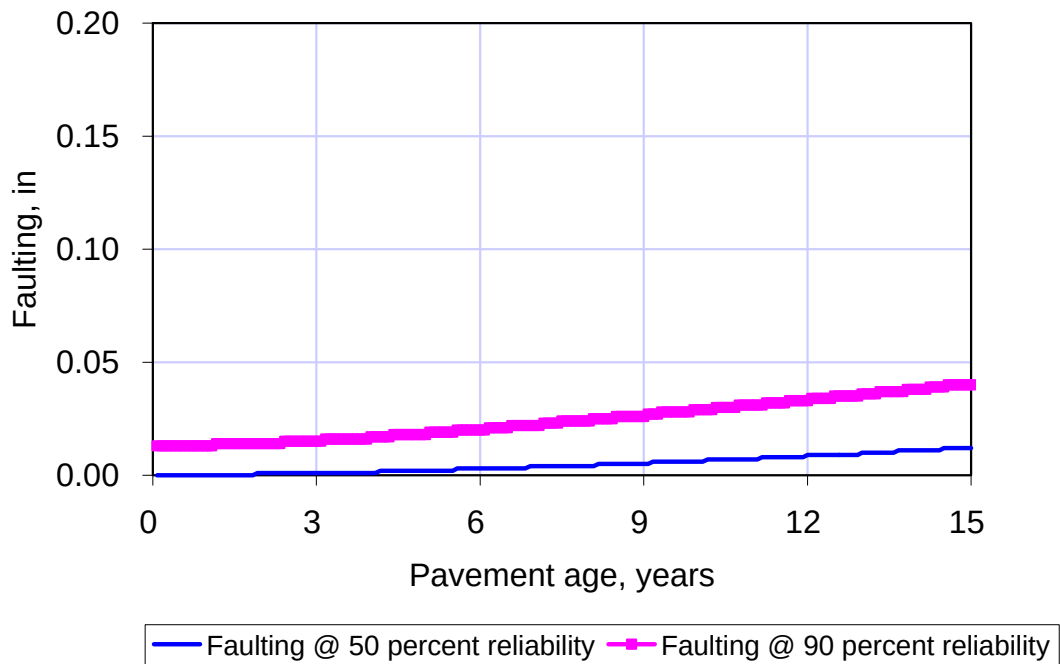


Figure 5b. Predicted joint faulting for CPR #2 trial design (add retrofit dowels and tied PCC shoulder).

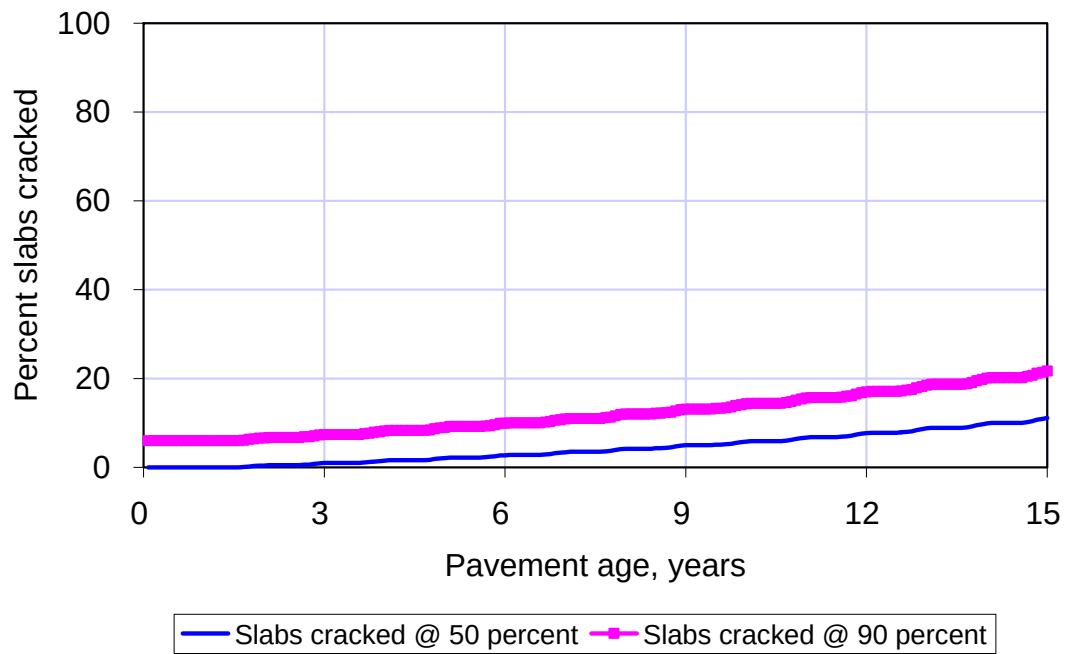


Figure 6a. Predicted slab cracking for CPR #1 trial design.

