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Pavement ME Evaluation of the NCHRP 1-61 Thin Concrete Overlay on Asphalt Sections

Authors:
Angel Mateos and John Harvey

Partnered Pavement Research Center (PPRC) Project Number 4.67 (DRISI Task 3198):
Development of Thin Concrete Overlay on Asphalt Design Method

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation, and System Information
Office of Materials and Infrastructure

PREPARED BY:

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UC Davis, UC Berkeley

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16. ABSTRACT

The thin concrete overlay on asphalt (COA) longitudinal cracking model of *Pavement ME* was calibrated with empirical data from COA sections with half-lane width slabs in Minnesota, Illinois, and Colorado. The NCHRP Project 1-61 has considerably expanded the range of climatic conditions for which reliable performance data are available by adding projects from Iowa, Kansas, and Philadelphia (in addition to Minnesota, Illinois, and Colorado). This technical memorandum assesses *Pavement ME* predictions based on the longitudinal cracking measured on 13 COA sections with half-lane width slabs evaluated as part of NCHRP Project 1-61. None of the 13 sections had more than 3% of slabs with longitudinal cracking, despite four of them being subjected to relatively high traffic volumes (annual average daily truck traffic over 500 vehicles on the design lane) and having been in service between 9 and 19 years. When design values were adopted for the different input variables, *Pavement ME* predicted less than 5% longitudinal cracking in 12 of the 13 sections, which agrees with measured cracking. The root mean square error (RMSE) of *Pavement ME* predictions was 2.4% for the set of 13 sections. The RMSE of the *Pavement ME* predictions improved to 1.2% when constructed slab thickness measured with ground penetration radar was used instead of the design thickness. However, *Pavement ME* predictions did not improve when measured values for concrete strength or load transfer efficiency were used rather than design values. The recommendation is that the nationally calibrated COA cracking model, implemented in *Pavement ME* version 2.5.5 (the current version as of the writing of this technical memorandum), be used for developing the California COA design catalog.

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7. PROPOSALS FOR IMPLEMENTATION
This report assesses *Pavement ME* longitudinal cracking predictions based on the cracking measured on 13 thin concrete overlay on asphalt (COA) sections with half-lane width slabs evaluated as part of NCHRP Project 1-61. Based on this assessment, the recommendation is that the nationally calibrated COA cracking model, implemented in *Pavement ME* version 2.5.5 (the current version as of the writing of this technical memorandum), be used for developing the California COA design catalog.

8. RELATED DOCUMENTS
Mateos, A. and Harvey, J. 2020. *Development of Thin Bonded Concrete Overlay of Asphalt Design Method: Evaluation of Existing Mechanistic-Empirical Design Methods* (Technical Memorandum: UCPRC-TM-2019-01). Davis and Berkeley, CA: University of California Pavement Research Center.

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The UCPRC laboratory is accredited by AASHTO re:source for the tests listed in this report

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10. SIGNATURES

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DISCLAIMER

ACKNOWLEDGMENTS

The evaluation of *Pavement ME* presented in this technical memorandum would not have been possible without the information collected as part of NCHRP 1-61 project. The authors of this technical memorandum would like to acknowledge and thank the NCHRP 1-61 research team, constituted by NCE, APTech, and the University of Illinois Urbana-Champaign, and the National Cooperative Highway Research Program.

PROJECT OBJECTIVES

The goal of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) Project 4.67, "Development of Thin Concrete Overlay on Asphalt Design Method," is to propose a mechanistic-empirical design method applicable to thin concrete overlay on asphalt (COA) for the Caltrans road network and to develop recommendations and guidelines for use of the proposed method. As a first step of 4.67 project, the strengths and limitations of two widely recognized mechanistic-empirical design procedures, BCOA-ME and *Pavement ME*, were analyzed *(1)*. Caltrans's decision was to adopt *Pavement ME* for COA design in Caltrans road network.

The COA cracking model of *Pavement ME* was calibrated with empirical data from COA sections in Minnesota, Illinois, and Colorado, which are states where COA performance data were readily available. NCHRP Project 1-61 has considerably expanded the range of climatic conditions for which reliable performance data are available by adding projects from Iowa, Kansas, and Philadelphia (in addition to Minnesota, Illinois, and Colorado). The goal of the work presented in this technical memorandum is to determine if the experimental data collected in NCHRP 1-61 for COA sections with half-lane width slabs validate *Pavement ME* COA cracking predictions or suggest the need to recalibrate this AASHTO design tool.

EXECUTIVE SUMMARY

The goal of Partnered Pavement Research Center Project 4.67, "Development of Thin Concrete Overlay on Asphalt Design Method," is to propose a mechanistic-empirical design method applicable to thin concrete overlay on asphalt (COA) for the Caltrans road network and to develop recommendations and guidelines for use of the proposed method. As part of 4.67 Project, Caltrans's decision was to adopt *Pavement ME* for COA design. The COA is referred as "short jointed plain concrete pavement" in *Pavement ME*.

The COA cracking model of *Pavement ME* was calibrated with empirical data from COA sections in Minnesota, Illinois, and Colorado. The NCHRP Project 1-61 "Evaluation of Bonded Concrete Overlays on Asphalt Pavements" (2018-2020) has considerably expanded the range of climatic conditions for which reliable performance data are available by adding projects from Iowa, Kansas, and Philadelphia (in addition to Minnesota, Illinois, and Colorado). A total of 20 COA sections nationwide were evaluated in NCHRP 1-61. Information was collected about design, construction, and performance through a thorough field investigation of each of the sections. Among the 20 COA sections evaluated, 13 have half-lane width slabs (mainly 6×6 ft.).

