Long-Term Pavement Performance Data Analysis Program: Effect of Dowel Misalignment on Concrete Pavement Performance

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FOREWORD

This report documents the analysis of data collected through the Long-Term Pavement Performance (LTPP) program to characterize the effects of dowel misalignment on concrete pavement performance. The objective of this research was to measure the alignment of dowels at the transverse joints of in-service pavements. This report documents this information on a State-by-State basis. Data were used to evaluate typical distribution of various types of misalignment and analyze how misalignment relates to pavement performance factors such as cracking, faulting, and spalling.

A majority of dowels in LTPP studies had good alignment with regard to horizontal skew, vertical tilt, longitudinal translation, and vertical translation. To characterize the entire transverse joint, rather than just the individual dowels, the joint score and equivalent dowel diameter measures were used for each pavement section. The researchers found that, while dowel misalignment may be a contributing factor, its effects were secondary, as there are many other factors that affect pavement performance. The biggest contribution of dowel misalignment was in terms of its effect on load transfer at the transverse joints, which may translate to poor faulting performance, depending on other factors that impact faulting.

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Director, Office of Infrastructure
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16. Abstract
Magnetic imaging tomography (MIT) scanning is a nondestructive method for measuring the alignment of dowels placed at transverse joints of jointed plain concrete pavements (JPCPs). Several highway agencies across the United States have adopted specifications for dowel alignment, with many using the joint score measure. However, this measure was developed intuitively and not based on any laboratory or field tests. National Cooperative Highway Research Program (NCHRP) Report 637 provides a methodology to determine an equivalent dowel diameter measure based on dowel misalignment (Khazanovich et al. 2009). This procedure was developed from laboratory tests and with limited field validation. The relationship between dowel misalignment and the performance of JPCP is unclear, but understanding it is imperative for developing construction guidelines. This report presents results of MIT scanning data collected on Long-Term Pavement Performance (LTPP) test sections and data analysis to assess the effects of dowel misalignment on JPCP performance. As part of this study, MIT scanning was performed on 121 Specific Pavement Studies-2 and 3 General Pavement Studies-3 test sections. Dowel alignment parameters, joint score, and equivalent dowel diameter were calculated as part of the analysis. Statistical analysis was performed to determine any relationship between the joint score and cracking and between the joint score and spalling. The analysis did not indicate any definitive relationship between the joint score and cracking or the joint score and spalling within the analysis range for most States, although some effect was observed for three States. This lack of relationship does not mean severely misaligned dowels have no effect on pavement performance, particularly localized distresses. Analysis of the equivalent dowel diameter as a measure of dowel misalignment for use with AASHTOWare® Pavement ME Design software suggests that using the equivalent dowel diameter is a less-biased estimator of long-term load-transfer efficiency (LTE), as modeled using AASHTOWare Pavement ME Design, than using the actual dowel diameter, suggesting a relationship between dowel misalignment and long-term LTE (AASHTO 2014). However, there is considerable scatter in the LTE modeled using AASHTOWare Pavement ME Design versus actual LTE. The remaining bias and scatter suggests that the models (i.e., equivalent dowel diameter and LTE in AASHTOWare Pavement ME Design) could potentially be improved using data collected as part of this study.

17. Key Words Long-term pavement performance, LTPP, concrete pavement performance, dowel misalignment, dowel alignment, MIT scanning, equivalent dowel diameter, dowel specifications	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACPA	American Concrete Pavement Association
DBI	dowel bar inserter
FHWA	Federal Highway Administration
GPS	General Pavement Studies
JPCP	jointed plain concrete pavement
LTE	load-transfer efficiency
LTPP	Long-Term Pavement Performance
MIT	magnetic imaging tomography
NCHRP	National Cooperative Highway Research Program
PCC	portland cement concrete
SMP	Seasonal Monitoring Program
SPS	Specific Pavement Studies

CHAPTER 1. BACKGROUND AND LITERATURE REVIEW

Transverse joints are essential features of jointed plain concrete pavements (JPCPs) that help relieve thermal- and moisture-induced stresses. At the same time, they are the weakest aspects of JPCPs, experiencing higher stresses and deflections compared to interior parts of the slab under the same loading conditions. With modern JPCPs, dowels are placed across transverse joints to allow for wheel-load shear transfer across slabs while also allowing unrestricted slab expansion and contraction due to changes in temperature and moisture. When compared to JPCPs with undoweled transverse joints, slab corner deflections in JPCPs with doweled transverse joints are reduced by the improved wheel-load shear transfer. Dowels help increase pavement life by providing greater smoothness and reducing the potential for pumping, base erosion, and faulting. These pavement-life-extending benefits have been demonstrated by several pavement studies (Yu et al. 1998; Khazanovich et al. 1998; Hoerner et al. 2000). Some researchers consider pumping and transverse joint faulting issues largely resolved if properly sized and aligned dowels are used at the transverse joints (Khazanovich et al. 1998; Lechner 2005).

To be effective, dowels must be parallel to both the centerline and surface of the pavement, placed with sufficient cover, and centered across the transverse joint. Any deviation from such positioning is considered dowel misalignment. Some engineers and researchers only consider rotation as misalignment and consider translation as mislocation, but for convenience and consistency, all deviations (e.g., rotational and translational) in this study are considered misalignments.

The major categories of dowel misalignment are translational—which includes horizontal, longitudinal, and vertical translation—and rotational—which includes horizontal skew and vertical tilt—as illustrated in figure 1 (Tayabji 1986; Rao 2009). Horizontal translation is often disregarded as a misalignment parameter because properly positioning dowels at regular spacing (typically 12 inches) along the transverse joint is not an issue and not considered a key factor affecting transverse joint performance.

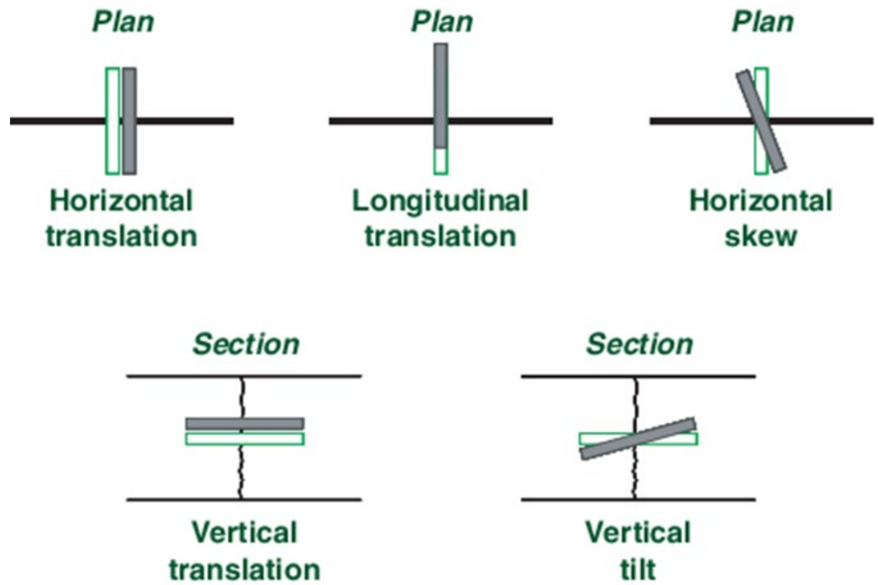


Figure 1. Illustration. Types of dowel misalignment (adapted from Tayabji 1986).

Potential adverse effects of dowel misalignment include the following:

- Reduced load-transfer efficiency (LTE), resulting in increased long-term faulting and, in some situations, increased corner cracking.
- Transverse joint spalling from excessive steel/concrete bearing stresses.
- Slab cracking from transverse joint lockup or restraint.

Dowels are placed in concrete using dowel baskets or dowel bar inserters (DBIs). Dowel baskets are carriages designed to support or link dowels and hold them at the desired alignment during paving operations. DBIs place dowels into fresh concrete as the concrete is laid, eliminating the need to manually place dowels in baskets prior to paving operations.

In the past two decades, highway agencies and paving contractors have increasingly used magnetic imaging tomography (MIT) scanning to evaluate dowel alignment in JPCPs. Numerous evaluations of the accuracy of MIT scanning have shown such devices are reliable tools for measuring dowel alignment with high accuracy for dowels inserted with dowel baskets with cut transport-tie wires or DBIs (Yu and Khazanovich 2005). Studies by Hossain and Elfino (2006) and Leong et al. (2006), respectively, confirmed the accuracy of MIT scanning devices. Researchers found MIT scanning devices to be robust and versatile for investigations requiring large numbers of measurements in a wide range of environments (Yu and Tayabji 2007). The robustness and versatility of the devices prompted the Federal Highway Administration's (FHWA) Concrete Pavement Technology Program to initiate a loan program encouraging the implementation of MIT technology. FHWA identified MIT scanning devices as practical, implementation-ready products with the potential to improve the quality of concrete pavements (Yu 2005).

The increased use of MIT scanning has exposed the issue of how much dowel misalignment is acceptable to an agency. Many agency's dowel alignment tolerances were established prior to a clear understanding of field-achievable tolerances and a real-world understanding of the effects of dowel misalignment on pavement performance. These once-acceptable dowel alignment tolerances are under scrutiny, launching renewed interest in dowel misalignment research, including laboratory and field studies by Khazanovich et al. (2009), Rao et al. (2009), Leong et al. (2006), Milind et al. (2006), and the American Concrete Pavement Association ((ACPA) 2006). These studies contributed significantly to the understanding of how dowel misalignment impacts transverse joint movements and the long-term performance of JPCPs.

In NCHRP Report 637, the effect of dowel misalignment on the performance of JPCP was evaluated through laboratory testing, analytical modeling, and limited field testing (Khazanovich et al. 2009). A procedure was developed to compute an equivalent dowel diameter for a transverse joint based on alignment of all dowels at that joint. Key results from Khazanovich et al. (2009) include the following:

- Extreme longitudinal and vertical translation can cause significant reductions in shear capacity.
- A combination of low concrete cover and low embedment length (resulting from vertical and longitudinal translation) has a more adverse effect on dowel performance than either of the two rotational misalignments.
- Dowel rotational misalignments of up to 2 inches have a negligible effect on pullout and shear performance measures.

The researchers concluded that rotational dowel misalignment is not a sufficient cause for transverse joint lockup and does not cause significant additional longitudinal stresses. The researchers developed a procedure to compute the equivalent dowel diameter for a transverse joint based on dowel misalignment that considers the effects of longitudinal translation, vertical translation, horizontal skew, and vertical tilt of all dowels within the joint. The equivalent dowel diameter calculated using this procedure can be used in mechanistic–empirical pavement design procedures, such as those used with AASHTOWare® Pavement ME Design software, to model the long-term performance of the pavement, primarily LTE and faulting, and the resulting International Roughness Index, but was shown to have minimal effect on transverse joint locking and slab cracking (AASHTO 2014).

Field studies show that slab or transverse joint distress may not always occur from rotational dowel misalignments (i.e., horizontal skews or vertical tilts). Khazanovich et al. (2009) observed that, within the nonextreme limits of rotational dowel misalignments measured in their study, there were no differences in the amount of transverse cracking and transverse joint spalling observed from rotational dowel misalignments. ACPA (2006) observed that projects with a significant number of rotationally misaligned dowels performed well without showing any signs of distress after 8 yr or more of service under heavy traffic, suggesting a limited number of rotationally misaligned dowels in JPCP transverse joints may be tolerable. A project constructed in 1977 that was surveyed and cored by Fowler and Gulden (1983) performed well under moderately high interstate traffic without any signs of increased distresses for over 25 yr despite the prevalence of severely rotationally misaligned dowels.

Some researchers conducted slab pullout tests to model the effects of severely rotationally misaligned dowels on transverse joint behavior during joint movement (Tayabji 1986; Prabhu et al. 2006; Khazanovich et al. 2009). Although the exact test configurations varied, in some cases, multiple dowels were tested together to represent a transverse joint. General observations from these tests were that the force required to displace a dowel increased with increasing rotational misalignment. When the dowels were nonuniformly rotationally misaligned, a greater amount of pullout force was required and showed a greater amount of cracking than transverse joints with dowels that were uniformly rotationally misaligned. Slabs developed cracking only at significant misalignment levels (greater than 0.75 inches) when the rotational misalignment of dowels along the transverse joint was nonuniform and excessive levels of joint opening were present (greater than 0.5 inches). Minor spalling around dowels was observed in slabs with severe rotational misalignment. Khazanovich et al. (2009) observed that rotational dowel misalignments of up to 2 inches have a negligible effect on pullout and shear performance measures.

One of the earliest methods to categorize dowel misalignment and consider the combined effects of all dowels at a transverse joint was developed by Yu and Khazanovich (2005) and calculates the rotational misalignment of all dowels within the transverse joint into a joint score. Transverse joints with a higher joint score correspond to more dowels with higher levels of rotational misalignment than transverse joints with a lower joint score. The joint score does not consider longitudinal and vertical translations, and the weight factors based on the extent of rotational misalignment for any individual dowel were developed intuitively and not based on any laboratory or field tests. Because of this limitation, the joint score measure was discussed in an FHWA Technical Brief as only a quick first step toward identifying transverse joints for further investigation with regard to lockup potential, but not necessarily as a measure for acceptance by highway agencies (Yu and Tayabji 2007).

Despite that stipulation, many highway agencies are adopting the joint score measure in their specifications for establishing acceptance criteria primarily because of its simplicity (CDOT 2015; Gancarz et al. 2015). A typical specification requires the joint score to be less than 10, above which corrective action is often specified. Corrective actions range from cutting misaligned dowels (to effectively reduce the joint score to less than 10 by eliminating any chance of the misaligned dowel contributing to transverse joint lockup) to removal and replacement of the transverse joint by performing full-depth repairs.

However, there is no evidence, empirical or otherwise, to support the aforementioned criterion for corrective action based on transverse joint lockup since it is inconsistent with the results from NCHRP Report 637 and limited transverse joint-opening and -closing studies conducted by Mallela et al. (2012). They measured joint openings and closings over a 48-hour period of transverse joints with a joint score ranging from 1 to 40 and found that all transverse joints tested, including those with the highest number and degree of dowel misalignment (i.e., joint scores ranging from 30 to 40), experienced transverse joint opening and closing as a function of temperature change, suggesting there were no transverse joint lockups.

Due to the limited scope of laboratory and field studies completed to date, there is still a significant lack of guidance for establishing effective construction specifications based on actual field performance. Practical questions yet unanswered include the following:

- Do one or two severely misaligned dowels at a transverse joint have the same impact as several dowels with minor misalignment?
- Do misaligned dowels in the wheel path have the same impact as those outside the wheel path?
- Does one out-of-compliance transverse joint warrant corrective action?
- How many consecutive transverse joints need to be misaligned before distress is evident?
- Are there other factors (e.g., climate, base type, dowel size, pavement thickness) that contribute to transverse joint lockup?
- Are the weighting factors used to compute the joint score representative of actual field performance?
- How can relative dowel misalignment (i.e., dowels misaligned in different directions) be best account for compared to uniform dowel misalignment (i.e., dowels misaligned in the same direction)?
- What are the effects of various types of misalignment on actual field performance?

The General Pavement Studies (GPS) and Specific Pavement Studies (SPS) test sections included in the Long-Term Pavement Performance (LTPP) database (i.e., GPS-3 and SPS-2) were used in this current study to evaluate and address some of the aforementioned questions (FHWA 2014). Much of the information needed to evaluate performance of these test sections vis-à-vis dowel alignment is contained in the LTPP database, including the following:

- Design, materials, construction, and support data.
- Climatic data.
- Traffic data.
- Pavement performance data.
- Falling weight deflectometer data.
- Distress data.
- Profile data.
- Transverse joint-opening and -closing data (for select test sections).

The key piece of information needed to evaluate performance of these test sections with regard to dowel alignment not included in the LTPP database is alignment data for each of the dowels within the transverse joints. This current research effort was conducted to collect MIT scanning data on various GPS-3 and SPS-2 test sections for inclusion in the LTPP database. Results of MIT scanning and analysis are presented in the following sections. MIT scanning data collected as part of this project were used in a preliminary analysis as part of this study and serve as a platform for detailed statistical analysis to address unanswered practical questions regarding effects of dowel misalignment on actual field performance. While a preliminary analysis was performed in this study, a more thorough and detailed statistical analysis and evaluation of the data were beyond the scope of this study, the primary purpose of which was to collect and document dowel misalignment data at these GPS-3 and SPS-2 test sections.

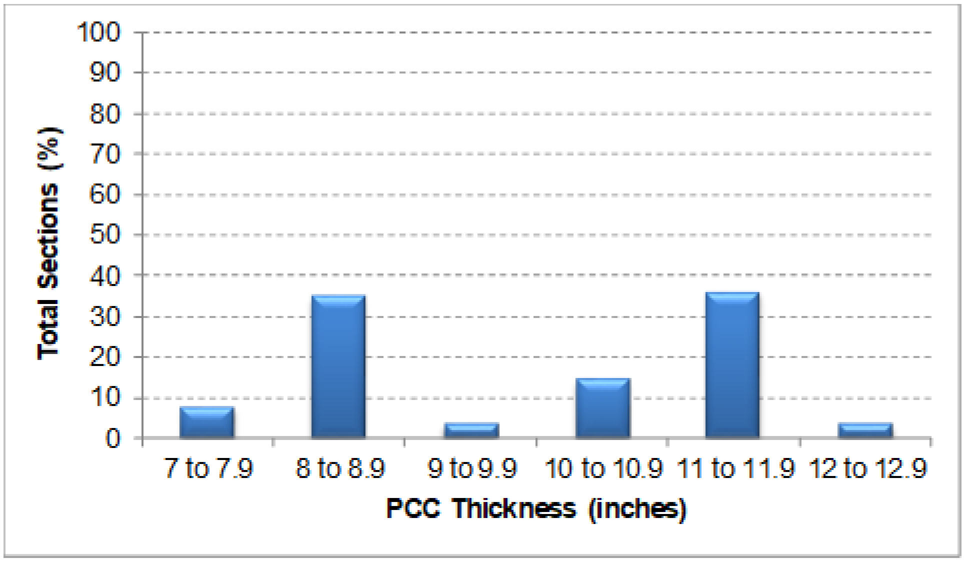
CHAPTER 2. SELECTION OF LTPP TEST SECTIONS

The LTPP database includes 181 doweled JPCP test sections ranging in thickness from 6.4 to 13.2 inches. Each test section is a driving lane (i.e., traffic or outside lane), 500 ft in length, with approximately 33 transverse joints. Based on scheduling and availability of lane closures for the LTPP test sections, a total of 3 GPS-3 and 121 SPS-2 test sections were included in field data collection using an MIT scanning device. At some SPS-2 sites, one or two test sections were not tested because of scheduling conflicts with lane closures and testing crew travel.