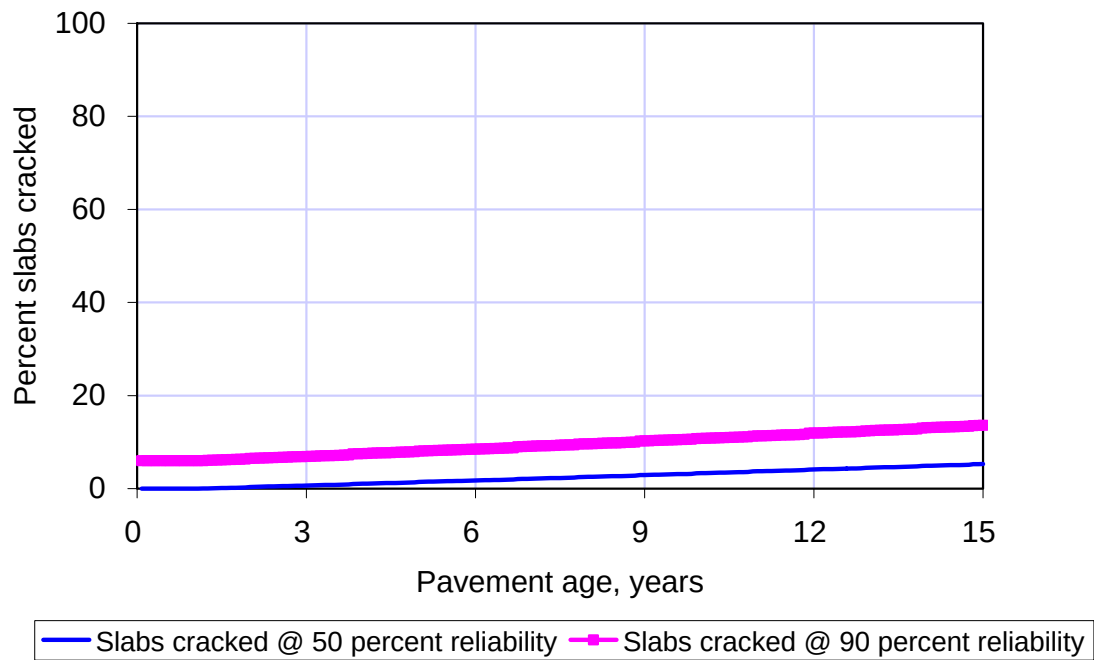


Figure 6b. Predicted slab cracking for CPR #2 trial design (add retrofit dowels and tied PCC shoulder).

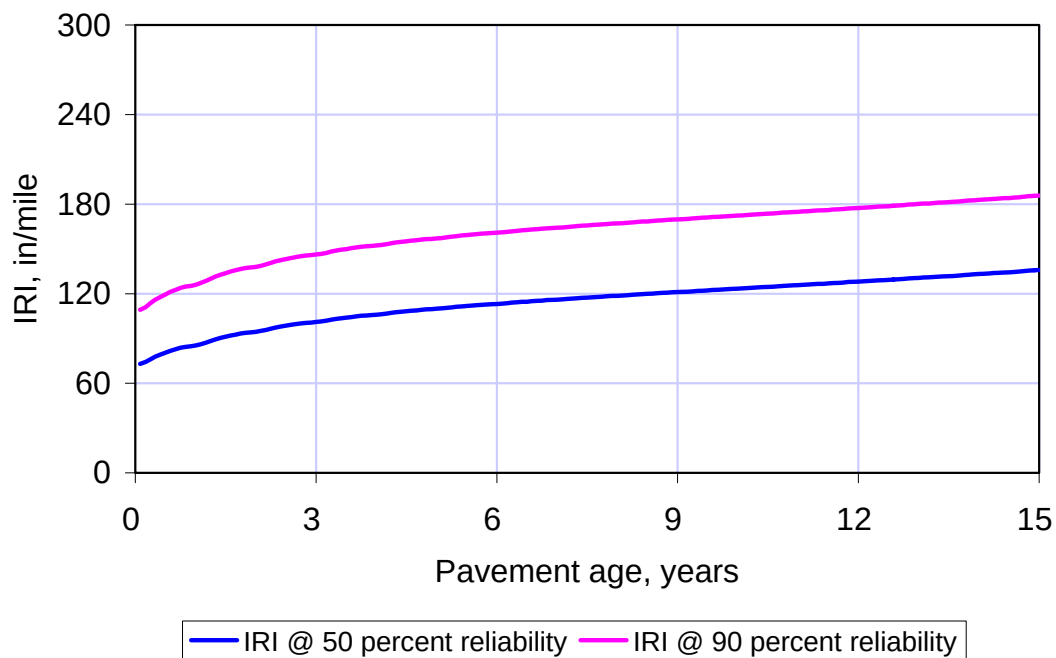


Figure 7a. Predicted IRI for CPR #1 trial design.