This technical memorandum presents a comparison of the cracking measured on those 13 COA sections with half-lane width slabs and *Pavement ME* predictions. The goal of this comparison is to determine if the experimental data collected in NCHRP 1-61 validate *Pavement ME* COA cracking predictions or suggest the need to recalibrate this AASHTO design tool.

General information about the 13 sections with half-lane width slabs is presented in Table 2.1 of this technical memorandum and design information is presented in Table 2.2. Overall, the range of variation of most design variables in these sections, including traffic level, slab thickness, asphalt thickness, shoulder type, concrete flexural strength, use of tie bars, and sealing of joints, is similar to the expected range of variation in future COA sections in California. However, California's climate conditions are not fully represented in the 13 sections.

As shown in the following table, the condition of all sections with half-lane width slabs was excellent. None of the 13 sections had more than 3% of slabs with longitudinal cracking despite four of them being subjected to relatively high traffic volumes (AADTT over 500 vehicles on the design lane) and having been in service between 9 and 19 years.

NCHRP 1-61 Sections with Half-Lane Width Slabs (Pavement Condition from APCS)

Section Code	Age (years)	AADTT Design Lane	IRI (in./mi)	Faulting (in.)	Corner Cr. (% slabs)	Long Cr. (% slabs)	Transv. Cr. (% slabs)
CO-I-70	6	857	97	0.026	0.0	0.0	0.0
CO-SR-83A	19	1,087	150	0.063	0.7	2.3	0.1
CO-SR-83B	14	978	141	0.058	0.2	0.5	0.1
CO-SR-121A	18	528	104	0.038	0.0	1.2	0.1
CO-SR-121B	7	577	80	0.033	0.1	0.6	0.0
IA-US-71	6	470	81	0.022	0.1	1.5	0.1
IL-CH-10	9	25[1]	91	0.019	0.2	0.1	0.0
IL-CH-27	15	25	149	0.027	0.1	0.2	0.1
KS-I-70	7	281[2]	99	0.024	0.1	0.1	0.0
MN-CSAH-7	9	24	90	0.032	0.2	2.9	0.3
MN-CSAH-22	7	297	96	0.034	0.1	0.0	0.0
MN-I-35	9	845	79	0.035	0.1	0.1	1.1
PA-SR-119	8	349	100	0.037	0.0	0.7	0.0

[1] Traffic information is not available, and AADTT is assumed to be the same as on IL-CH-27.
[2] Assumed 10% trucks.

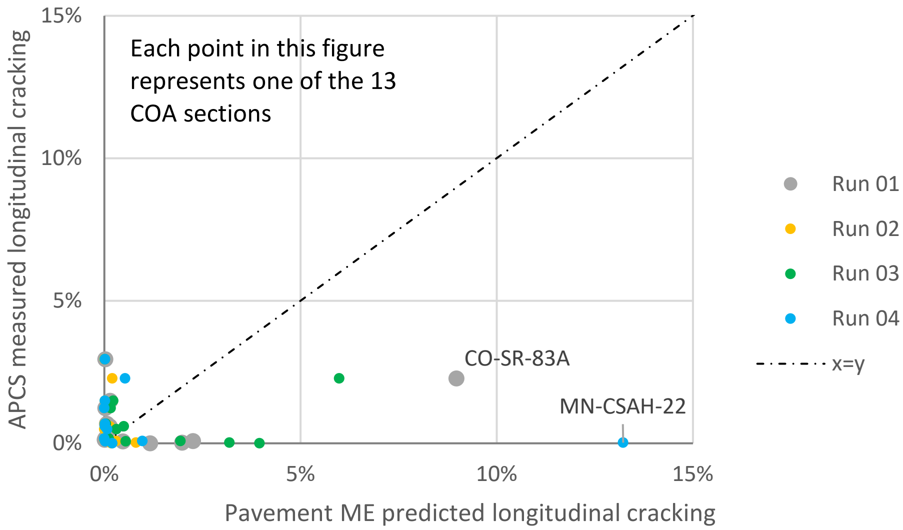
Pavement ME can predict the mid-slab bottom-up longitudinal cracking of COA. This type of cracking is regarded as one of the critical distresses of COA with half-lane width slabs. Faulting and longitudinal roughness, which are also critical to the performance of this type of pavements, cannot be predicted by *Pavement ME*. Four sets of *Pavement ME* calculations were conducted:

- Run 01: Either design or default values are chosen for all the variables.
- Run 02: Slab thickness is the average value measured for each section with ground-penetrating radar (GPR) (Run 01 was based on design thickness). The rest of the inputs are the same as Run 01.
- Run 03: Concrete 28-day flexural strength is estimated based on laboratory testing of compressive strength on cores extracted from each section (Run 01 was based on 28-day design flexural strength). The rest of the inputs are the same as Run 01.
- Run 04: The load transfer efficiency (LTE) is the average value measured with a falling weight deflectometer (FWD) (Run 01 assumed LTE was the *Pavement ME* 80% default value). The rest of the inputs are the same as Run 01.

The comparison of measured longitudinal cracking and *Pavement ME* predictions, for each of the four sets of calculations, is presented in the following figure. The comparison is summarized below:

- When design values were adopted for the different input variables (Run 01), *Pavement ME* predicted less than 5% longitudinal cracking in 12 out of the 13 sections, which agrees with measured cracking. The root mean square error (RMSE) of *Pavement ME* predictions was 2.4% for the set of 13 sections.
- The RMSE of the Pavement ME predictions improved to 1.2% when constructed slab thickness measured with GPR was used instead of the design thickness (Run 02).