Five test sections (one each in Iowa and Kentucky and two in both North Dakota and Wisconsin) were not included in the analysis because they had skewed transverse joints. One test section (Wisconsin) was not included in the analysis because it had only four dowels per transverse joint. One test section (Arkansas) with 1-inch-diameter dowels was eliminated from analysis due to an error with the MIT parameter file. Table 1 represents the breakdown of the numbers of LTPP test sections by State. Arkansas included 1 GPS-3 and 12 SPS-2 test sections. The distribution of LTPP test sections by portland cement concrete (PCC) thickness and construction year are shown in figure 2 and figure 3.

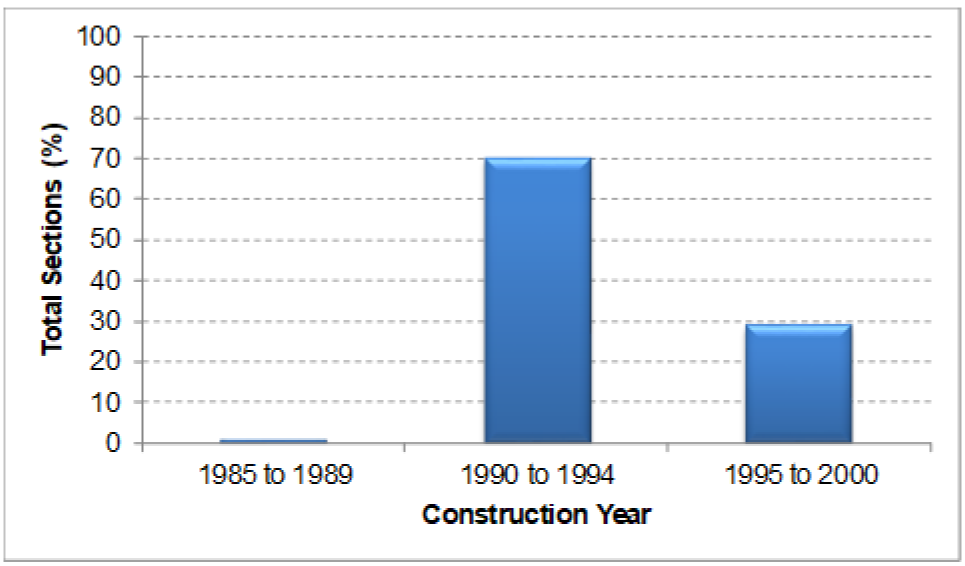
Table 1. Number of LTPP test sections by State for MIT scanning and analyses.

State	Experiment Type	Number of LTPP Test Sections for Field Data Collection	Number of LTPP Test Sections Used in Analyses
Arizona	SPS-2	12	12
Arkansas	GPS-3/SPS-2	13	12
California	SPS-2	12	12
Colorado	SPS-2	12	12
Delaware	SPS-2	14	14
Iowa	SPS-2	13	12
Kansas	SPS-2	12	12
Kentucky	GPS-3	1	0
North Carolina	SPS-2	8	8
North Dakota	SPS-2	14	12
South Dakota	GPS-3	1	1
Wisconsin	SPS-2	12	10
Total	GPS-3/SPS-2	124	117



Source: FHWA.

Figure 2. Chart. Percentage of analysis pavement test sections with respect to PCC thickness.



Source: FHWA.

Figure 3. Chart. Percentage of analysis pavement test sections with respect to construction year.

CHAPTER 3. MIT SCANNING

In recent years, highway agencies and paving contractors have increasingly used MIT scanning devices, as shown in figure 4, for evaluating dowel alignments in JPCPs. The measuring process involves setting rails on the transverse joint to be scanned, entering pavement information into a handheld computer, and then pulling the unit along the joint. During scanning, the device emits a weak, pulsating magnetic signal and detects the transient magnetic response signal induced in the metal dowels. The methods of tomography are then used to determine the position and alignment of the dowels. The data analysis process is performed using software provided with such devices.

Figure 4. Photo. Testing a pavement transverse joint using an MIT scanning device.

The accuracy of MIT scanning results depends on the position and alignment of the dowels. MIT scanning devices are designed to provide the most accurate results under the following conditions (Yu and Khazanovich 2005; ACPA 2006):

- Mean dowel depth of 4 to 8 inches.
- Maximum rotational misalignment of 0.75 inches.
- Maximum longitudinal translation of 2 inches.

When these conditions are satisfied, the accuracy is typically within 0.12 inches on rotational misalignment and vertical translation (Yu and Khazanovich 2005). For dowels placed in baskets, MIT scanning results are accurate only if the dowels are insulated from the basket by a coating (either paint or epoxy) and the transport ties on the basket are cut or removed. Even if the transport tie wires are not cut during construction, they eventually break due to cyclic movements of the adjacent slabs and the resulting stresses in the tie wires. Thus, older pavements originally constructed with uncut transport tie wires reflect MIT scanning signals as if the tie wires were cut. MIT scanning results are also sensitive to the lateral placement of the dowel basket. The best results are obtained when the dowel basket is centered under the transverse joint saw cut. The presence of other sources of metal (e.g., dowels close to tie bars, steel mesh reinforcement, metal conduit, and overhead power lines) may cause interference and will induce errors in the data.

For the current study, a two-person crew was deployed for field testing. Testing was restricted to the LTPP lane (i.e., traffic or outside lane) for all test sections with lane closures provided by State highway agencies. The rail assembly was set up along the transverse joint of the outside lane to test the joint in one complete scan. For safety reasons due to live traffic in the inside lane, the scan was terminated about 6 inches before the centerline longitudinal joint. In most cases, data from all dowels in the LTPP lane were collected because the last dowel is typically 6 inches away from the centerline longitudinal joint and MIT scanning devices can collect alignment data as long as the front end of the unit is reasonably close (i.e., within a few inches).

For each LTPP test section, scanning commenced at the beginning of the test section and proceeded along the direction of traffic until the end of the test section. Any notes taken during scanning were documented through test logs for every LTPP test section. Each day, upon completion of field data collection, data files were saved to a local server and uploaded to a secure server for backup purposes.

To reduce processing errors and for consistency and efficiency during data collection, the settings shown in table 2 were used for all LTPP test sections. The raw MIT data files were rerun with the appropriate dowel diameter parameter file during post data collection analysis, correcting for dowel alignment results to reflect the actual dowel diameter from the LTPP database. Based on the PCC thickness of each test section included in the LTPP database, the depth deviation parameter was recalculated. This recalculation did not impact the results of the analysis as compared to collecting data using the correct inputs for PCC thickness and dowel size. Images documented during MIT scanning are shown in figure 5 through figure 8.

Table 2. MIT scanning field input.

MIT Input	Value
PCC thickness	11.0 inches
Dowel spacing	12.0 inches
Offset of first dowel	6.0 inches
Dowel size (length × diameter)	18.0 inches × 1.5 inches

Source: FHWA.

Figure 5. Photo. MIT scanning of North Carolina LTPP test section 37_0207.

Source: FHWA.

Figure 6. Photo. Cracking and spalling on Arkansas LTPP test section 05_0217.

Source: FHWA.

Figure 7. Photo. Full-width spray patching on Delaware LTPP test section 10_0208.

Source: FHWA.

Figure 8. Photo. Skewed transverse joints on Iowa LTPP test section 19_0259.

CHAPTER 4. DOWEL ALIGNMENT DATA ANALYSES

This section discusses the analysis of dowel alignment data collected using an MIT scanning device. Major data analysis tasks included the following:

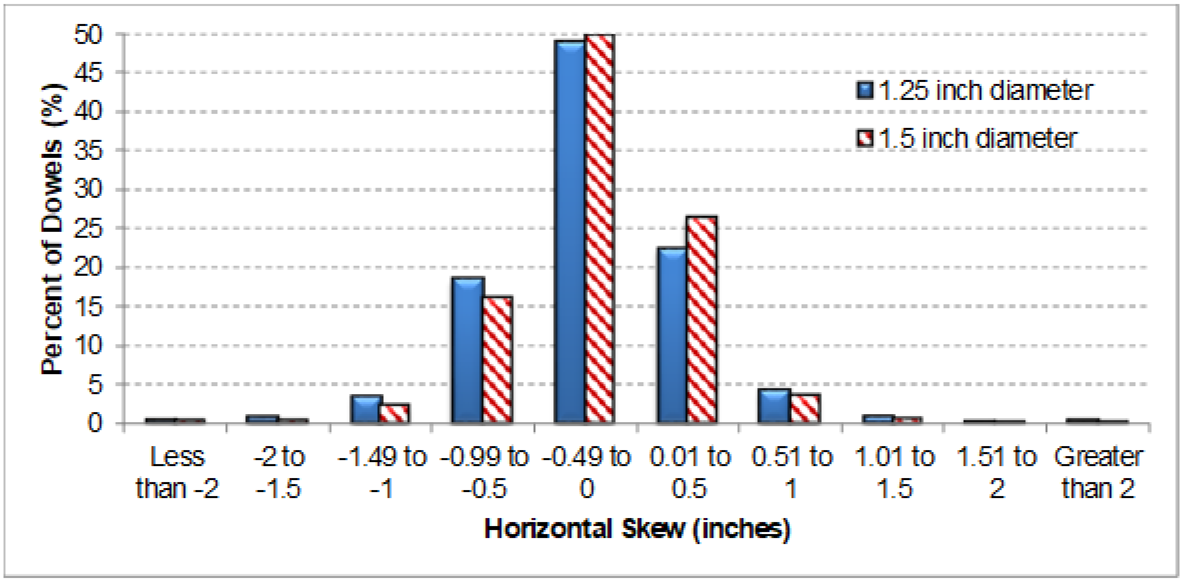
- Analyzing raw MIT scanning files to generate misalignment data, including vertical translation, longitudinal translation, horizontal skew, and vertical tilt, for each dowel at each transverse joint.
- Computing a joint score for each transverse joint.
- Computing the equivalent dowel diameter using NCHRP Report 637 methodology for each transverse joint.
- Analyzing the effects of joint score on slab cracking and transverse joint spalling.
- Comparing predicted distress from AASHTOWare Pavement ME Design and LTPP field distress using both the actual and equivalent dowel diameter for each test section.

DOWEL ALIGNMENT ANALYSES

MIT scanning data were analyzed using the software provided with the MIT scanning device. For each transverse joint successfully analyzed, software provides outputs that include the positions and depths of the dowels; horizontal, vertical, and total rotational misalignments; and longitudinal translations. The vertical translations are estimates and computed based on the average PCC thickness from the LTPP database, dowel diameter, and measured depth of dowels from the surface.

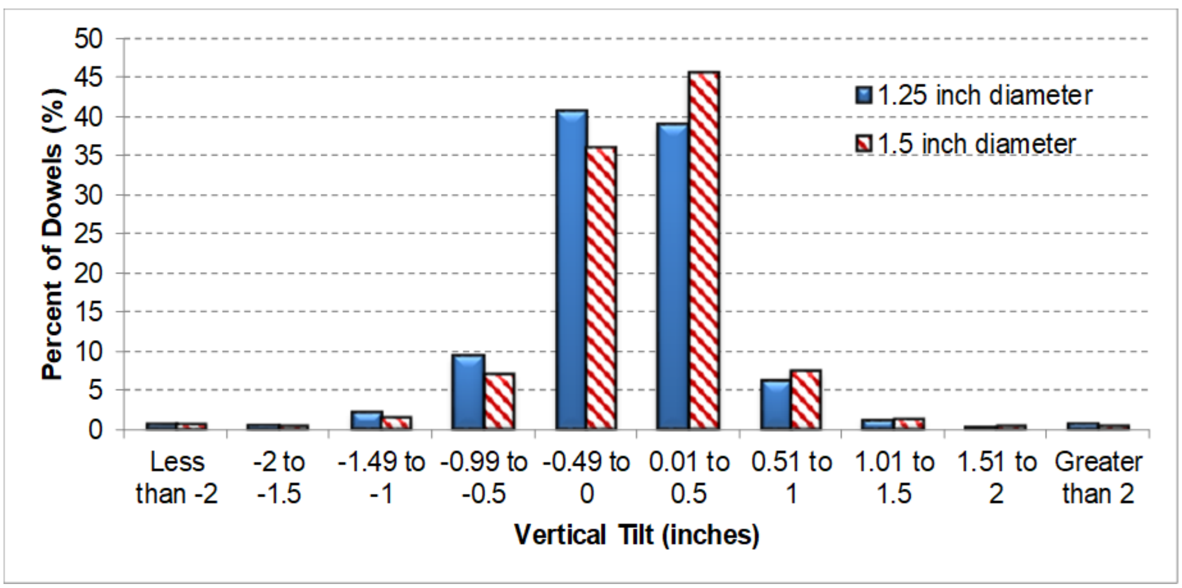
Results from the analysis were compared with the field notes to ensure consistency in transverse joint numbering. Quality checks were included to eliminate extraneous signals from errant tie bars or dowels, other metallic objects, or overhead power lines. These extraneous signals can be clearly seen in the software output as aberrations in the contour plots generated by the software. In case of potential influence due to tie bars, the affected dowels were eliminated from analysis.

The analysis in this current study was limited to dowels with 1.25- and 1.5-inch diameters because almost all test sections surveyed had dowels of one of these two diameters—the two most common dowel diameters used in the United States. The only 1-inch-diameter dowel test section (Arkansas) was eliminated from analysis due to an error with the MIT parameter file. The misalignment distributions for the dowels are shown in figure 9 through figure 20 and are based on the MIT scanning results of 23,300 1.5-inch-diameter dowels from 1,997 transverse joints and 21,240 1.25-inch-diameter dowels from 1,824 transverse joints. The results show that approximately 73, 80, and 62 percent of the dowels with horizontal skew, vertical tilt, and vertical translation, respectively, have misalignments ranging between 0 and ±0.5 inches. There is more variation in the longitudinal translation data, and approximately 29 percent of the dowels have greater than 1.5 inches magnitude of longitudinal translation. There was no observed effect of PCC thickness on the amount of variation for any of the misalignment parameters. MIT scanning results for individual States are shown in the MIT Scanning Analysis by State chapter.



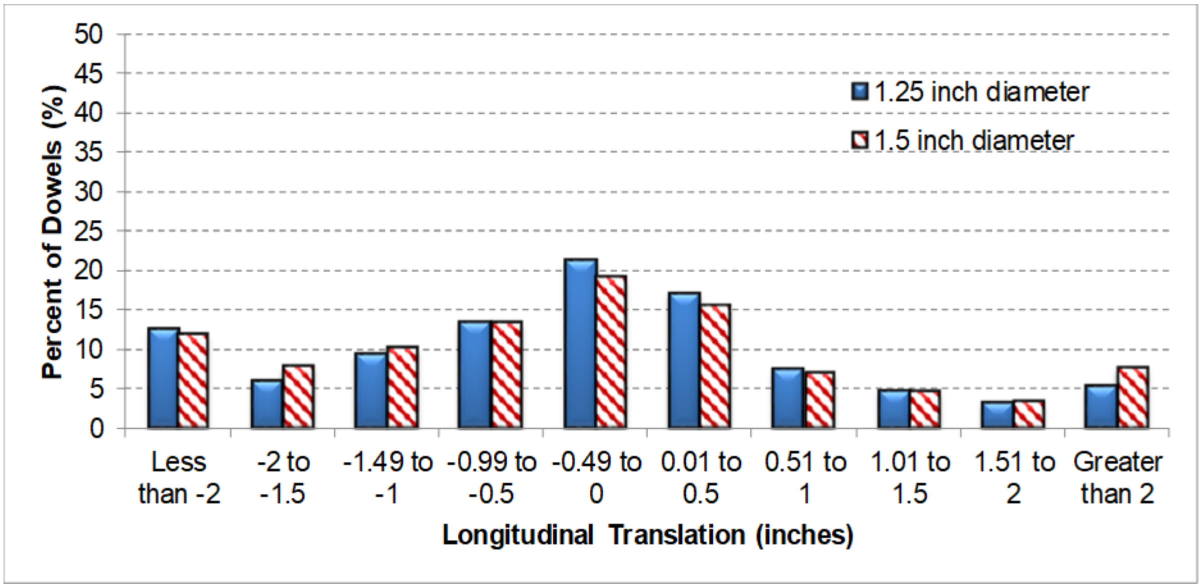
Source: FHWA.

Figure 9. Chart. Horizontal skew distribution of dowels (23,300 1.5-inch-diameter dowels from 1,997 transverse joints and 21,240 1.25-inch-diameter dowels from 1,824 transverse joints).