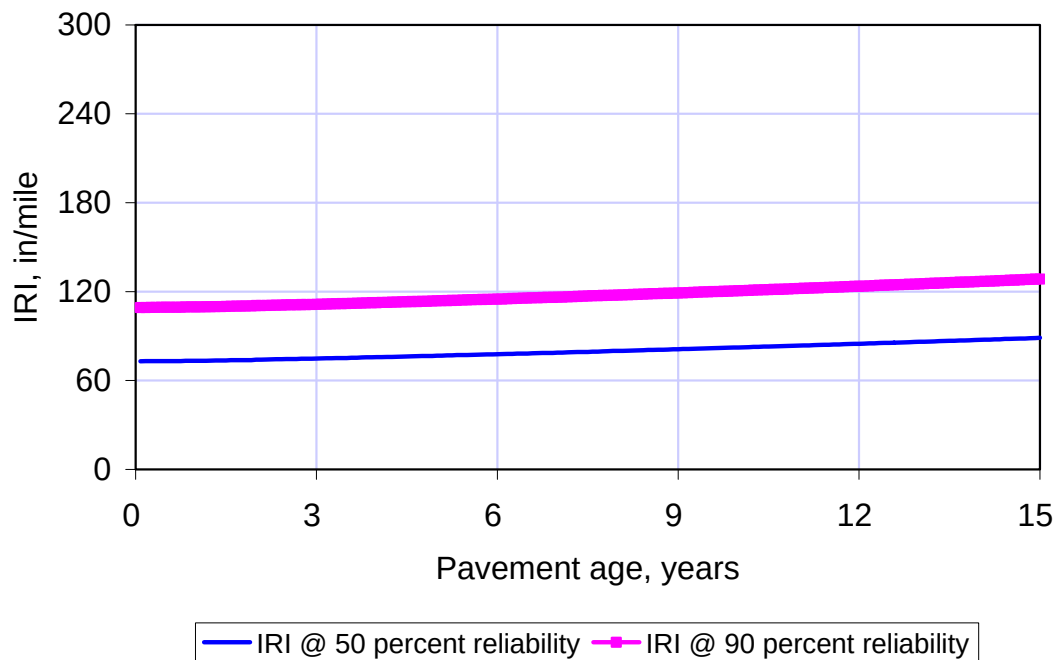


Figure 7b. Predicted IRI for CPR #2 trial design (add retrofit dowels and tied PCC shoulder).

Thus, CPR #2 would be judged as a feasible CPR design for the truck lane. It should perform well over the next 15-years at a fairly high level of design reliability, 90 percent.

All of the previous results were for the outer truck lane. The same analysis can be done for the inner passing lane. The percent of truck traffic using this lane must be estimated. Traffic count data showed about a 90/10 split in one direction. This would result in lower numbers of trucks in the passing lane and thus the CPR design for this lane may be not as critical. Table 2 shows the CPR #1 design for the inner lane meets the design criteria for joint faulting, slab cracking, and IRI. Therefore, there is no need for retrofit dowels and a tie PCC shoulder for the inner traffic lane.

Summary and Conclusions

This paper has summarized the new design methodology for CPR of JPCP through a design example. Details of the theory, models, and algorithms used in the Design Guide can be found in the final report under NCHRP 1-37A (Chapter 6). (ARA, 2004) The methodology provides a calibrated analysis and design procedure for CPR of JPCP. Use of this procedure will require implementation efforts that involve a number of steps before the procedure can be used by an agency with confidence in design of CPR projects.

As a minimum, input data from existing CPR projects in the region should be assembled and each project run to establish a library of case studies. The prediction capability of the faulting, cracking, and IRI models should be validated using these case studies. The models were calibrated using national data, but it may very well

be the case that for certain regions the models are biased, either over- or under-predicting the distress or IRI. Running as many case studies as possible would make it possible to assess the adequacy of the models to predict CPR project performance in the highway agency.

Acknowledgement

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