- Pavement ME predictions did not improve when measured values for concrete strength (Run 03) or LTE (Run 04) were used rather than design values.



Comparison between *Pavement ME* (50% reliability) and measured cracking.

Based on the comparison presented in the figure above, the recommendation is that the nationally calibrated COA cracking model, implemented in *Pavement ME* version 2.5.5 (the current version as of the writing of this technical memorandum), be used for developing the California COA design catalog.

LIST OF ABBREVIATIONS

AADTT	Average annual daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
APCS	Automated pavement condition survey
BCOA	Bonded concrete overlay of asphalt
COA	Concrete overlay on asphalt
Cr	Cracking
FWD	Falling weight deflectometer
GPR	Ground penetrating radar
IRI	International roughness index
LTE	Load transfer efficiency
LTPP	Log-Term Pavement Performance
ME	Mechanistic-empirical
MR	Modulus of rupture
NCHRP	National Cooperative Highway Research Program
PCC	Portland cement concrete
RMSE	Root mean square error
SJPCP	Short-jointed plain concrete pavement

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
		MASS		
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
		AREA		
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised April 2021

1 INTRODUCTION

National Cooperative Highway Research Program (NCHRP) Project Number 1-61, "Evaluation of Bonded Concrete Overlays on Asphalt Pavements," investigated factors that may impact concrete overlay on asphalt (COA) performance based on the documented data and measured condition of 20 COA sections nationwide. Information was collected about design, construction, and performance through a thorough field investigation of each of the sections *(2)*. This NCHRP project began in February 2018 and was completed in mid-2020. Among the 20 COA sections evaluated, 13 have half-lane width slabs (mainly 6×6 ft.). The cracking measured in these 13 sections can be used to assess *AASHTOWare Pavement ME Design* (referred to as *Pavement ME* in this technical memorandum) predictions and, depending on the outcomes, to determine the need to recalibrate the short-jointed plain concrete pavement (SJPCP) module of this AASHTO design tool. SJPCP is the term used in *Pavement ME* to denote thin COA with half-lane width slabs. This type of pavement was implemented in version 2.3 of *Pavement ME* in 2016 *(3,4)*.

This technical memorandum presents a comparison of the cracking measured on the 13 COA sections with half-lane width slabs and *Pavement ME* predictions. This comparison is an important step toward the development of a Caltrans COA design catalog, which is the main goal of the Caltrans/UCPRC 4.67 research project "Development of Thin Concrete Overlay on Asphalt Design Method."

Only the performance of the COA sections with half-lane width slabs is considered in this technical memorandum since Caltrans made the decision to not build "thin" (up to 7 in.) COA with full-lane width slabs (e.g., 12x12 ft.), based on the outcomes of a previous Caltrans/UCPRC research project *(5)*.

1.1 Goal

The goal of the work presented is to determine if the experimental data collected in NCHRP 1-61 for COA sections with half-lane width slabs validate *Pavement ME* COA cracking predictions or suggest the need to recalibrate this AASHTO design tool.

The evaluation of *Pavement ME* is only presented in terms of cracking—specifically, longitudinal cracking—since the current version (2.5.5) does not predict faulting and international roughness index (IRI) of COA.

2 NCHRP 1-61 SECTIONS WITH HALF-LANE WIDTH SLABS

General information about the 13 sections with half-lane width slabs is presented in Table 2.1 and design information is presented in Table 2.2. The information in these two tables has been extracted from NCHRP 1-61 Technical Memorandum on Performance *(2)*. Overall, the range of variation of most design variables in these sections, including traffic level, slab thickness, asphalt thickness, shoulder type, concrete flexural strength, use of tie bars, and sealing of joints, is similar to the expected range of variation in future COA sections in California. However, California's climate conditions are not fully represented in the 13 sections. This limitation is due to the fact that Caltrans's first COA project was built in 2018 and, due to the lack of distresses, its inclusion in NCHRP 1-61 would not have contributed to this project's goals. Additionally, COA construction in other dry-warm states has been very limited to date. Consequently, long-term performance of COA under the dry and warm weather conditions present in many areas of California still remains uncertain.

Table 2.1: NCHRP 1-61 Sections with Half-Lane Width Slabs (General Information)

Section Code	State	County	Route	Length (mi.)	Age (years)	LTPP Climate Zone	Highway Class	AADTT[1]
CO-I-70	CO	Mesa	I-70	4.5	6	Dry, Freeze	Primary, Rural	High
CO-SR-83A	CO	Arapahoe	SR-83	2.0	19	Dry, Freeze	Secondary, Urban	High
CO-SR-83B	CO	Arapahoe	SR-83	1.8	14	Dry, Freeze	Secondary, Urban	High
CO-SR-121A	CO	Denver	SR-121	3.3	18	Dry, Freeze	Primary, Urban	Moderate
CO-SR-121B	CO	Denver	SR-121	2.1	7	Dry, Freeze	Primary, Urban	Moderate
IA-US-71	IA	Clay	US-71	9.1	6	Wet, Freeze	Primary, Rural	Moderate
IL-CH-10	IL	Logan	CH-10	8.5	9	Wet, Freeze	Secondary, Rural	Low
IL-CH-27	IL	Macon	CH-27	4.1	15	Wet, Freeze	Secondary, Rural	Low
KS-I-70	KS	Saline	I-70	7.3	7	Dry, Freeze	Primary, Rural	Moderate
MN-CSAH-7	MN	McLeod	CSAH-7	2.5	9	Wet, Freeze	Secondary, Rural	Low
MN-CSAH-22	MN	Anoka	CSAH-22	3.3	7	Wet, Freeze	Secondary, Rural	Moderate
MN-I-35	MN	Chicago	I-35	6.6	9	Wet, Freeze	Primary, Rural	High
PA-SR-119	PA	Fayette	SR-119	4.1	8	Wet, Freeze	Primary, Urban	Moderate

[1] In NCHRP 1-61, design lane (one-way) annual average daily truck traffic (AADTT) is defined as low (< 200), moderate (200 to 800), and high (> 800) in the construction year. The low, moderate, and high traffic levels represent 44.2%, 34.1%, and 21.7%, respectively, of Caltrans's non-interstate highway network, as shown in Figure 2.1.