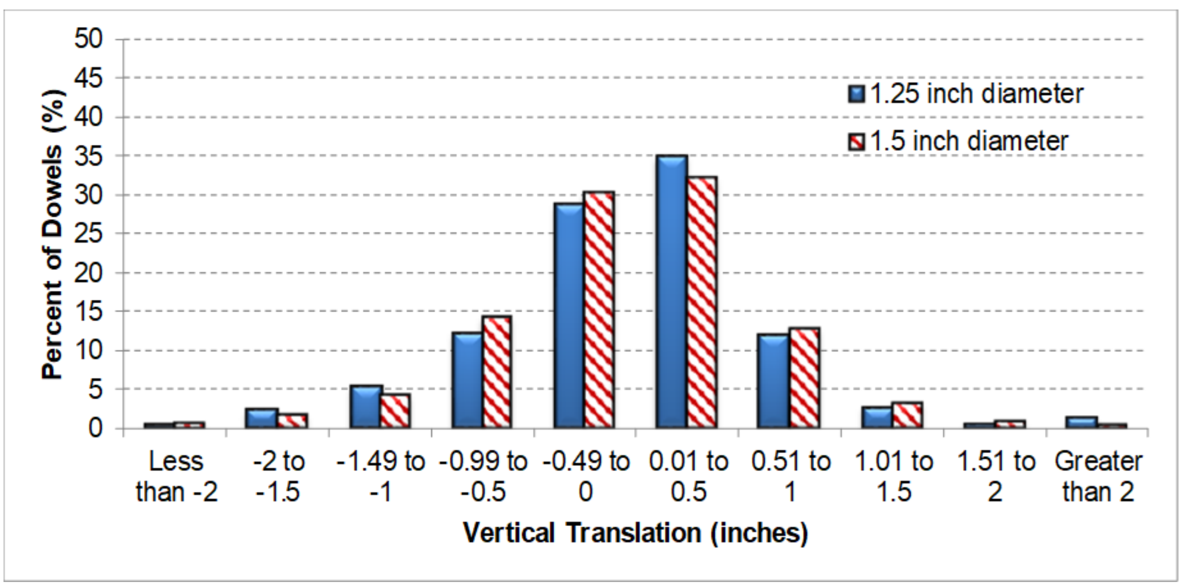
Source: FHWA.

Figure 10. Chart. Vertical tilt distribution of dowels (23,300 1.5-inch-diameter dowels from 1,997 transverse joints and 21,240 1.25-inch-diameter dowels from 1,824 transverse joints).



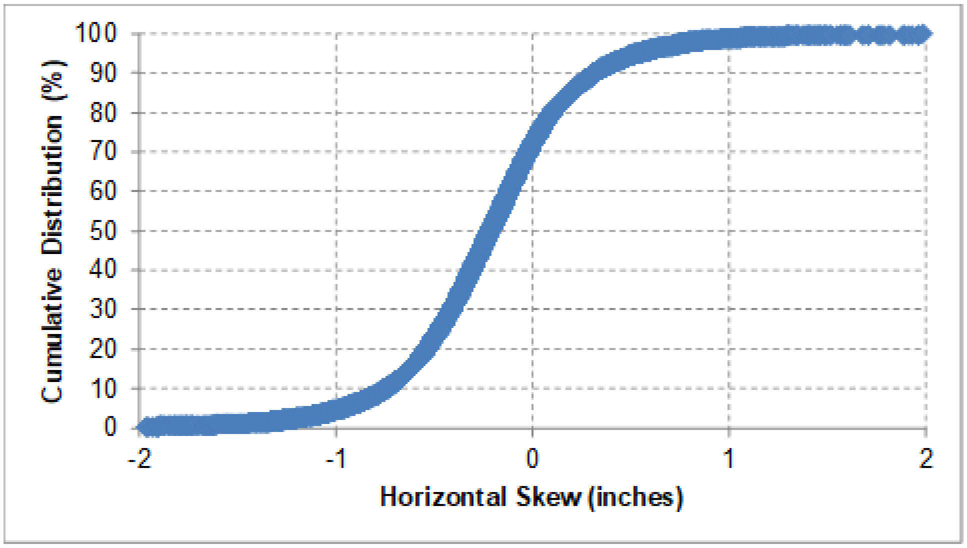
Source: FHWA.

Figure 11. Chart. Longitudinal translation distribution of dowels (23,300 1.5-inch-diameter dowels from 1,997 transverse joints and 21,240 1.25-inch-diameter dowels from 1,824 transverse joints).



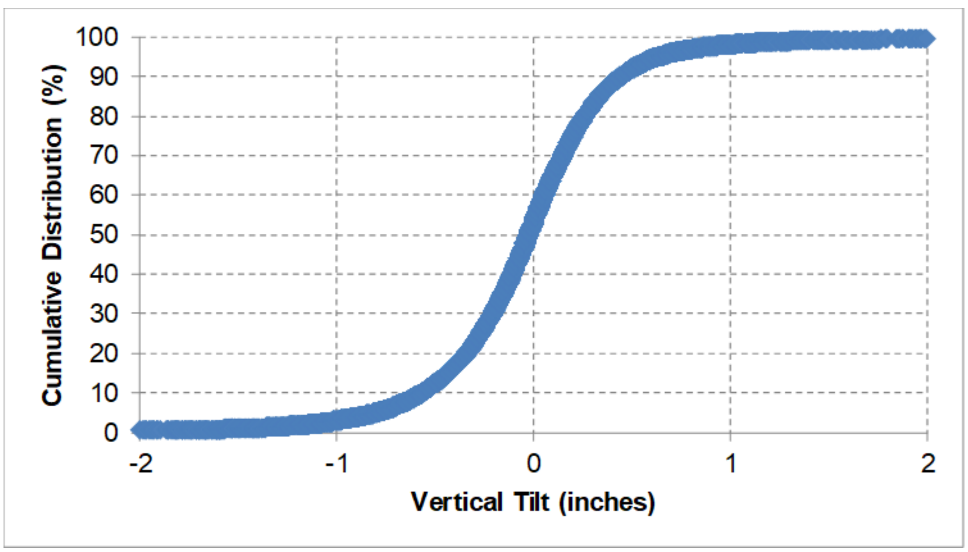
Source: FHWA.

Figure 12. Chart. Vertical translation distribution of dowels (23,300 1.5-inch-diameter dowels from 1,997 transverse joints and 21,240 1.25-inch-diameter dowels from 1,824 transverse joints).



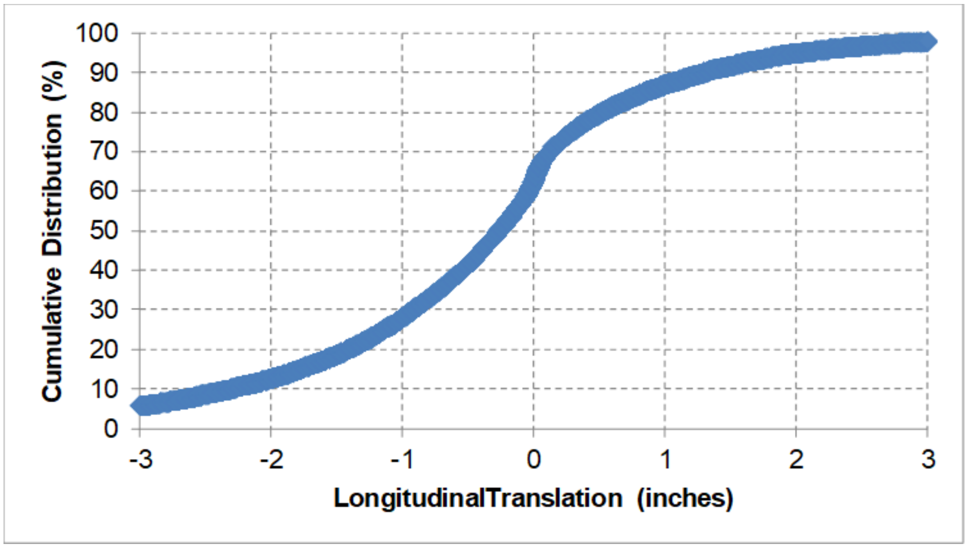
Source: FHWA.

Figure 13. Chart. Cumulative horizontal skew distribution of 21,240 1.25-inch-diameter dowels from 1,824 transverse joints.



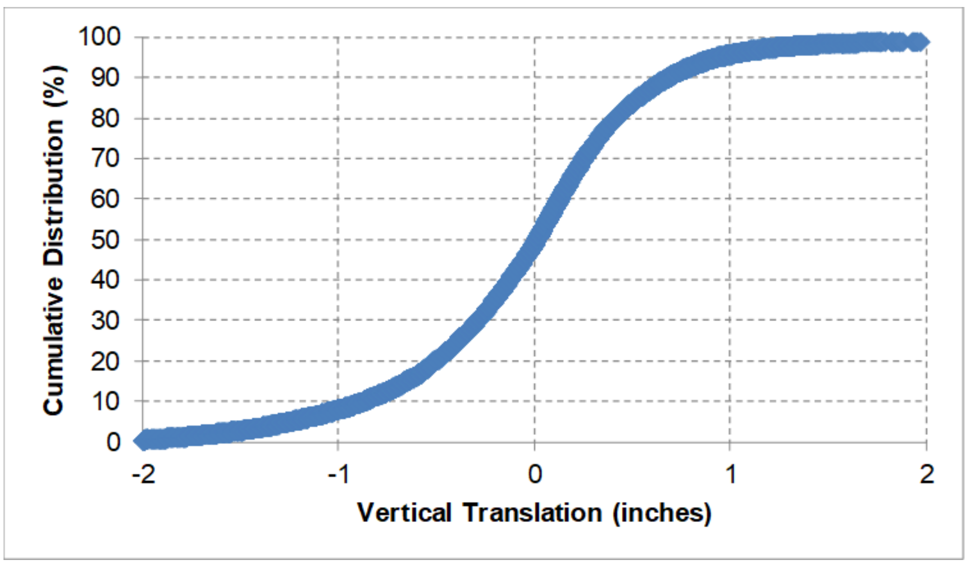
Source: FHWA.

Figure 14. Chart. Cumulative vertical tilt distribution of 21,240 1.25-inch-diameter dowels from 1,824 transverse joints.



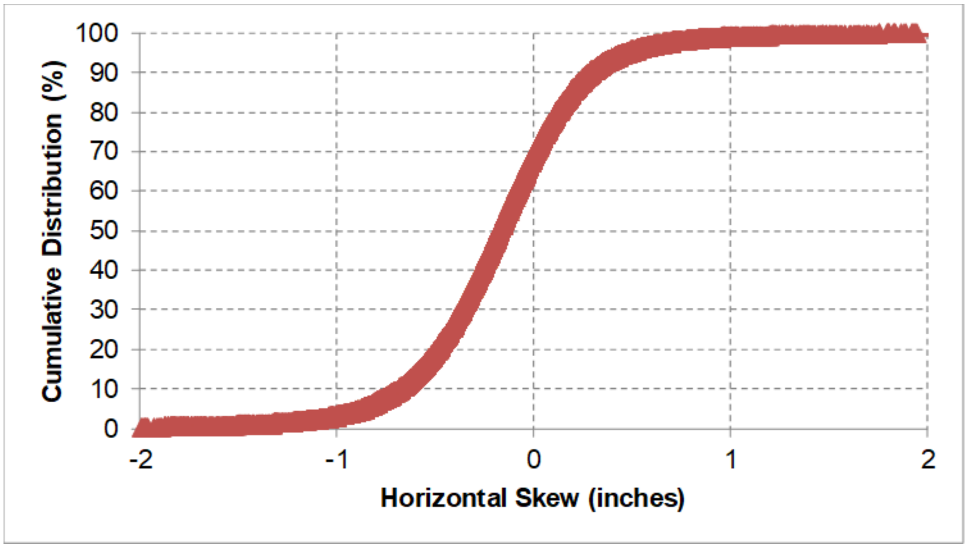
Source: FHWA.

Figure 15. Chart. Cumulative longitudinal translation distribution of 21,240 1.25-inch-diameter dowels from 1,824 transverse joints.



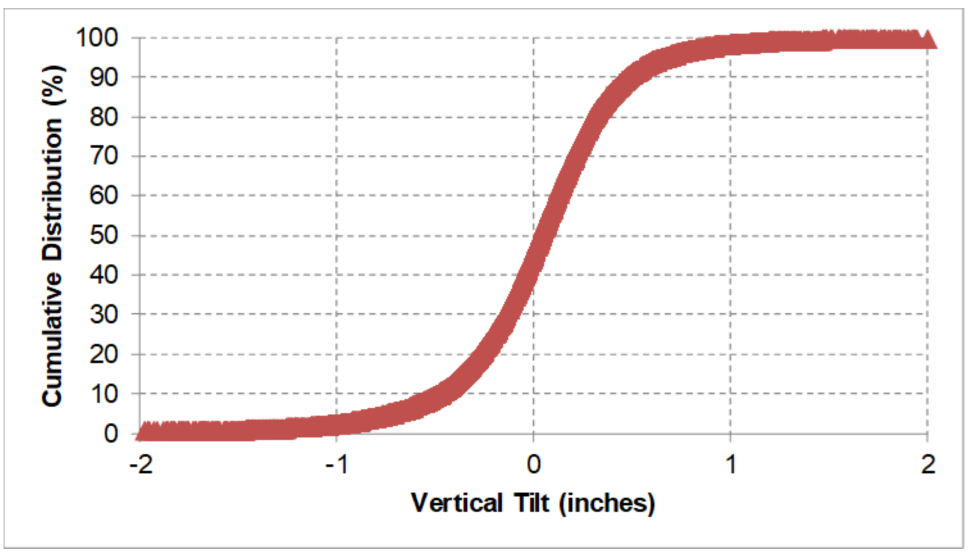
Source: FHWA.

Figure 16. Chart. Cumulative vertical translation distribution of 21,240 1.25-inch-diameter dowels from 1,824 transverse joints.



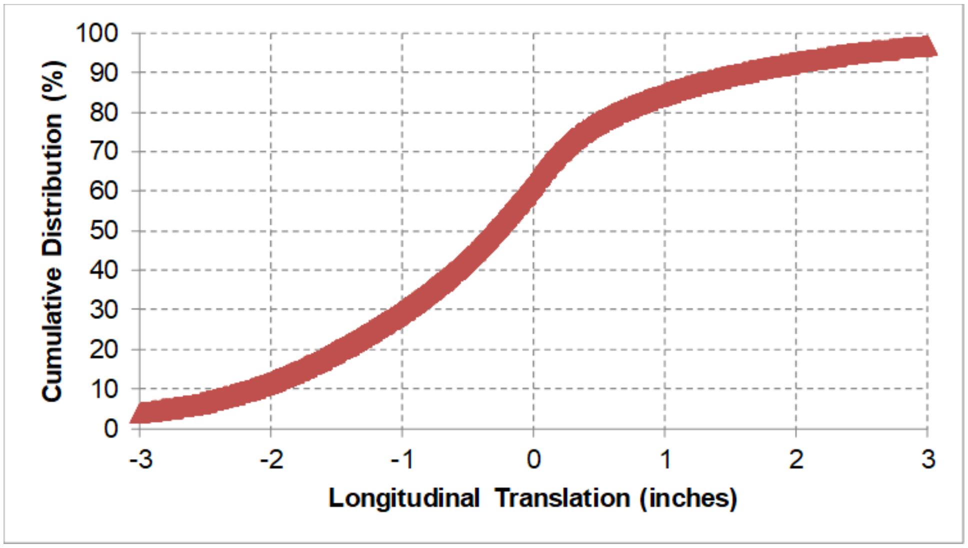
Source: FHWA.

Figure 17. Chart. Cumulative horizontal skew distribution of 23,300 1.5-inch-diameter dowels from 1,997 transverse joints.



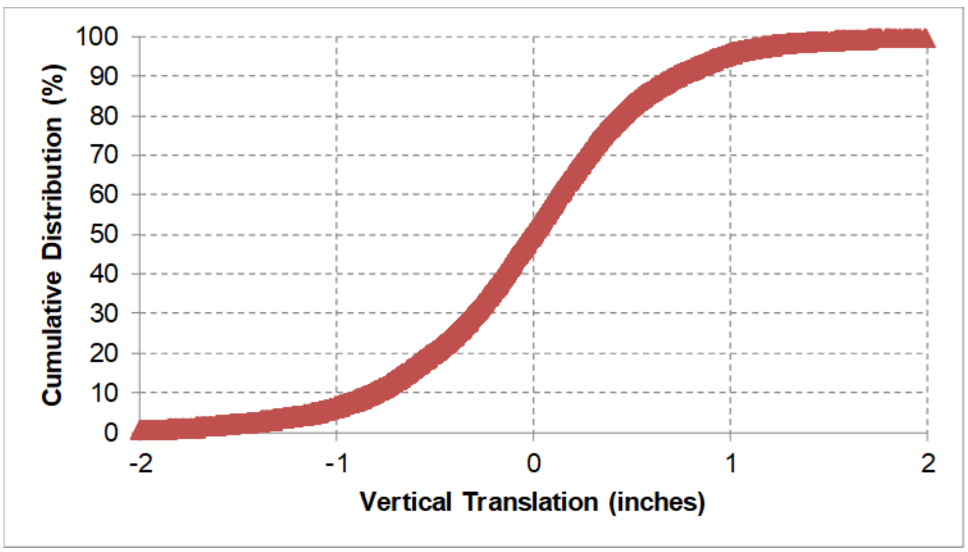
Source: FHWA.

Figure 18. Chart. Cumulative vertical tilt distribution of 23,300 1.5-inch-diameter dowels from 1,997 transverse joints.



Source: FHWA.

Figure 19. Chart. Cumulative longitudinal translation distribution of 23,300 1.5-inch-diameter dowels from 1,997 transverse joints.



Source: FHWA.

Figure 20. Chart. Cumulative vertical translation distribution of 23,300 1.5-inch-diameter dowels from 1,997 transverse joints.