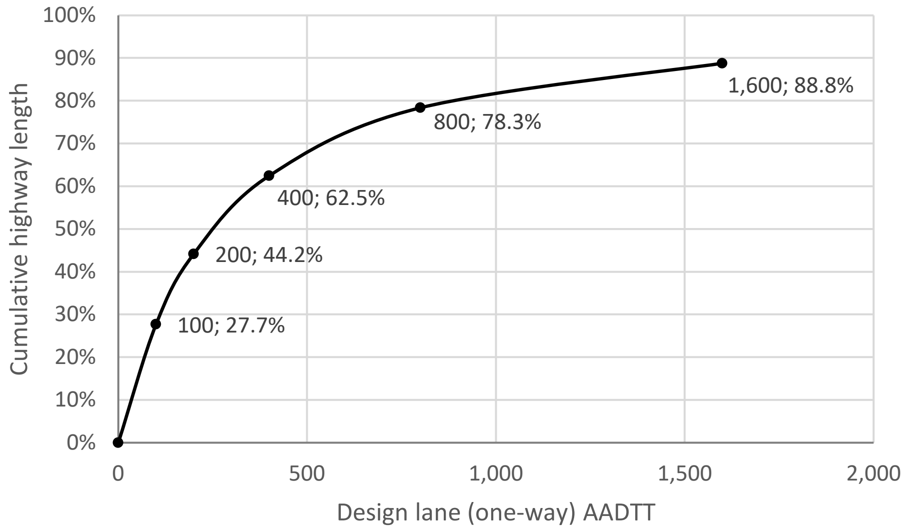


Figure 2.1: Truck volume in Caltrans's non-interstate highway network.

Table 2.2: NCHRP 1-61 Sections with Half-Lane Width Slabs (Design Information)

Section Code	Slab Size (ft.)	Slab Thickness (in.)	Asphalt Thickness (in.)	Shoulder	Tie Bars[1]	PCC MR 28-day[2] (psi)	PCC Fibers	Sealed Joints
CO-I-70	6×6	6	8	Tied PCC	Yes	650	No	Yes
CO-SR-83A	6×6	5	6	Tied PCC	Yes	650	No	Yes
CO-SR-83B	6×6	6	7	Tied PCC	Yes	650	No	Yes
CO-SR-121A	6×6	6	6	Tied PCC	Yes	650	Yes	Yes
CO-SR-121B	6×6	6	6	Tied PCC	Yes	650	No	Yes
IA-US-71	6×6	6	6	Untied PCC	No	n/a[3]	No	No
IL-CH-10	6×6	5.25	n/a[3]	Granular	No	n/a[3]	Yes	No
IL-CH-27	5.5×5.5	5.25	10	Granular	No	750	No	No
KS-I-70	6×6	6	18	Tied PCC	Yes	600	No	No
MN-CSAH-7	6×6	5	n/a[3]	Asphalt	No	n/a[3]	No	No
MN-CSAH-22	6×6	6	3	Asphalt	No	n/a[3]	No	Yes
MN-I-35	6×6	6	13	Asphalt	Yes	n/a[3]	No	Yes
PA-SR-119	6×6	6	9	Untied PCC	Yes	650	No	Yes

[1] Tie bars other than lane-shoulder joint tie bars.
[2] This value refers to the flexural strength value used for mechanistic-empirical design. In theory, this value should target the expected value (50% reliability) of the 28-day concrete flexural strength, which is typically greater than state specifications.
[3] n/a stands for information "not available."

3 EXPERIMENTAL DATA

The NCHRP 1-61 team conducted a thorough field investigation of the COA sections. For each section, the investigation included: (1) an automated pavement condition survey (APCS) scan; (2) a ground penetrating radar (GPR) survey; (3) a detailed field inspection conducted in three 0.1 mi. segments, with performance rated as "good," "fair," or "poor" according to categories established by the National Highway Performance Program *(6)* that consider cracking, faulting, and smoothness; (4) FWD, dynamic cone penetrometer, and multi-element ultrasonic imaging device testing conducted on the same three 0.1 mi. segments; and (5) laboratory testing of concrete cores and subgrade soil sampled during the field inspections. The findings presented in this technical memorandum are based mainly on the following data:

- Longitudinal cracking collected in the APCS survey.
  Longitudinal cracking is the critical distress mechanism of COA pavements. It is also the type of cracking predicted by *Pavement ME* for COA. Measured longitudinal cracking is presented in Table 3.1 together with other distresses measured in the APCS (September 2018).
- Concrete slab thickness measured with GPR.
- Concrete compressive and indirect tensile strength, measured on specimens prepared from slab cores that were extracted during the field inspections.
- Subgrade soil gradation and plasticity analysis (two samples per project).
  Based on the results of the analyses, the soils were classified according to the AASHTO system.

As shown in Table 3.1, the condition of all sections with half-lane width slabs was excellent, despite four of them being subjected to relatively high traffic volumes (AADTT over 500 vehicles on the design lane) and having been in service between 9 and 19 years. While this outcome is very positive for the structural capacity of COA, it represents a limitation for the evaluation of *Pavement ME* predictions. Based on the measured condition of these 13 sections, the capability of *Pavement ME* to predict cracking is limited by having only sections with low levels of cracking.