JOINT SCORE ANALYSES

Many highway agencies specify evaluating dowel alignment following construction at a sample number of transverse joints using an MIT scanning device (CDOT 2015; Gancarz et al. 2015). Rotational misalignments of individual dowels within a transverse joint are used to compute the joint score, and acceptance and rejection decisions are made based on criteria detailed in each highway agency's specification. A joint score is calculated as 1 plus the sum of the product of the weights empirically assigned to each degree of misalignment and the number of dowels in each misalignment category (Yu and Khazanovich 2005; Yu and Tayabji 2007). Weighting factors for determining the joint score are shown in table 3. In table 3, the range of misalignment represents the total misalignment, which is calculated as the square root of the sum of squares of the horizontal skew and vertical tilt. In general, transverse joints with joint scores greater than 10 have a higher potential for joint lockup and are recommended for further evaluation and monitoring (Yu and Khazanovich 2005). Yu and Khazanovich (2005) developed the joint score measure intuitively as a quick first step toward identifying transverse joints for further investigation with regard to lockup potential, not as a measure for acceptance by highway agencies.

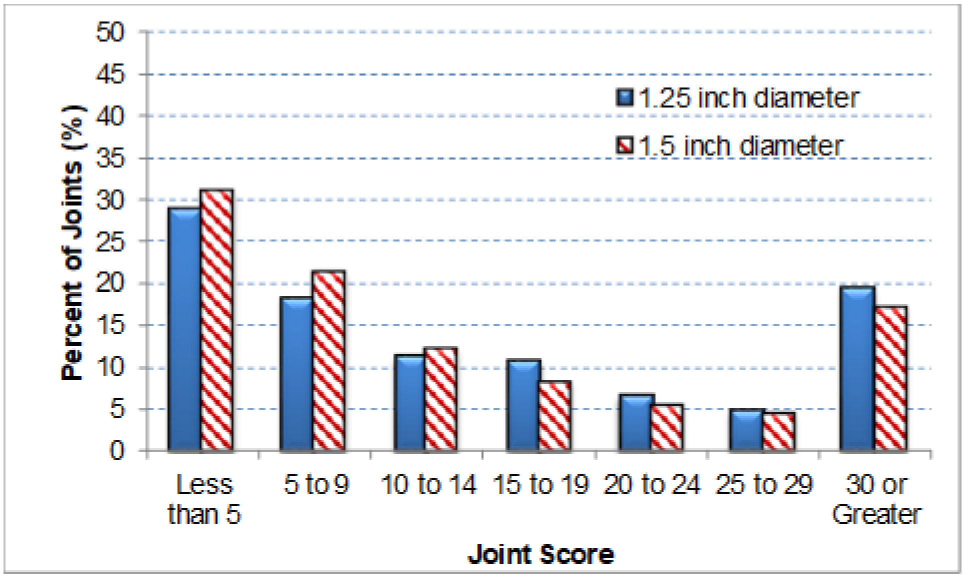
In this study, the original measure for computing the joint score established by Yu and Khazanovich (2005) was used. The original measure did not consider the number of dowels at a transverse joint or slab width because it was meant as a quick first step toward identifying transverse joints for further investigation, not as a measure for acceptance. Since the original measure was developed, some practitioners have redefined the joint score measure by scaling it to the slab width and the number of dowels at the transverse joint.

Table 3. Weighting factors used to determine the joint score (Yu and Khazanovich 2005).

Range of Misalignment (Inches)	Weighting Factor
$0.4 < d < 0.6$	0
$0.6 < d < 0.8$	2
$0.8 < d < 1.0$	4
$1.0 < d < 1.5$	5
$d > 1.5$	10

d = dowel diameter.

The joint score was calculated for all transverse joints tested as part of this study. The distribution of the joint score for 1,824 1.25-inch-diameter and 1,997 1.5-inch-diameter dowels is shown in figure 21. The average and standard deviation of the joint scores for each State is shown in table 4. Since two GPS-3 test sections (one each in Kentucky and Arkansas) were not included in the analysis, table 4 represents one test site (with one GPS-3 test section (South Dakota) or multiple SPS-2 test sections) in each State. Figure 21 shows that 52 percent of transverse joints with 1.5-inch-diameter dowels and 47 percent of transverse joints with 1.25-inch-diameter dowels have joint scores less than 10. However, close to 20 percent of the transverse joints indicate high joint scores (i.e., values greater than 30).



Source: FHWA.

Figure 21. Chart. Joint score distribution for 1.25- and 1.5-inch-diameter dowels from 3,821 transverse joints (23,300 1.5-inch-diameter dowels from 1,997 transverse joints and 21,240 1.25-inch-diameter dowels from 1,824 transverse joints).

Table 4. Average joint score for States with LTPP test sections.

State	Average Joint Score	Joint Score Standard Deviation	Number of 1.25-Inch-Diameter Dowel Transverse Joints	Number of 1.5-Inch-Diameter Dowel Transverse Joints
Arizona	11	12	197	195
Arkansas	18	16	169	202
California	27	20	196	194
Colorado	11	17	199	198
Delaware	19	22	228	219
Iowa	14	17	198	200
Kansas	18	19	198	203
North Carolina	11	15	26	232
North Dakota	11	13	190	194
South Dakota	18	8	25	0
Wisconsin	21	21	198	160

EQUIVALENT DOWEL DIAMETER ANALYSES

NCHRP Report 637 provided a methodology to calculate an equivalent dowel diameter using dowel misalignment (Khazanovich et al. 2009). The equivalent dowel diameter can be used in AASHTOWare Pavement ME Design to model the long-term performance of a pavement test section and compare it with actual field distresses.

The equivalent dowel diameter for the various dowel diameters was calculated for the individual transverse joints of each LTPP test section, and the values are presented in table 5. The average effective percent reduction in dowel diameter from the actual dowel diameter in place is also shown in table 5.

Table 5. Equivalent dowel diameter and effective percent reduction in dowel diameter for States with LTPP test sections.

State	Dowel Diameter (Inches)	Number of Transverse Joints	Equivalent Dowel Diameter (Inches)	Standard Deviation Equivalent Dowel Diameter (Inches)	Effective Reduction in Dowel Diameter (Percent)
Arizona	1.25	197	1.20	0.05	4.2
	1.50	195	1.40	0.09	6.4
Arkansas	1.25	169	1.13	0.18	9.3
	1.50	202	1.42	0.11	5.5
California	1.25	196	0.94	0.26	25.0
	1.50	194	1.25	0.24	17.8
Colorado	1.25	199	1.18	0.27	8.3
	1.50	198	1.44	0.13	4.1
Delaware	1.25	228	1.05	0.36	16.8
	1.50	219	1.46	0.11	2.7
Iowa	1.25	198	1.17	0.18	6.4
	1.50	200	1.43	0.15	4.4
Kansas	1.25	198	1.14	0.20	8.9
	1.50	203	1.44	0.11	4.3
North Carolina	1.25	26	1.20	0.14	3.8
	1.50	232	1.42	0.24	6.1
North Dakota	1.25	190	1.23	0.06	1.8
	1.50	194	1.46	0.07	2.7
South Dakota	1.25	25	1.21	0.03	3.5
Wisconsin	1.25	198	1.15	0.17	8.1
	1.50	160	1.39	0.21	7.2

CHAPTER 5. MIT SCANNING ANALYSES BY STATE

Details of the LTPP test sections in each State, along with results of MIT scanning analyses, are described in this section.

ARIZONA

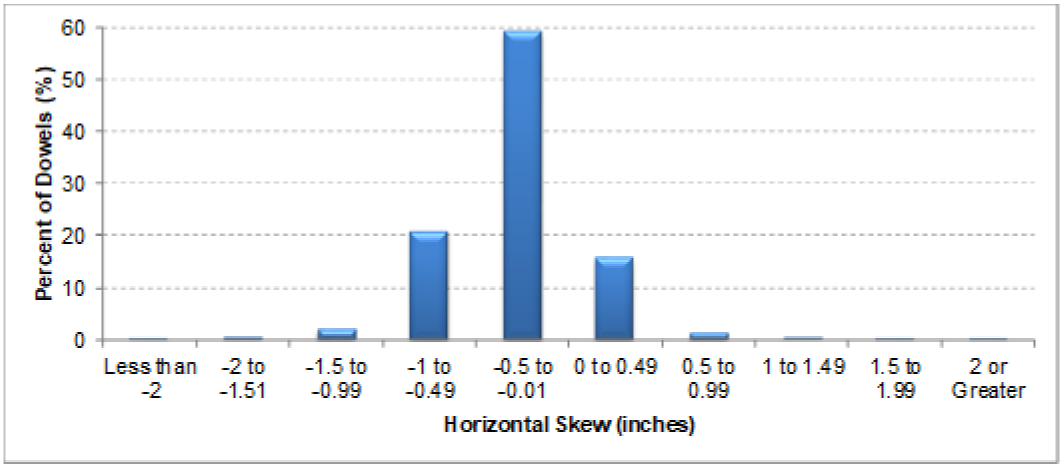
The dowel alignments of 12 SPS-2 test sections in Arizona were evaluated using an MIT scanning device as part of this study. All test sections are in the eastbound direction of I–10 and were constructed in 1993. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 6. Results of MIT scanning analyses are shown in figure 22 through figure 25 and table 7.

Table 6. Details of LTPP test sections in Arizona.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
4_0213	7.9	1.25	12/10/2014	14
4_0214	8.3	1.25	12/09/2014	12
4_0215	11.0	1.50	12/10/2014	12
4_0216	11.2	1.50	12/11/2014	14
4_0217	8.1	1.25	12/10/2014	14
4_0218	8.3	1.25	12/09/2014	12
4_0219	10.8	1.50	12/10/2014	12
4_0220	11.2	1.50	12/09/2014	14
4_0221	8.1	1.25	12/10/2014	14
4_0222	8.6	1.25	12/09/2014	12
4_0223	11.1	1.50	12/11/2014	12
4_0224	10.6	1.50	12/11/2014	14

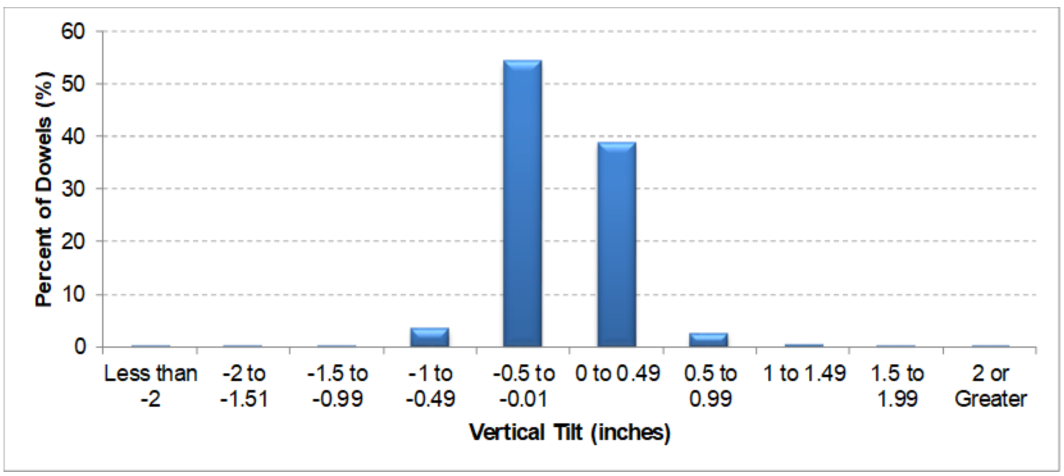
MIT scanning results from Arizona show that approximately 75, 93, and 54 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 45 percent of dowels have greater than 1 inch magnitude of longitudinal translation.

The joint score distribution and equivalent dowel diameter are shown in figure 26 and table 8. Approximately 63 percent of transverse joints have a joint score less than 10, while 10 percent of transverse joints have a joint score greater than 30. Figure 27 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in Arizona. Whereas the joint score considers only vertical tilt and horizontal skew, the equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



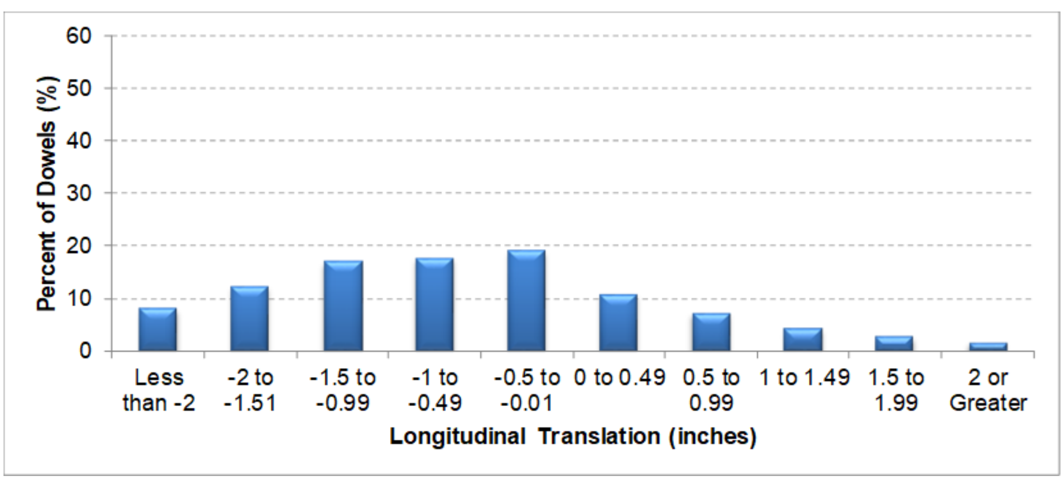
Source: FHWA.

Figure 22. Chart. Horizontal skew distribution for LTPP test sections in Arizona.



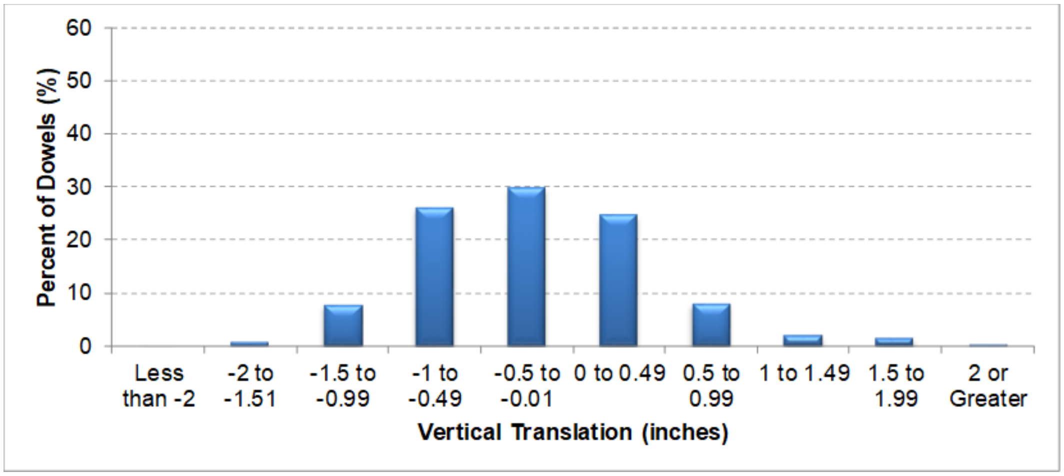
Source: FHWA.

Figure 23. Chart. Vertical tilt distribution for LTPP test sections in Arizona.



Source: FHWA.

Figure 24. Chart. Longitudinal translation distribution for LTPP test sections in Arizona.

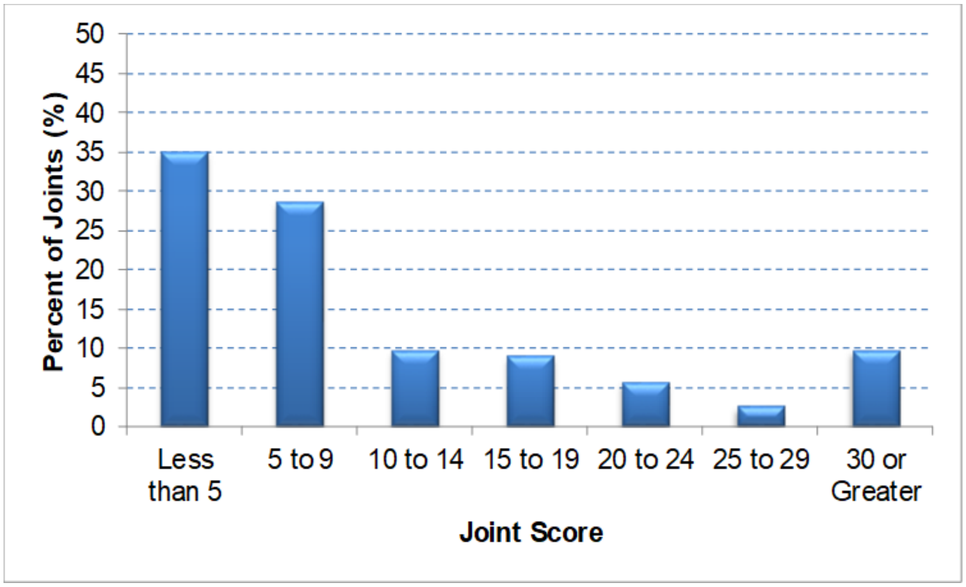


Source: FHWA.

Figure 25. Chart. Vertical translation distribution for LTPP test sections in Arizona.

Table 7. Dowel misalignment summary for LTPP test sections in Arizona.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
4_0213	0.27	0.29	0.22	0.17	0.97	0.72	0.31	0.25
4_0214	0.44	0.51	0.19	0.22	0.87	0.59	0.42	0.27
4_0215	0.50	0.35	0.29	0.19	1.28	0.75	0.64	0.43
4_0216	0.50	0.49	0.38	0.25	1.56	0.71	0.64	0.46
4_0217	0.24	0.19	0.17	0.22	0.72	0.71	0.22	0.20
4_0218	0.31	0.25	0.15	0.12	0.80	0.54	0.46	0.31
4_0219	0.32	0.24	0.16	0.17	0.77	0.56	0.30	0.26
4_0220	0.27	0.25	0.28	0.20	0.94	0.63	0.91	0.40
4_0221	0.34	0.32	0.22	0.43	0.90	0.69	0.42	0.35
4_0222	0.61	0.34	0.16	0.16	0.66	0.44	0.39	0.29
4_0223	0.40	0.42	0.27	0.28	1.41	0.77	0.52	0.42
4_0224	0.29	0.26	0.27	0.40	1.22	0.69	0.89	0.38

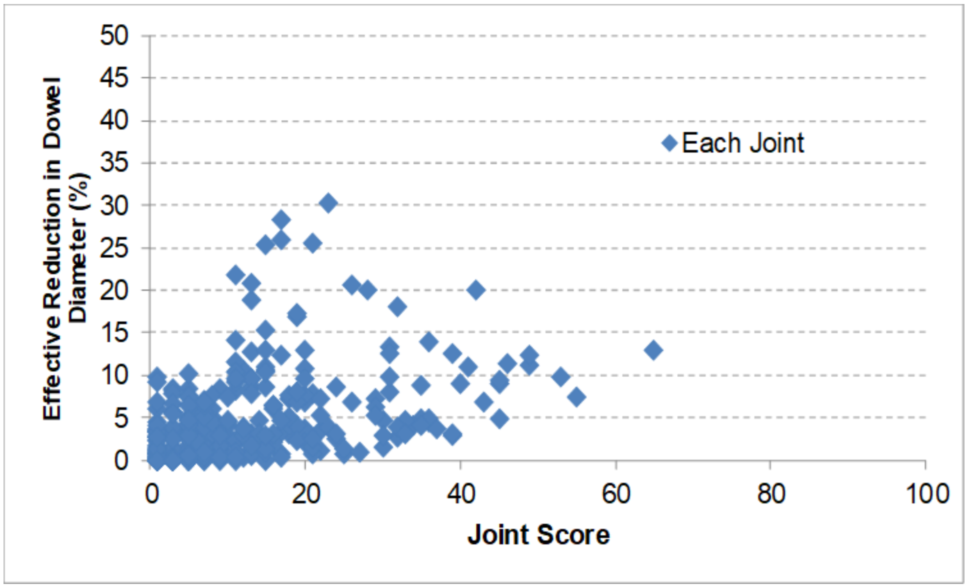


Source: FHWA.

Figure 26. Chart. Joint score distribution for LTPP test sections in Arizona.

Table 8. Joint score and equivalent dowel diameter for LTPP test sections in Arizona.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
4_0213	7	8	7.9	1.25	1.21	0.07	1.5
4_0214	9	7	8.3	1.25	1.18	0.21	6.6
4_0215	18	16	11.0	1.50	1.43	0.06	8.6
4_0216	22	12	11.2	1.50	1.39	0.21	4.8
4_0217	5	12	8.1	1.25	1.24	0.04	0.5
4_0218	6	7	8.3	1.25	1.23	0.02	6.4
4_0219	6	6	10.8	1.50	1.48	0.03	5.6
4_0220	8	8	11.2	1.50	1.42	0.06	4.3
4_0221	9	9	8.1	1.25	1.19	0.09	2.6
4_0222	20	13	8.6	1.25	1.17	0.08	7.9
4_0223	11	12	11.1	1.50	1.42	0.16	9.0
4_0224	7	8	10.6	1.50	1.38	0.18	6.5



Source: FHWA.

Figure 27. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in Arizona.

ARKANSAS

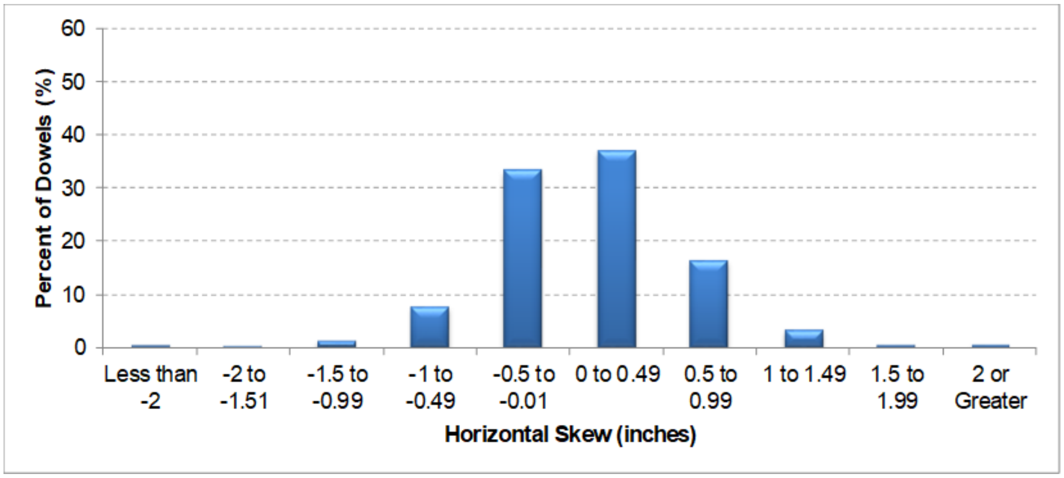
The dowel alignments of 12 SPS-2 test sections in Arkansas were evaluated using an MIT scanning device as part of this study. All test sections are in the westbound direction of I–30 and were constructed in 1995. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 9. Results of the MIT scanning analyses are shown in figure 28 through figure 31 and table 10.

Table 9. Details of LTPP test sections in Arkansas.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
5_0214	8.4	1.25	09/29/2014	12
5_0215	11.5	1.50	09/29/2014	12
5_0216	11.0	1.50	10/01/2014	14
5_0217	8.3	1.25	09/30/2014	14
5_0218	8.2	1.25	09/30/2014	12
5_0219	11.1	1.50	09/30/2014	12
5_0220	10.7	1.50	09/30/2014	14
5_0221	8.3	1.25	10/01/2014	14
5_0222	8.3	1.25	09/29/2014	12
5_0223	10.9	1.50	09/29/2014	12
5_0224	10.9	1.50	09/30/2014	14

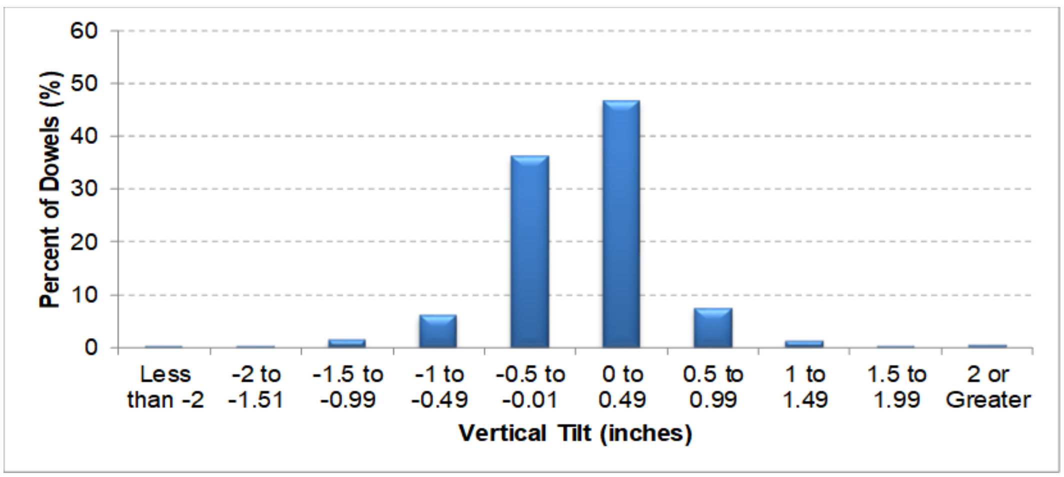
MIT scanning results from Arkansas show that approximately 70, 83, and 62 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and only approximately 48 percent of dowels have side shift ranging between 0 and ±0.5 inches.

The joint score distribution and equivalent dowel diameter are shown in figure 32 and table 11. Approximately 40 percent of transverse joints have a joint score less than 10, while 17 percent of transverse joints have a joint score greater than 30. Figure 33 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in Arkansas. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



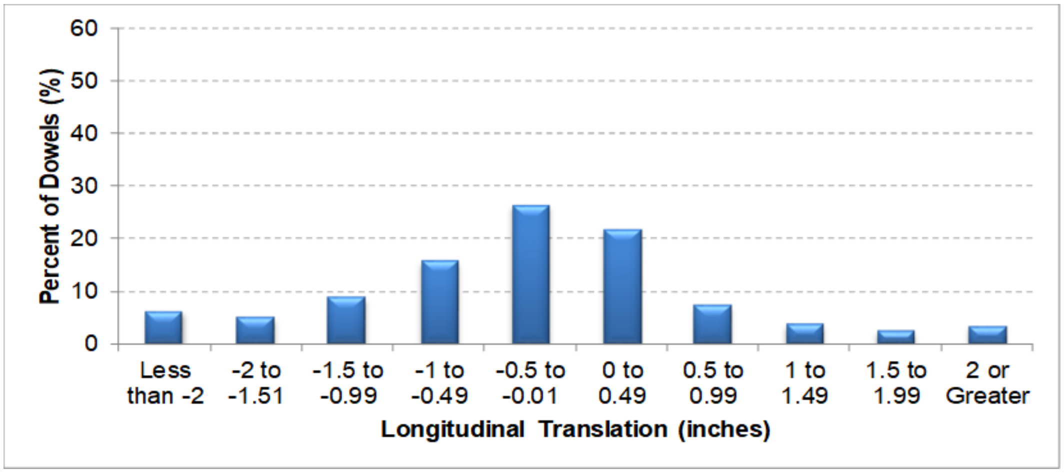
Source: FHWA.

Figure 28. Chart. Horizontal skew distribution for LTPP test sections in Arkansas.



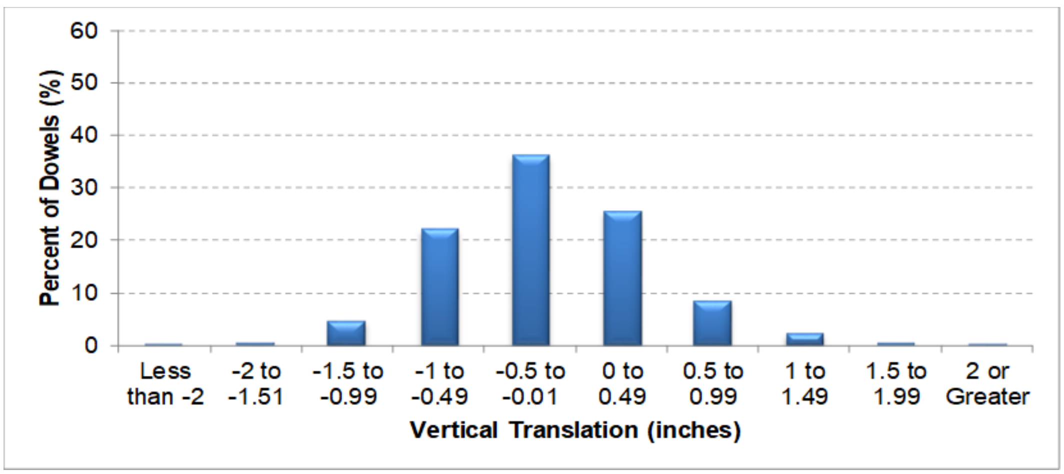
Source: FHWA.

Figure 29. Chart. Vertical tilt distribution for LTPP test sections in Arkansas.



Source: FHWA.

Figure 30. Chart. Longitudinal translation distribution for LTPP test sections in Arkansas.

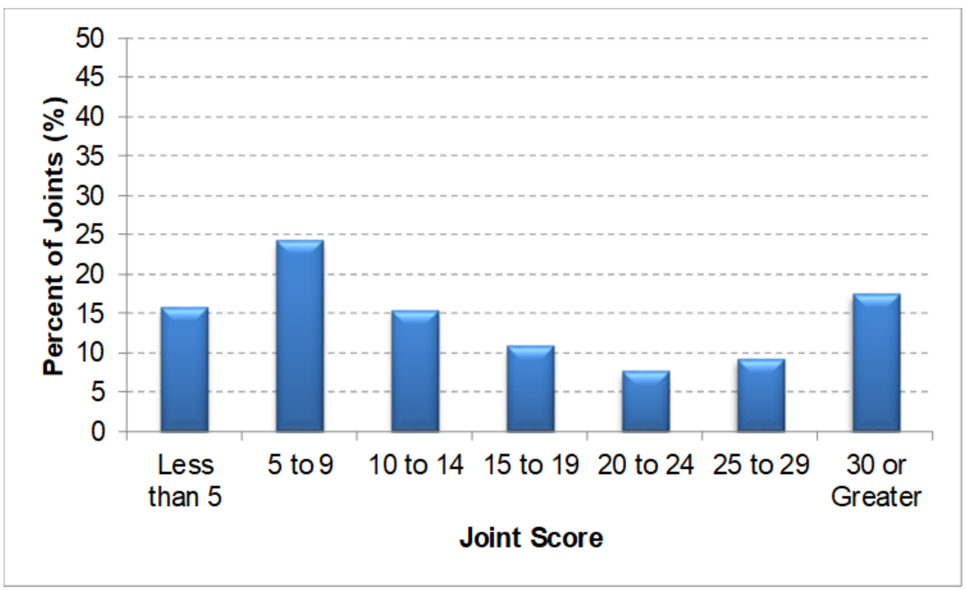


Source: FHWA.

Figure 31. Chart. Vertical translation distribution for LTPP test sections in Arkansas.

Table 10. Dowel misalignment summary for LTPP test sections in Arkansas.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
5_0214	0.53	0.46	0.38	0.36	0.92	0.99	0.50	0.30
5_0215	0.32	0.35	0.27	0.27	0.75	0.60	0.69	0.37
5_0216	0.43	0.40	0.35	0.34	0.67	0.59	0.54	0.42
5_0217	0.56	0.53	0.40	0.61	1.16	1.68	0.44	0.52
5_0218	0.59	1.01	0.49	0.98	1.19	1.50	0.73	0.58
5_0219	0.43	0.34	0.32	0.29	0.93	0.83	0.36	0.37
5_0220	0.36	0.58	0.28	0.58	0.82	0.81	0.55	0.36
5_0221	0.31	0.26	0.30	0.31	0.40	0.58	0.33	0.25
5_0222	0.32	0.26	0.22	0.23	0.45	0.65	0.22	0.20
5_0223	0.32	0.27	0.27	0.31	1.09	1.02	0.44	0.25
5_0224	0.37	0.30	0.25	0.27	0.81	0.68	0.32	0.28

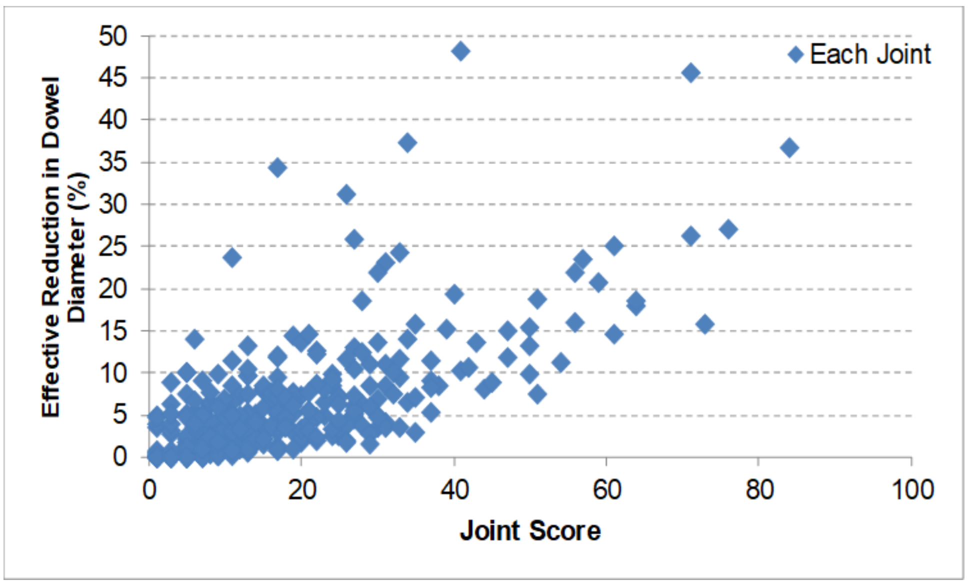


Source: FHWA.

Figure 32. Chart. Joint score distribution for LTPP test sections in Arkansas.

Table 11. Joint score and equivalent dowel diameter for LTPP test sections in Arkansas.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
5_0214	27	15	8.4	1.25	1.14	0.07	8.4
5_0215	9	10	11.5	1.50	1.40	0.04	6.4
5_0216	21	15	11.0	1.50	1.42	0.09	5.6
5_0217	33	18	8.3	1.25	1.15	0.19	8.1
5_0218	27	24	8.2	1.25	0.97	0.31	22.6
5_0219	19	12	11.1	1.50	1.41	0.04	5.7
5_0220	13	14	10.7	1.50	1.39	0.25	7.1
5_0221	11	11	8.3	1.25	1.22	0.03	2.5
5_0222	9	11	8.3	1.25	1.18	0.03	5.3
5_0223	11	9	10.9	1.50	1.41	0.04	6.0
5_0224	14	9	10.9	1.50	1.47	0.05	2.1



Source: FHWA.

Figure 33. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in Arkansas.