Table 3.1: NCHRP 1-61 Sections with Half-Lane Width Slabs (Pavement Condition from APCS)

Section Code	Age (years)	AADTT Design Lane	IRI (in./mi)	Faulting (in.)	Corner Cr. (% slabs)	Long Cr. (% slabs)	Transv. Cr. (% slabs)
CO-I-70	6	857	97	0.026	0.0	0.0	0.0
CO-SR-83A	19	1,087	150	0.063	0.7	2.3	0.1
CO-SR-83B	14	978	141	0.058	0.2	0.5	0.1
CO-SR-121A	18	528	104	0.038	0.0	1.2	0.1
CO-SR-121B	7	577	80	0.033	0.1	0.6	0.0
IA-US-71	6	470	81	0.022	0.1	1.5	0.1
IL-CH-10	9	25[1]	91	0.019	0.2	0.1	0.0
IL-CH-27	15	25	149	0.027	0.1	0.2	0.1
KS-I-70	7	281[2]	99	0.024	0.1	0.1	0.0
MN-CSAH-7	9	24	90	0.032	0.2	2.9	0.3
MN-CSAH-22	7	297	96	0.034	0.1	0.0	0.0
MN-I-35	9	845	79	0.035	0.1	0.1	1.1
PA-SR-119	8	349	100	0.037	0.0	0.7	0.0

[1] Traffic information is not available, and AADTT is assumed to be the same as on IL-CH-27.
[2] Assumed 10% trucks.

4 PAVEMENT ME PREDICTIONS

Pavement ME predicts cracking at 50% reliability, first, and then introduces design reliability. The difference between observed cracking and *Pavement ME* calculated cracking is due to model limitations and errors in the estimation of the input variables. *Pavement ME* assumes the prediction error follows a normal distribution with the standard deviation calculated in equation (4.1). The parameters of this equation were determined in the national calibration process *(3,4)*:

$$Cr\ estimated\ Std.\ Dev = 3.5522\ Cr^{0.4315} + 0.5 \qquad \textbf{(4.1)}$$

Where:
Cr = predicted cracking at 50% reliability.

Pavement ME initial prediction targets 50% reliability, and the value adopted for each of the design variables should be the median, at least conceptually. In practice, the problem is more complicated because the designer lacks this information for many of the relevant design variables, particularly related to concrete and other materials that will be delivered to the project, and only knows that they will likely meet standard specifications. In practice, *Pavement ME* predictions should be unbiased if the input variables are determined the same way they were determined during the calibration process. The national calibration of the *Pavement ME* COA cracking model was based on a combination of design and measured values of the different inputs *(3,4)*.

The following sets of *Pavement ME* calculations are discussed:

- Run 01: Either design or default values are chosen for all the variables.
- Run 02: Slab thickness is the average value measured for each section with GPR (Run 01 was based on design thickness). The rest of the inputs are the same as Run 01.
- Run 03: Concrete 28-day flexural strength is estimated based on laboratory testing of compressive strength on cores extracted from each section (Run 01 was based on 28-day design flexural strength). The rest of the inputs are the same as Run 01.
- Run 04. The load transfer efficiency (LTE) is the average value measured with a falling weight deflectometer (FWD) (Run 01 assumed LTE was the *Pavement ME* 80% default value). The rest of the inputs are the same as Run 01.

4.1 Pavement ME Run 01

The approaches for determining each of the most relevant input variables are as follows:

- Climate: The exact locations of the 13 sections were known. Two to four weather stations were selected for each section. Depth of water table was assumed to be 20 ft. (the default *Pavement ME* value).
- Traffic: The team collected AADTT (two-way, construction year) and truck percentage data. *Pavement ME* default values were chosen for all traffic-related variables, including hourly and monthly adjustment factors; axles per truck (distribution of axle types for Class 4 through Class 13 trucks); load distribution of single, tandem, and tridem axles; wheel wander; axle configuration; and wheelbase distribution. The truck traffic composition of Class 4 through Class 13 trucks was set to the *Pavement ME* defaults for Classification 3 (primary highways) or Classification 14 (secondary highways). Truck traffic was assumed to increase linearly 3% per year.
- Subgrade: Subgrade soil samples were extracted during the field inspections (two samples per project). The soil samples were classified following the AASHTO procedure, which is the system used in *Pavement ME*. Overall, subgrade soil quality was excellent, classified as A-3 or better, in all sections. For the *Pavement ME* calculations, subgrade soil was assumed to be A-3 in all sections. *Pavement ME* default values were assigned for this soil type, and the stiffness of the soil was allowed to change depending on the seasonal temperature and moisture.
- Subbase: In all sections, a granular subbase was assumed to be present. The subbase material was assumed to be A-1-a, and the thickness was assumed to be 8 in. *Pavement ME* default values were assigned to this soil type, and its stiffness was allowed to change depending on the seasonal temperature and moisture.
- Asphalt base: Asphalt thickness was assumed to be the design value (Table 2.2) up to a maximum of 6 in. (asphalt thickness was assumed to be 6 in. in *Pavement ME* if the thickness was greater than 6 in.). The asphalt binder type, which has an impact on asphalt stiffness, was determined using the FHWA LTPPBind online tool *(7)*. Default values were used for the rest of the asphalt-related input variables.
- PCC overlay:
  - o The PCC thickness was assumed to be the design value (Table 2.2).
  - o The slab size was assumed to be the design value (Table 2.2).
  - o The concrete 28-day flexural strength was assumed to be the design value (Table 2.2) or 650 psi when the design value was not known. For fiber-reinforced concrete, the 28-day flexural strength was increased by 20%. The *Pavement ME* option of computing modulus of elasticity from the flexural strength using American Concrete Institute (ACI) formulas was selected for all sections. The default time evolution of concrete strength and stiffness was adopted for all sections.
  - o Default values were adopted for all concrete thermal properties—including the coefficient of thermal expansion, thermal conductivity, heat capacity, density, and albedo—and concrete

composition. Thermal effects have very small impacts on *Pavement ME* COA cracking predictions, and concrete composition has no impact.