CALIFORNIA

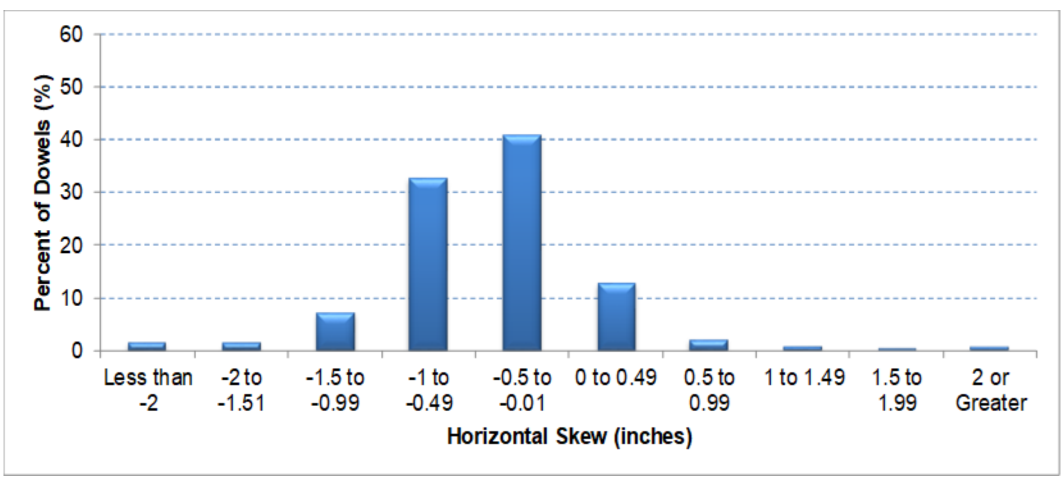
The dowel alignments of 12 SPS-2 test sections in California were evaluated using an MIT scanning device as part of this study. All test sections are in the northbound direction of SR 99 and were constructed in 1999. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 12. Results of the MIT scanning analyses are shown in figure 34 through figure 37 and table 13.

Table 12. Details of LTPP test sections in California.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
6_0201	8.3	1.50	10/22/2014	12
6_0202	8.0	1.25	10/21/2014	13
6_0203	11.4	1.50	10/20/2014	13
6_0204	11.1	1.25	10/21/2014	12
6_0205	8.2	1.50	10/21/2014	12
6_0206	8.0	1.25	10/20/2014	13
6_0207	11.0	1.50	10/20/2014	13
6_0208	10.7	1.25	10/21/2014	12
6_0209	8.4	1.50	10/21/2014	12
6_0210	8.6	1.25	10/21/2014	13
6_0211	12.1	1.50	10/20/2014	13
6_0212	11.1	1.25	10/21/2014	12

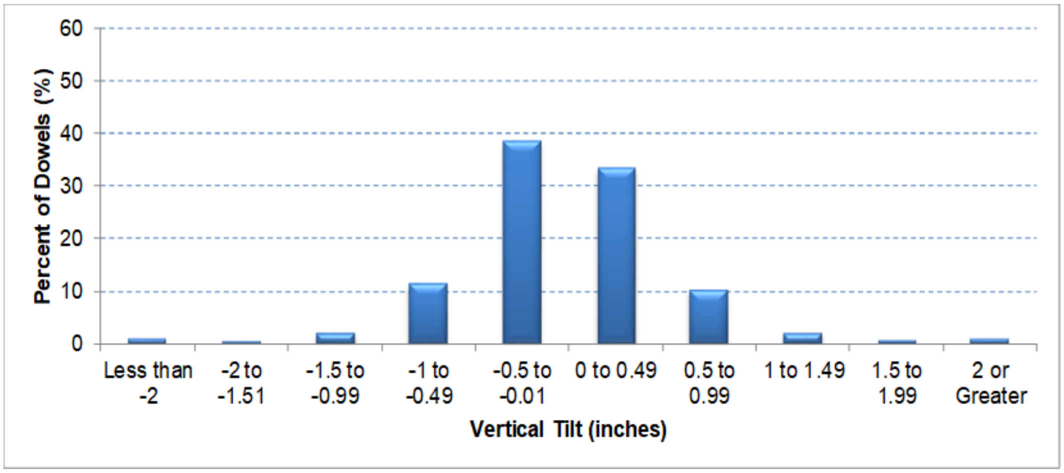
MIT scanning results from California show that approximately 53, 71, and 23 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 40 percent of dowels have greater than 2 inches (absolute) longitudinal translation.

The joint score distribution and equivalent dowel diameter are shown in figure 38 and table 14. Approximately 20 percent of transverse joints have a joint score less than 10, while 38 percent of transverse joints have a joint score greater than 30. Figure 39 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in California. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



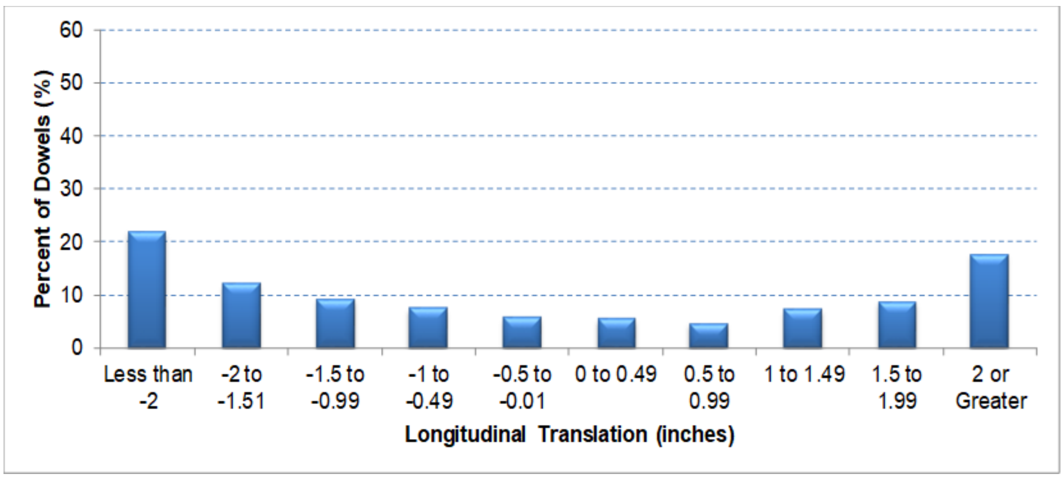
Source: FHWA.

Figure 34. Chart. Horizontal skew distribution for LTPP test sections in California.



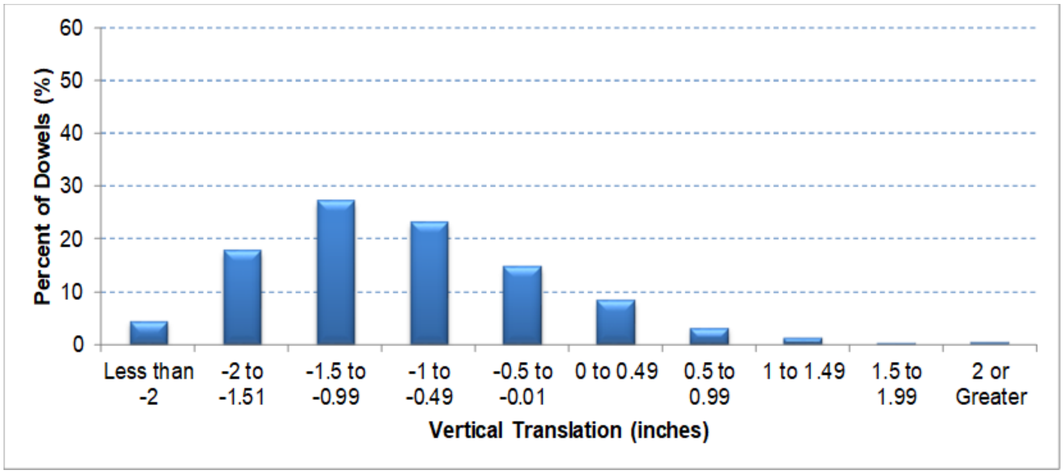
Source: FHWA.

Figure 35. Chart. Vertical tilt distribution for LTPP test sections in California.



Source: FHWA.

Figure 36. Chart. Longitudinal translation distribution for LTPP test sections in California.

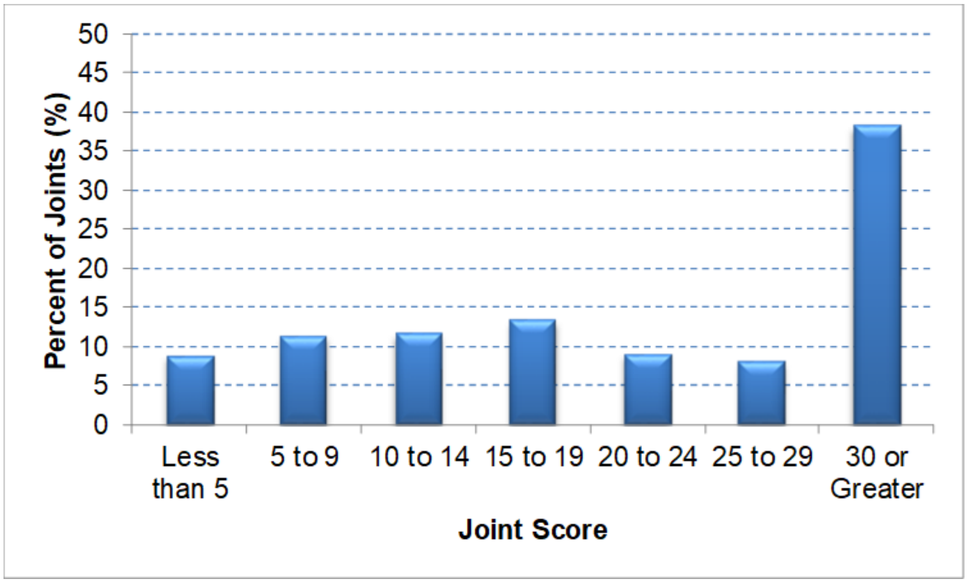


Source: FHWA.

Figure 37. Chart. Vertical translation distribution for LTPP test sections in California.

Table 13. Dowel misalignment summary for LTPP test sections in California.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
6_0201	0.90	0.54	0.47	0.68	2.18	1.29	0.78	0.57
6_0202	0.53	0.30	0.23	0.24	1.69	0.83	1.14	0.42
6_0203	0.47	0.55	0.48	0.51	1.92	2.20	1.33	0.90
6_0204	0.59	0.83	0.54	0.51	1.77	1.03	1.13	0.58
6_0205	0.57	0.43	0.33	0.60	1.60	1.03	0.68	0.49
6_0206	0.62	0.55	0.40	0.64	1.76	1.07	1.07	0.53
6_0207	0.38	0.60	0.53	0.45	2.15	1.13	0.84	0.72
6_0208	0.54	0.82	0.46	0.43	1.98	0.99	1.16	1.43
6_0209	0.47	0.34	0.36	0.48	1.49	1.56	0.71	1.37
6_0210	0.53	0.36	0.32	0.30	1.67	1.11	0.80	0.53
6_0211	0.83	1.64	0.62	0.86	2.00	0.96	1.37	0.68
6_0212	0.62	0.91	0.53	0.67	1.64	0.87	1.38	0.59

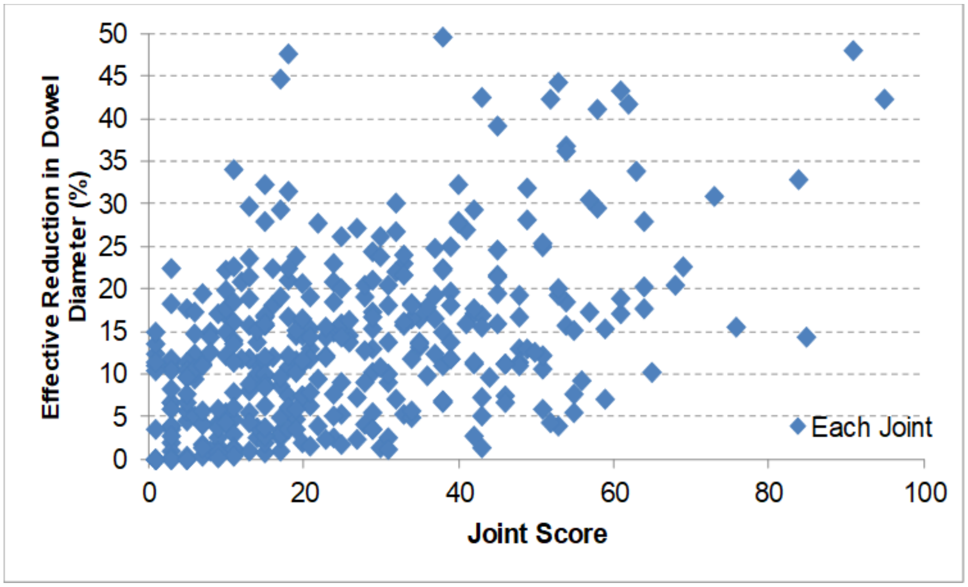


Source: FHWA.

Figure 38. Chart. Joint score distribution for LTPP test sections in California.

Table 14. Joint score and equivalent dowel diameter for LTPP test sections in California.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
6_0201	44	25	8.3	1.50	1.14	0.23	24.1
6_0202	20	17	8.0	1.25	0.80	0.27	35.7
6_0203	28	18	11.4	1.50	1.22	0.13	18.4
6_0204	27	18	11.1	1.25	1.00	0.16	19.7
6_0205	23	20	8.2	1.50	1.29	0.22	13.7
6_0206	29	16	8.0	1.25	0.79	0.36	36.4
6_0207	23	19	11.0	1.50	1.31	0.15	12.7
6_0208	22	17	10.7	1.25	1.03	0.16	17.4
6_0209	21	18	8.4	1.50	1.29	0.20	13.8
6_0210	23	20	8.6	1.25	1.05	0.13	15.9
6_0211	37	26	12.1	1.50	1.21	0.38	19.4
6_0212	27	17	11.1	1.25	0.96	0.24	23.1



Source: FHWA.

Figure 39. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in California.

COLORADO

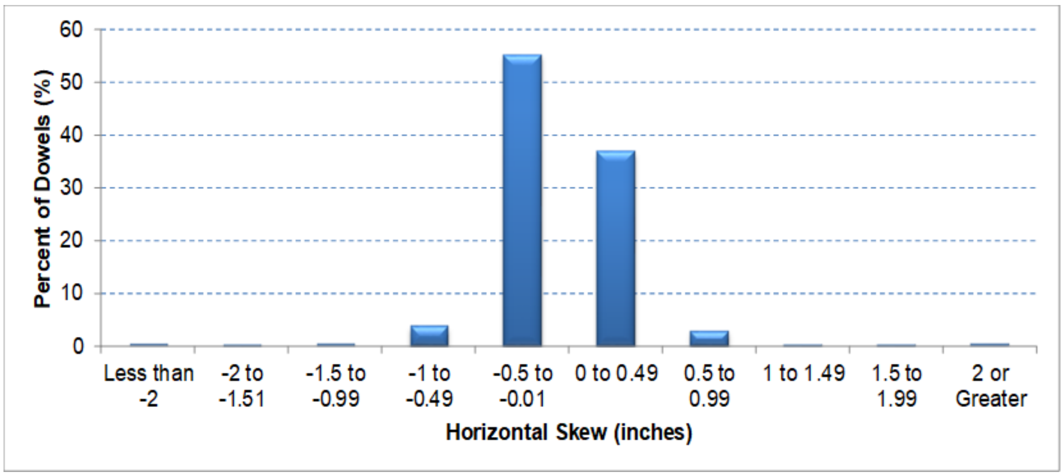
The dowel alignments of 12 SPS-2 test sections in Colorado were evaluated using an MIT scanning device as part of this study. All test sections are in the eastbound direction of I–76 and were constructed in 1993. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 15. Results of the MIT scanning analyses are shown in figure 40 through figure 43 and table 16.

Table 15. Details of LTPP test sections in Colorado.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
8_0213	8.6	1.25	09/10/2014	14
8_0214	8.4	1.25	09/10/2014	12
8_0215	11.5	1.50	09/11/2014	12
8_0216	11.9	1.50	09/10/2014	14
8_0217	8.6	1.25	09/11/2014	14
8_0218	7.6	1.25	09/11/2014	12
8_0219	9.9	1.50	09/11/2014	12
8_0220	11.2	1.50	09/12/2014	14
8_0221	8.3	1.25	09/12/2014	14
8_0222	8.5	1.25	09/12/2014	12
8_0223	11.7	1.50	09/12/2014	12
8_0224	11.6	1.50	09/12/2014	14

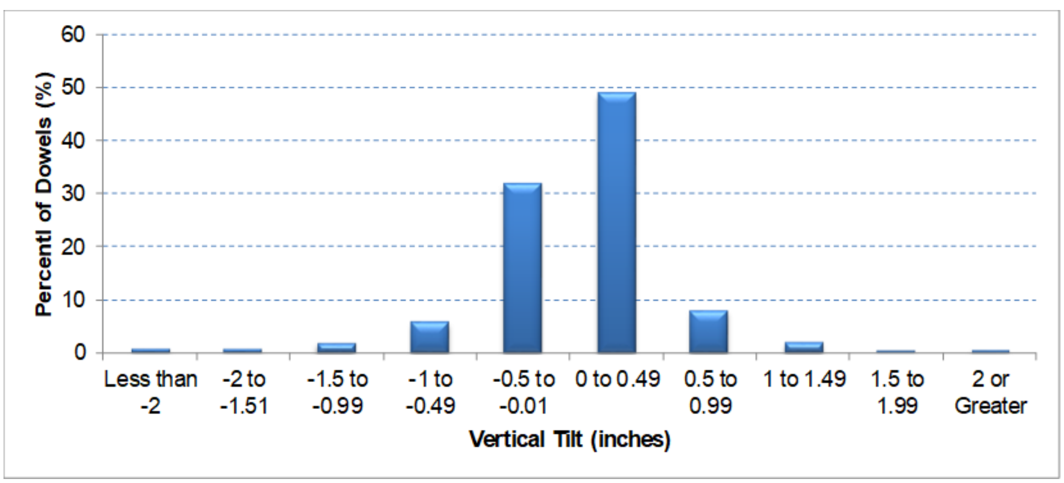
MIT scanning results from Colorado show that approximately 92, 81, and 79 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 41 percent of dowels have longitudinal translation ranging between 0 and ±0.5 inches.