- Other design features:
  - Shoulder type, tied (40% LTE) or untied (0% LTE), was selected based on available design information (Table 2.2).
  - The default *Pavement ME* value for load transfer efficiency, 80%, was adopted for all the sections.

Figure 4.1 includes the comparison between the longitudinal cracking predicted by *Pavement ME* and the longitudinal cracking measured in the APCS conducted in September 2018. With just one exception (section CO-SR-83A), *Pavement ME* predicts less than 5% longitudinal cracking, which agrees with the measured values. The root mean square error of *Pavement ME* Run 01 predictions is 2.4%. Even though section CO-SR-83A was subjected to relatively high traffic volumes (the design lane supports about 1,000 trucks per day) and it has 5 in. thick slabs and has been in service for 19 years, only 2.3% of the slabs had longitudinal cracking. In any case, the prediction error for CO-SR-83A section (9.0% predicted versus 2.3% measured) is relatively small considering that the standard error of the *Pavement ME* predictions is 9.7% for this particular cracking level (equation (4.1)).

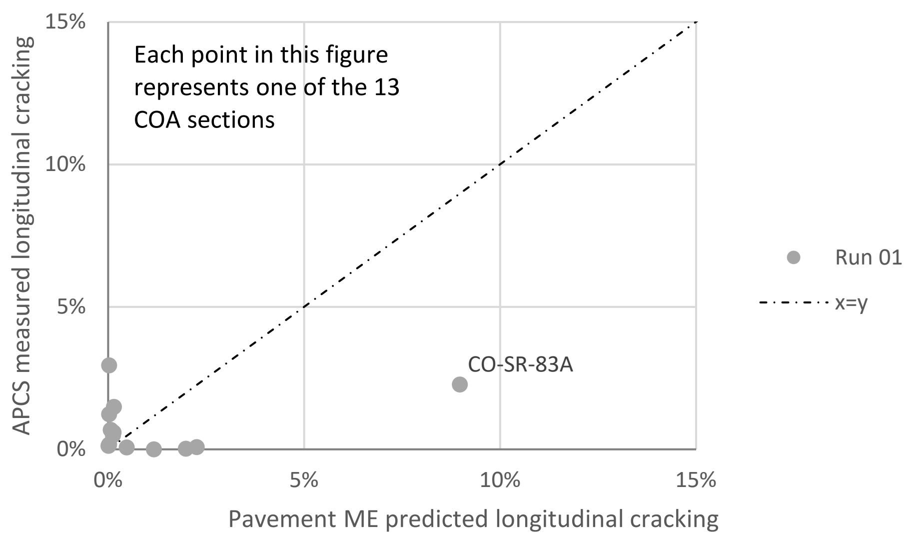


Figure 4.1: Comparison between Run 01 predictions (50% reliability) and measured cracking.

4.2 Pavement ME Run 02

Pavement ME Run 02 differed from Run 01 in the thickness of the concrete overlay. While the design thickness was used in the Run 01 calculations, the actual thickness measured with GPR was used in Run 02. On average, the thickness measured with GPR was 0.5 in. more than the design thickness. The actual differences between the design and GPR overlay thicknesses varied from 0 in. (section CO-SR-121B) to 1.6 in. (section CO-SR-83B).

The comparison between measured and predicted longitudinal cracking is presented in Figure 4.2. Compared to Run 01, the points corresponding to Run 02 shift left (less predicted cracking) since the slab thickness increases. The root mean square error of Run 02 predictions is 1.2%. For the Run 02 calculations, *Pavement ME* correctly predicted that cracking is below 5% in all sections.

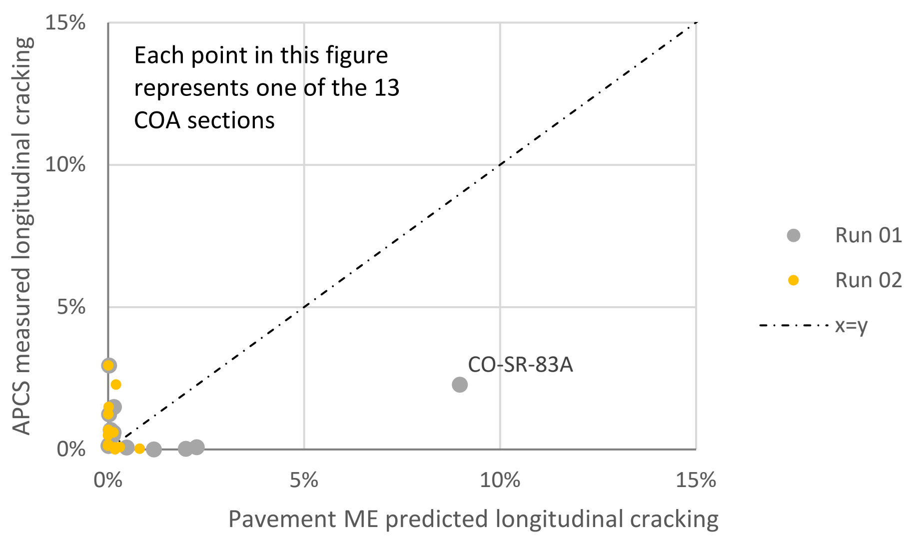


Figure 4.2: Comparison between Run 02 predictions (50% reliability) and measured cracking (Run 02 overlay thickness is based on GPR).