The joint score distribution and equivalent dowel diameter are shown in figure 44 and table 17. Approximately 65 percent of transverse joints have a joint score less than 10, while 12 percent of transverse joints have a joint score greater than 30. Figure 45 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in Colorado. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



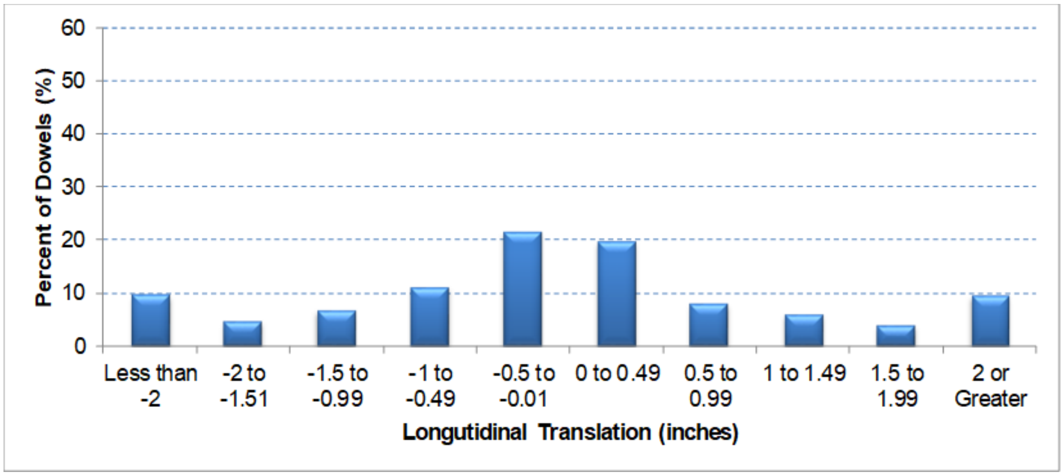
Source: FHWA.

Figure 40. Chart. Horizontal skew distribution for LTPP test sections in Colorado.



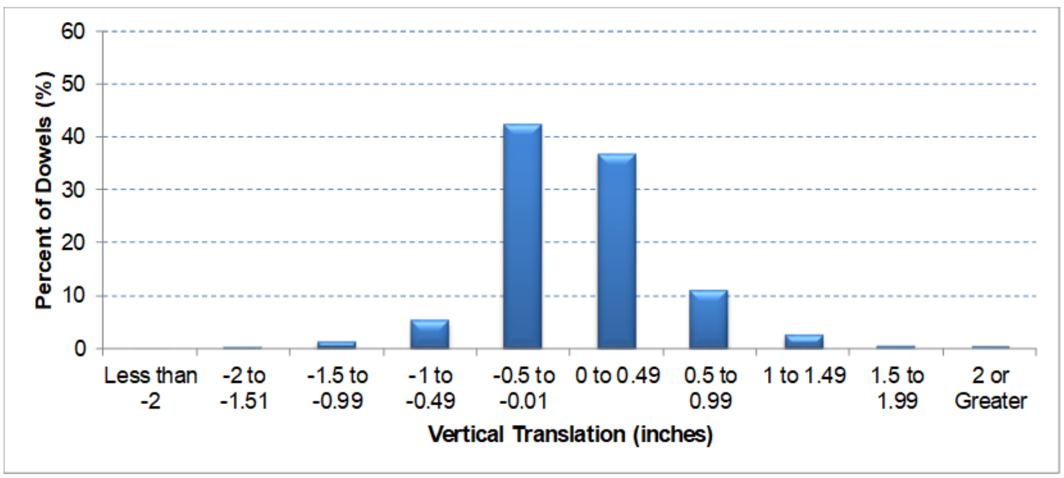
Source: FHWA.

Figure 41. Chart. Vertical tilt distribution for LTPP test sections in Colorado.



Source: FHWA.

Figure 42. Chart. Longitudinal translation distribution for LTPP test sections in Colorado.

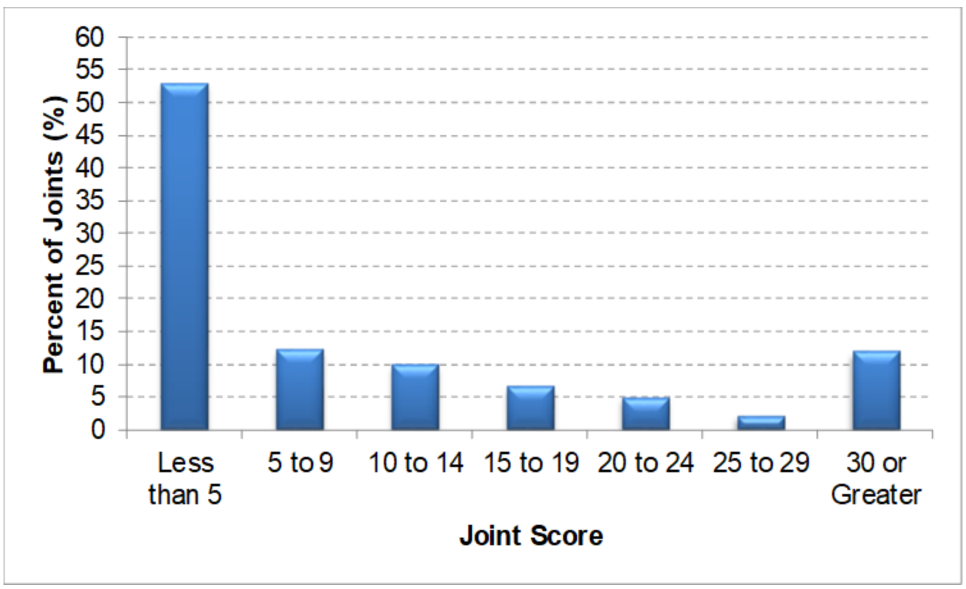


Source: FHWA.

Figure 43. Chart. Vertical translation distribution for LTPP test sections in Colorado.

Table 16. Dowel misalignment summary for LTPP test sections in Colorado.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
8_0213	0.12	0.09	0.16	0.12	0.36	0.37	0.29	0.26
8_0214	0.24	0.29	0.29	0.26	0.75	0.62	0.18	0.13
8_0215	0.30	0.77	0.33	0.61	0.79	0.91	0.32	0.27
8_0216	0.16	0.25	0.18	0.23	0.55	0.72	0.19	0.15
8_0217	0.44	0.67	0.61	0.81	1.85	2.08	0.36	0.54
8_0218	0.32	0.37	0.47	0.72	1.48	1.58	0.35	0.73
8_0219	0.25	0.40	0.60	0.83	1.81	1.56	0.74	0.60
8_0220	0.21	0.19	0.25	0.24	1.18	0.93	0.19	0.14
8_0221	0.21	0.18	0.34	0.30	1.70	1.11	0.42	0.33
8_0222	0.19	0.15	0.25	0.23	0.63	0.76	0.34	0.19
8_0223	0.21	0.28	0.36	0.32	1.30	1.14	0.22	0.27
8_0224	0.16	0.29	0.25	0.50	1.06	1.18	0.62	0.44

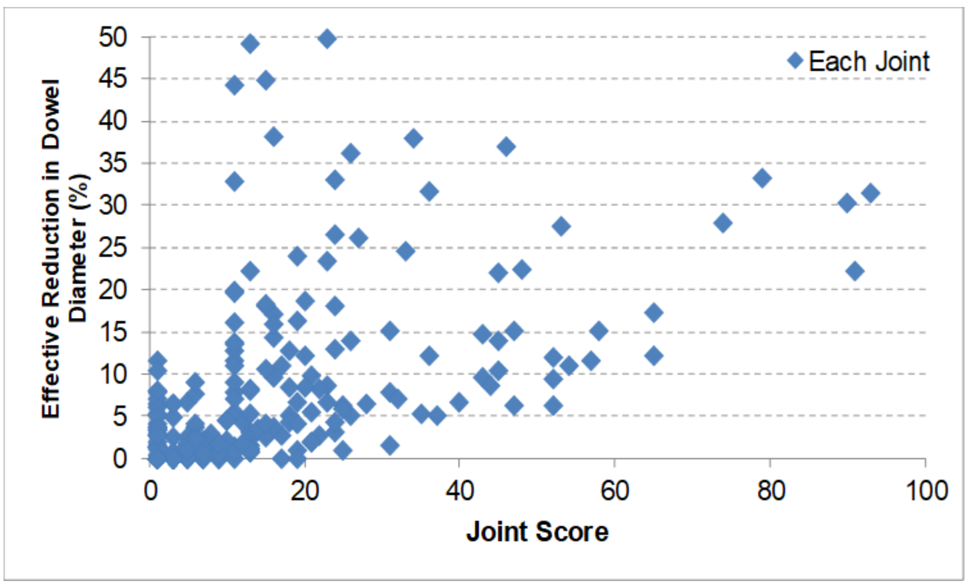


Source: FHWA.

Figure 44. Chart. Joint score distribution for LTPP test sections in Colorado.

Table 17. Joint score and equivalent dowel diameter for LTPP test sections in Colorado.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
8_0213	1	0	8.6	1.25	1.24	0.21	0.6
8_0214	9	9	8.4	1.25	1.22	0.05	2.2
8_0215	12	14	11.5	1.50	1.45	0.12	3.6
8_0216	5	7	11.9	1.50	1.48	0.07	1.2
8_0217	29	26	8.6	1.25	1.09	0.42	12.8
8_0218	21	26	7.6	1.25	1.05	0.42	16.0
8_0219	23	23	9.9	1.50	1.32	0.21	12.3
8_0220	6	7	11.2	1.50	1.48	0.04	1.2
8_0221	11	15	8.3	1.25	1.19	0.07	4.9
8_0222	4	8	8.5	1.25	1.24	0.02	0.6
8_0223	10	9	11.7	1.50	1.47	0.07	2.0
8_0224	9	19	11.6	1.50	1.43	0.12	4.8



Source: FHWA.

Figure 45. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in Colorado.

DELAWARE

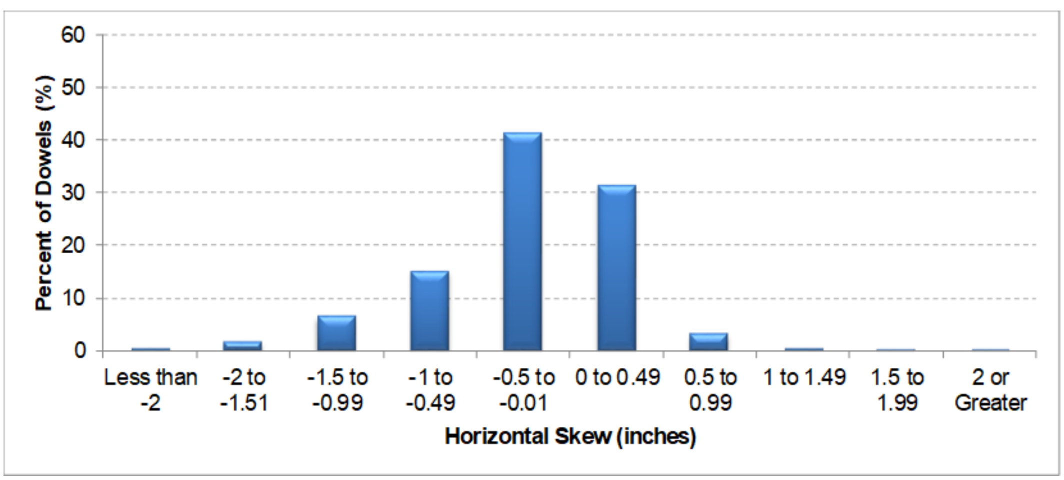
The dowel alignments of 14 SPS-2 test sections in Delaware were evaluated using an MIT scanning device as part of this study. All test sections are in the southbound direction of US 113 and were constructed in 1992. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 18. Results of the MIT scanning analyses are shown in figure 46 through figure 49 and table 19.

Table 18. Details of LTPP test sections in Delaware.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
10_0201	8.3	1.25	05/28/2015	12
10_0202	8.8	1.25	05/27/2015	14
10_0203	11.7	1.50	05/28/2015	14
10_0204	11.0	1.50	05/26/2015	12
10_0205	9.2	1.25	05/28/2015	12
10_0206	8.9	1.25	05/27/2015	14
10_0207	11.3	1.50	05/27/2015	14
10_0208	12.1	1.50	05/26/2015	12
10_0209	8.2	1.25	05/28/2015	12
10_0210	8.3	1.25	05/27/2015	14
10_0211	11.8	1.50	05/28/2015	14
10_0212	12.4	1.50	05/26/2015	12
10_0259	10.2	1.50	05/26/2015	12
10_0260	10.2	1.25	05/28/2015	12

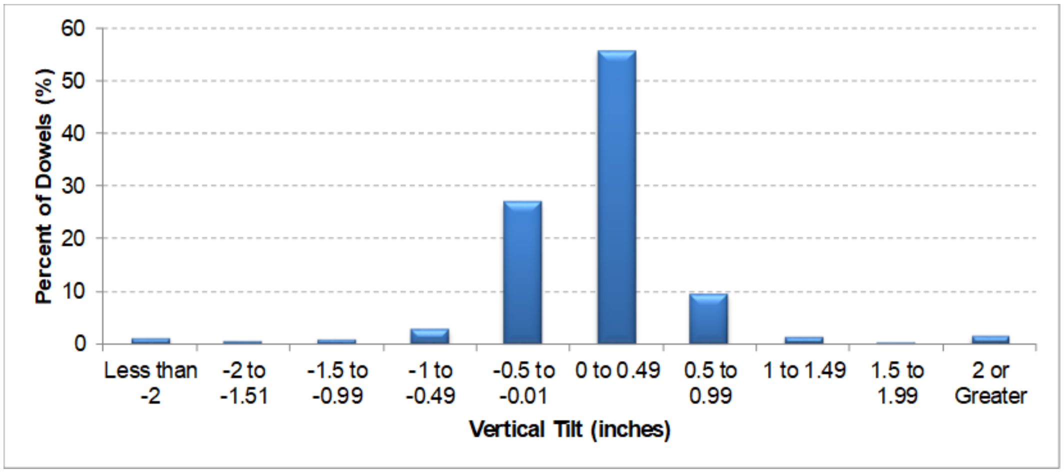
MIT scanning results from Delaware show that approximately 72, 83, and 59 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 59 percent of dowels have longitudinal translation ranging between 0 and ±0.5 inches.

The joint score distribution and equivalent dowel diameter are shown in figure 50 and table 20. Approximately 50 percent of transverse joints have a joint score less than 10, while 25 percent of transverse joints have a joint score greater than 30. Figure 51 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in Delaware. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



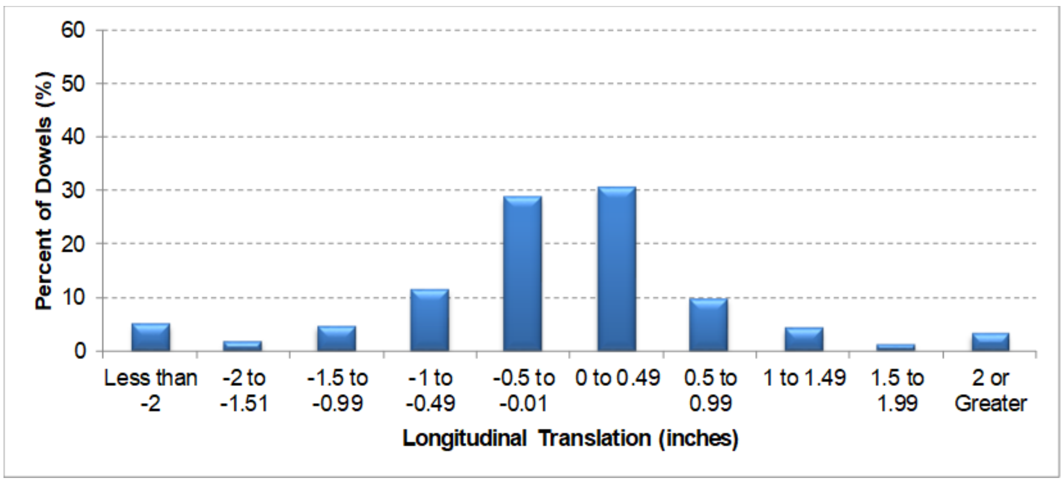
Source: FHWA.

Figure 46. Chart. Horizontal skew distribution for LTPP test sections in Delaware.



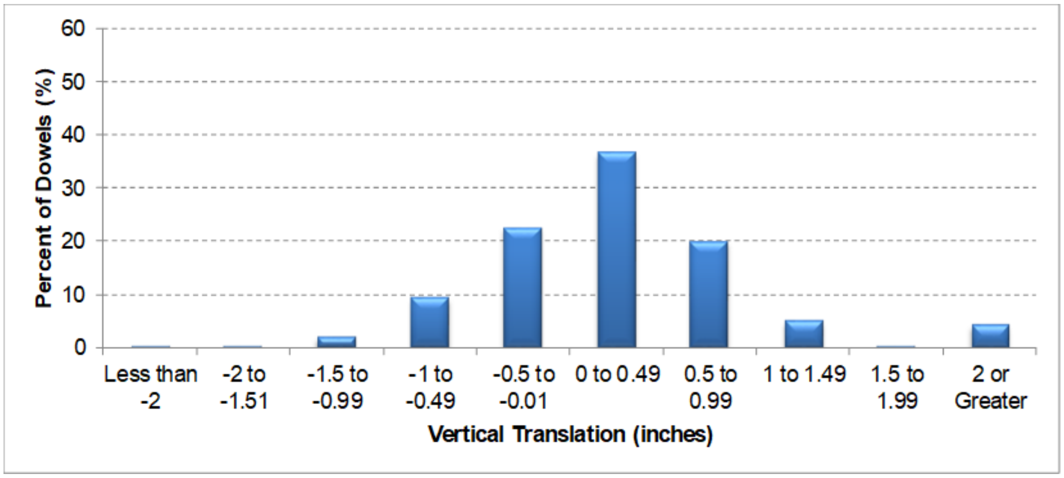
Source: FHWA.