4.3 Pavement ME Run 03

Pavement ME Run 03 differed from Run 01 in the 28-day flexural strength of the concrete ($MR_{28\text{-day}}$). While design values were used for the $MR_{28\text{-day}}$ Run 01 calculations, estimates based on laboratory testing of the actual concrete were used in Run 03.

The team extracted crores from the different sections. For seven sections, concrete compressive strength (*fc*) was measured for specimens prepared from those cores. For the rest of the sections, concrete indirect tensile strength was measured and then used to estimate *fc*. The measured or estimated compressive strength was converted to flexural strength using the ACI formula implemented in *Pavement ME*: $MR = 9.5 \times fc\text{^}0.5$. Finally, *MR* was corrected to 28 days by using the concrete strength time evolution function implemented in *Pavement ME*. Run 01 values (design values) were used for $MR_{28\text{-day}}$ for two sections: IL-CH-10, since the detailed field inspection of the section could not be conducted due to a road closure issue, and MN-I-35, since the flexural strength estimated value (608 psi) was unrealistically low.

The comparison between measured and predicted longitudinal cracking is presented in Figure 4.3. The root mean square error of Run 03 predictions is 2.1%, almost the same as Run 01.

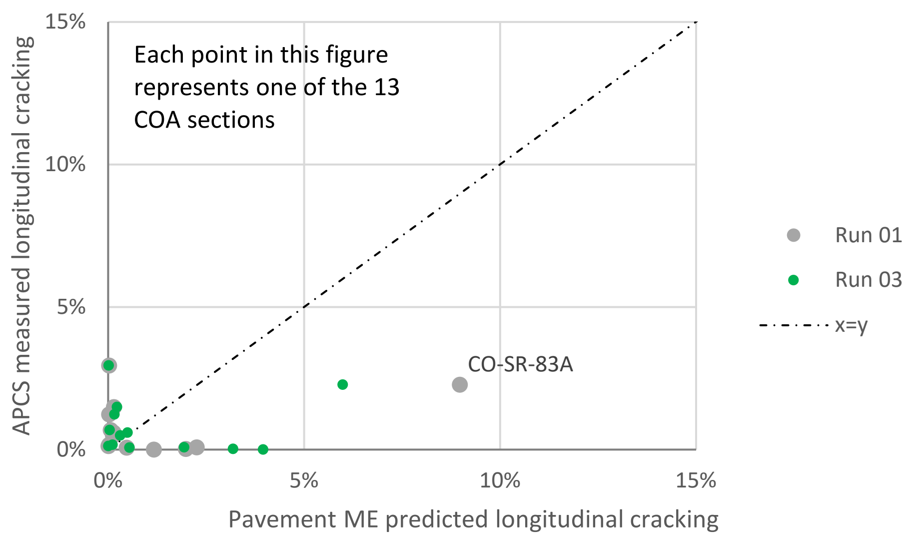


Figure 4.3: Comparison between Run 03 predictions (50% reliability) and measured cracking (Run 03 $MR_{28\text{-day}}$ is based on laboratory testing of actual concrete).

4.4 Pavement ME Run 04

Pavement ME Run 04 inputs differ from Run 01 inputs in terms of the load transfer efficiency (LTE) of the transverse joints. While the *Pavement ME* default value (80%) was used in Run 01 calculations, the LTE measured with the FWD was used in Run 04.

The team conducted FWD testing on three 0.1 mi. segments for 12 out of the 13 projects (the FWD evaluation of section IL-CH-10 could not be conducted). The performance of the three segments had been rated as "good," "fair," and "poor," according to categories established by the National Highway Performance Program *(6)*. In each 0.1 mi. segment, three sets of five consecutive slabs were tested. Overall, the LTE was excellent. With one exception, the average LTEs of the different sections were over 80%. The exception was the MN-CSAH-22 section, where the average LTE was 70%. This section happened to have the thinnest asphalt base (3 in.) of the 13 sections (Table 2.2). The *Pavement ME* default LTE value (80%) was adopted for the section that could not be evaluated with the FWD (IL-CH-10).

The comparison between measured and predicted longitudinal cracking is presented in Figure 4.4. With the exception of the MN-CSAH-22 section, Run 04 predictions shift left (less predicted cracking) compared to Run 01 since the Run 04 LTE is larger than the 80% assumed in Run 01. The cracking predicted for the MN-CSAH-22 section does not match measured cracking. The root mean square error of the Run 04 predictions is 4.0%, about twice the error obtained for Run 01.

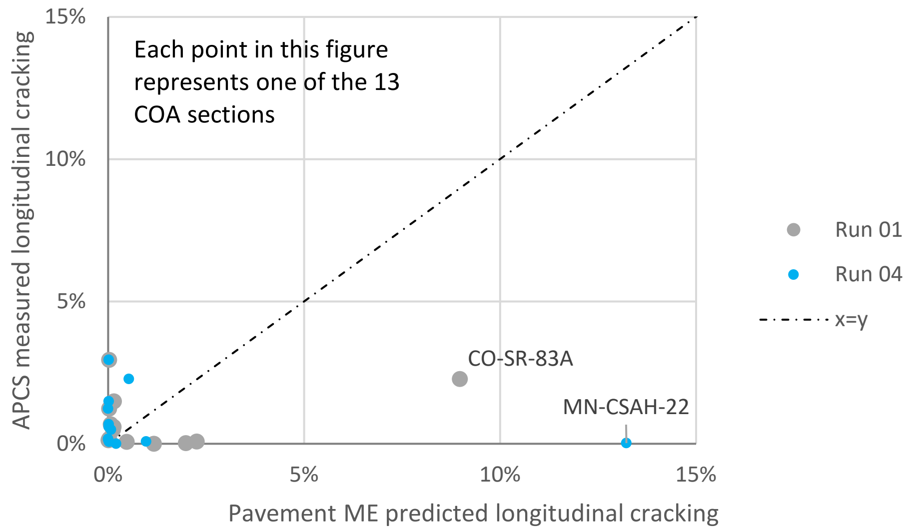


Figure 4.4: Comparison between Run 04 predictions (50% reliability) and measured cracking (Run 04 LTE is based on FWD testing).

The actual thickness of the asphalt base (H_{AB}) was measured on cores extracted at the FWD testing locations in the 0.1 mi. "good" and "poor" performance segments of each section. The comparison of LTE and asphalt base thickness is presented in Figure 4.5. The data in this figure suggests that asphalt thickness has some effect on LTE. When analyzed as a single set of data (classical regression analysis, LTE versus H_{AB}), the relation between LTE and H_{AB} is statistically significant (p-value < 0.01). When between-section variability is considered (mixed effect model), the relationship between the two variables is also statistically significant (p-value = 0.09). Compared to the classical regression model, the mixed effect model equation includes a term that is allowed to vary from section to section, as shown in equation (4.2):

$$LTE = ci + a + b \times H_{AB} \quad \textbf{(4.2)}$$

In equation (4.2), H_{AB} is the thickness of the asphalt base in inches, a is the mean offset (equivalent to the 78.17 value in the Figure 4.5 equation), b is the slope (equivalent to the 0.81 value in the Figure 4.5 equation), and ci is the section deviation from the mean offset (i is 1 to 13), representing section-to-section variability of the intercept that is not related to the thickness of the asphalt base. The statistical analysis, conducted with SPSS software, resulted in a = 81.1(%) and b = 0.48(%/in.) and ci standard error of 19.6%. The standard error of ci represents the unexplained part of the LTE variation from section to section. The calculated standard error of ci is very high, indicating that a considerable part of the section-to-section variation cannot be explained by the variation in asphalt thickness. Slab thickness, AADTT, and age were tried as explanatory variables for LTE but none of them had a statistically significant effect.

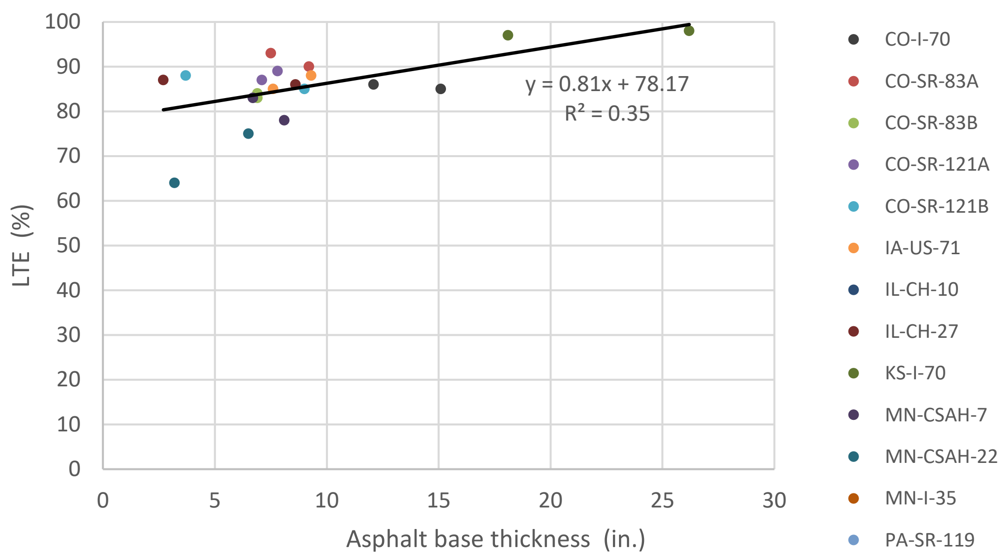


Figure 4.5: Comparison between LTE measured with FWD and thickness of asphalt measured from cores.

5 CONCLUSIONS

This technical memorandum assesses *Pavement ME* longitudinal cracking predictions based on the cracking measured on 13 concrete overlay on asphalt (COA) sections with half-lane width slabs evaluated as part of NCHRP Project 1-61. None of the 13 sections had more than 3% of slabs with longitudinal cracking, despite four of them being subjected to relatively high traffic volumes (AADTT over 500 on the design lane) and had been in service between 9 and 19 years.

When design values were adopted for the different input variables, *Pavement ME* predicted less than 5% longitudinal cracking in 12 out of the 13 sections, which agrees with measured cracking. The root mean square error (RMSE) of *Pavement ME* predictions was 2.4% for the set of 13 sections.

The RMSE of the *Pavement ME* predictions improved to 1.2% when constructed slab thickness measured with GPR was used instead of the design thickness. On the contrary, *Pavement ME* predictions did not improve when measured values for concrete strength or LTE were used rather than design values.

It is recommended that the nationally calibrated COA cracking model, implemented in *Pavement ME* version 2.5.5 (the current version as of the writing of this technical memorandum), be used for developing the California COA design catalog.

An additional recommendation is that future evaluations of the *Pavement ME* COA cracking model include sections with longitudinal cracking levels greater than 10%.

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