Figure 47. Chart. Vertical tilt distribution for LTPP test sections in Delaware.



Source: FHWA.

Figure 48. Chart. Longitudinal translation distribution for LTPP test sections in Delaware.

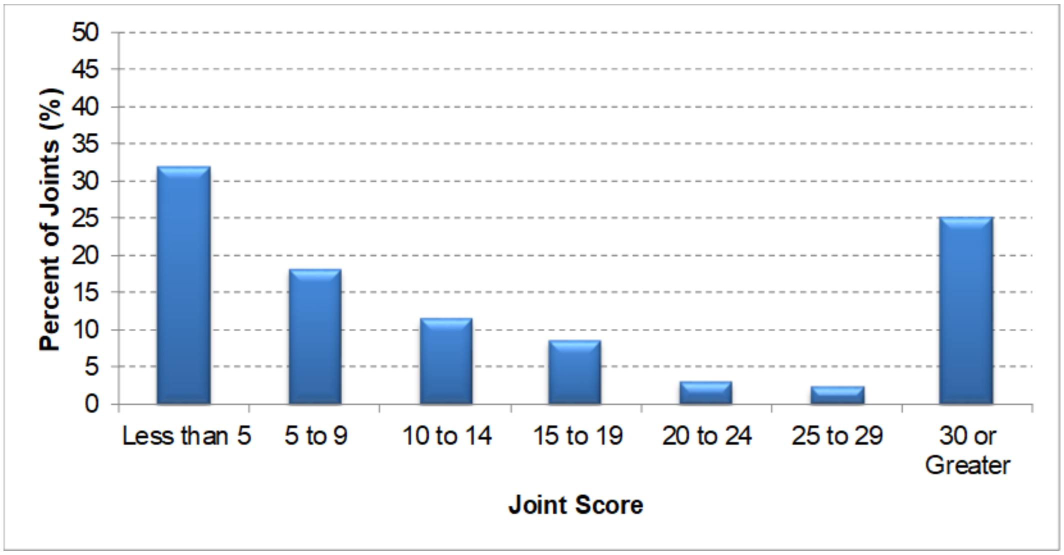


Source: FHWA.

Figure 49. Chart. Vertical translation distribution for LTPP test sections in Delaware.

Table 19. Dowel misalignment summary for LTPP test sections in Delaware.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
10_0201	0.94	0.45	0.25	0.21	0.52	0.42	0.60	0.33
10_0202	0.56	0.41	0.29	0.30	0.49	0.44	0.47	0.29
10_0203	0.24	0.19	0.26	0.23	0.45	0.42	0.26	0.23
10_0204	0.23	0.20	0.27	0.26	0.66	1.13	0.41	0.44
10_0205	0.43	0.41	0.23	0.30	0.48	0.55	0.26	0.23
10_0206	0.55	0.45	0.29	0.35	0.43	0.40	0.69	0.38
10_0207	0.26	0.73	0.26	0.22	0.49	0.49	0.28	0.25
10_0208	0.27	0.37	0.33	0.42	0.72	0.89	0.55	0.45
10_0209	0.74	0.95	0.23	0.19	0.50	0.52	0.62	0.33
10_0210	0.22	0.16	0.19	0.30	0.54	0.52	0.37	0.30
10_0211	0.34	0.29	0.32	0.25	0.57	0.48	0.26	0.21
10_0212	0.30	0.26	0.36	0.30	0.71	0.79	0.55	0.34
10_0259	0.28	0.41	0.32	0.26	0.27	0.44	0.48	0.33
10_0260	0.74	0.93	2.37	2.71	9.64	12.43	3.95	2.70

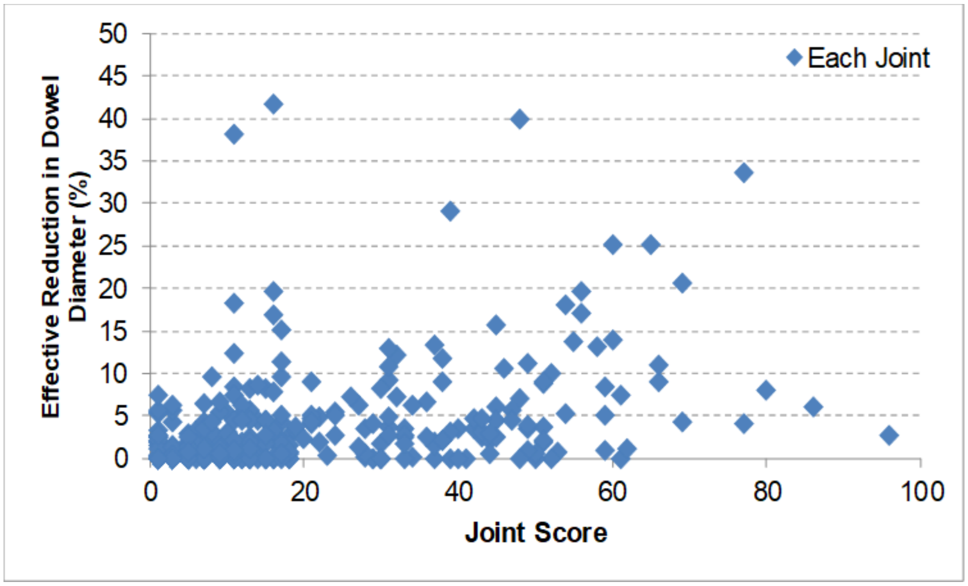


Source: FHWA.

Figure 50. Chart. Joint score distribution for LTPP test sections in Delaware.

Table 20. Joint score and equivalent dowel diameter for LTPP test sections in Delaware.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
10_0201	47	20	8.3	1.25	1.07	0.11	14.7
10_0202	24	16	8.8	1.25	1.19	0.06	5.1
10_0203	7	10	11.7	1.50	1.49	0.02	0.7
10_0204	8	10	11.0	1.50	1.48	0.03	1.1
10_0205	9	13	9.2	1.25	1.22	0.06	2.2
10_0206	26	17	8.9	1.25	1.10	0.17	12.0
10_0207	7	9	11.3	1.50	1.47	0.07	1.7
10_0208	11	15	12.1	1.50	1.42	0.17	5.5
10_0209	30	18	8.2	1.25	1.14	0.10	8.9
10_0210	4	7	8.3	1.25	1.23	0.05	1.6
10_0211	13	15	11.8	1.50	1.48	0.04	1.4
10_0212	13	15	12.4	1.50	1.47	0.05	2.2
10_0259	9	8	10.2	1.50	1.41	0.19	6.0
10_0260	68	22	10.2	1.25	0.30	0.43	76.0



Source: FHWA.

Figure 51. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in Delaware.

IOWA

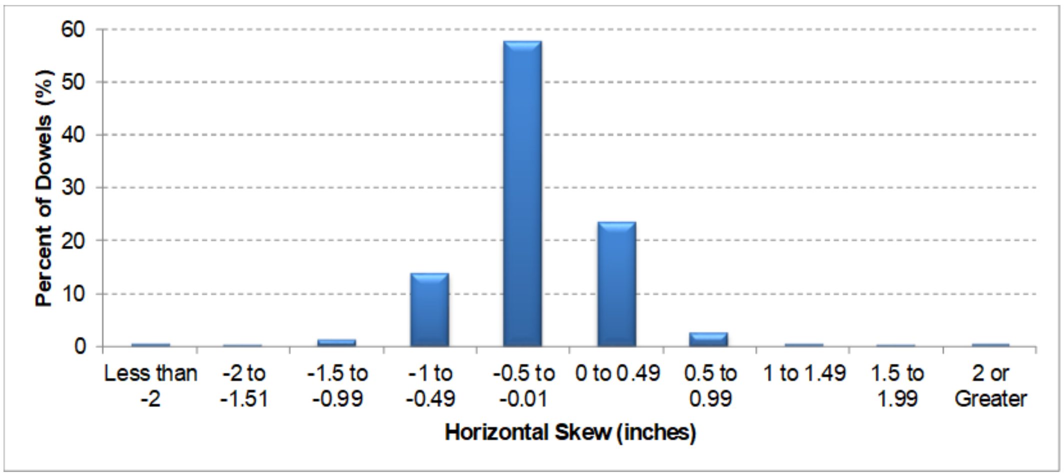
The dowel alignments of 12 SPS-2 test sections in Iowa were evaluated using an MIT scanning device as part of this study. All test sections are in the northbound direction of US 65 and were constructed in 1994. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 21. Results of the MIT scanning analyses are shown in figure 52 through figure 55 and table 22.

Table 21. Details of LTPP test sections in Iowa.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
19_0213	8.9	1.25	11/19/2014	14
19_0214	8.4	1.25	11/19/2014	12
19_0215	11.4	1.50	11/18/2014	12
19_0216	11.4	1.50	11/18/2014	12
19_0217	8.1	1.25	11/18/2014	14
19_0218	8.4	1.25	11/18/2014	12
19_0219	11.5	1.50	11/17/2014	14
19_0220	11.5	1.50	11/18/2014	14
19_0221	9.4	1.25	11/20/2014	14
19_0222	8.3	1.25	11/20/2014	12
19_0223	12.5	1.50	11/20/2014	12
19_0224	10.0	1.50	11/20/2014	14

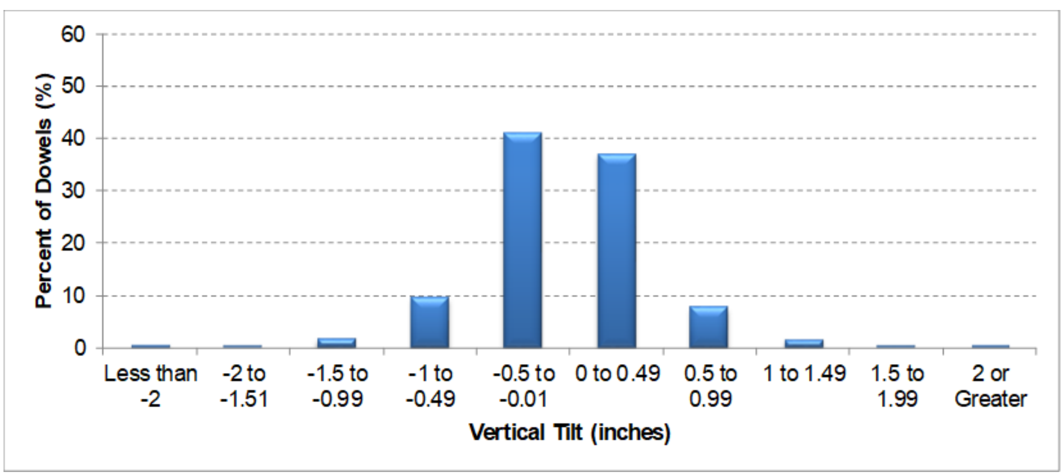
MIT scanning results from Iowa show that approximately 81, 78, and 76 percent of dowels have misalignments ranging between 0 and ± 0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 31 percent of dowels have longitudinal translation ranging between 0 and ±1.0 inch.

The joint score distribution and equivalent dowel diameter are shown in figure 56 and table 23. Approximately 55 percent of transverse joints have a joint score less than 10, while 14 percent of transverse joints have a joint score greater than 30. Figure 57 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in Iowa. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



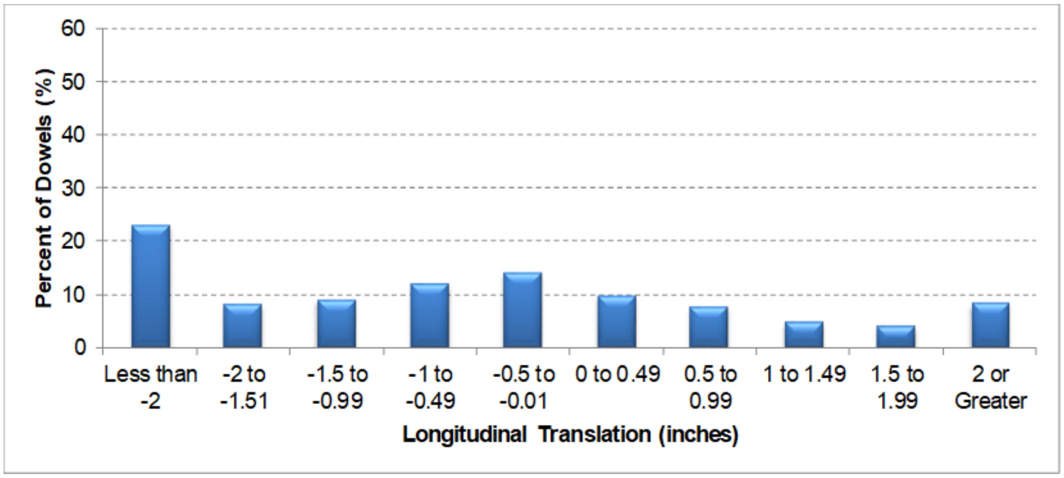
Source: FHWA.

Figure 52. Chart. Horizontal skew distribution for LTPP test sections in Iowa.



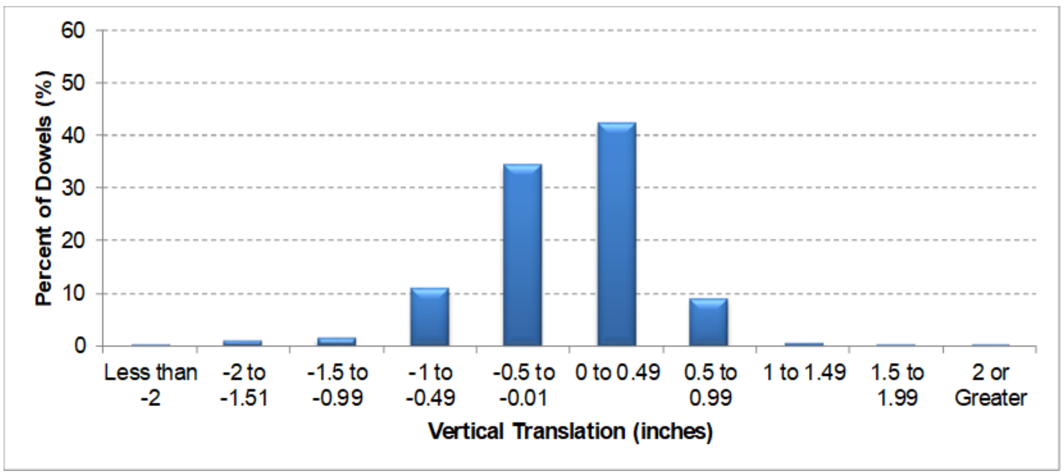
Source: FHWA.

Figure 53. Chart. Vertical tilt distribution for LTPP test sections in Iowa.



Source: FHWA.

Figure 54. Chart. Longitudinal translation distribution for LTPP test sections in Iowa.

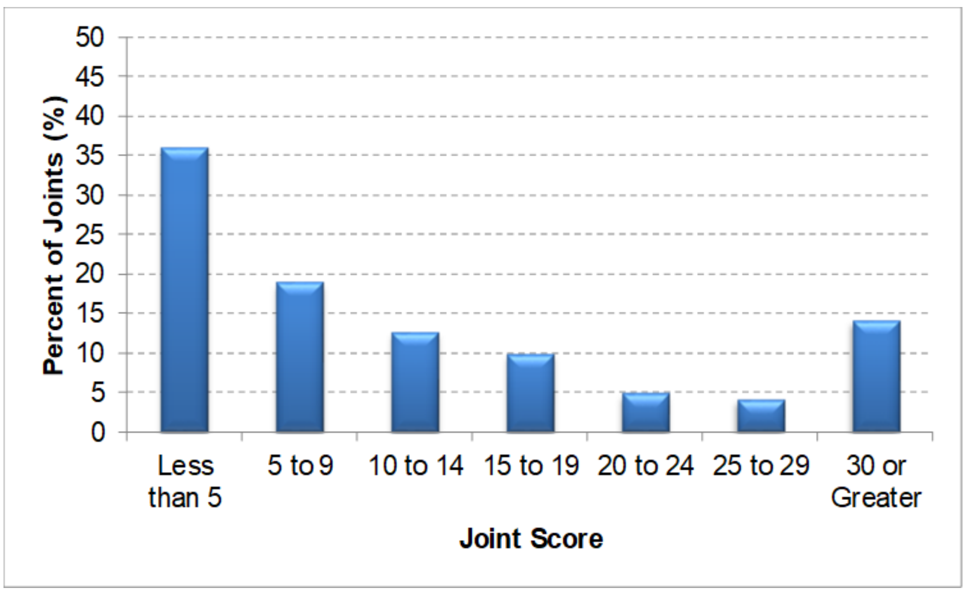


Source: FHWA.

Figure 55. Chart. Vertical translation distribution for LTPP test sections in Iowa.

Table 22. Dowel misalignment summary for LTPP test sections in Iowa.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
19_0213	0.32	0.51	0.35	0.34	1.74	1.15	0.31	0.43
19_0214	0.26	0.22	0.41	0.34	1.82	1.35	0.19	0.27
19_0215	0.26	0.25	0.19	0.24	0.83	0.85	0.15	0.12
19_0216	0.22	0.23	0.27	0.36	1.34	1.07	0.20	0.26
19_0217	0.38	0.61	0.39	0.49	1.32	1.06	0.49	0.62
19_0218	0.42	0.58	0.35	0.39	1.25	0.94	0.17	0.24
19_0219	0.33	0.52	0.34	0.44	1.77	1.36	0.47	0.29
19_0220	0.41	0.33	0.64	0.80	2.79	2.07	0.43	0.97
19_0221	0.37	0.21	0.22	0.19	0.87	0.82	0.61	0.27
19_0222	0.41	0.31	0.49	0.48	2.25	1.53	0.26	0.37
19_0223	0.37	0.36	0.28	0.28	1.57	1.22	0.48	0.23
19_0224	0.28	0.26	0.28	0.23	1.46	1.08	0.42	0.24

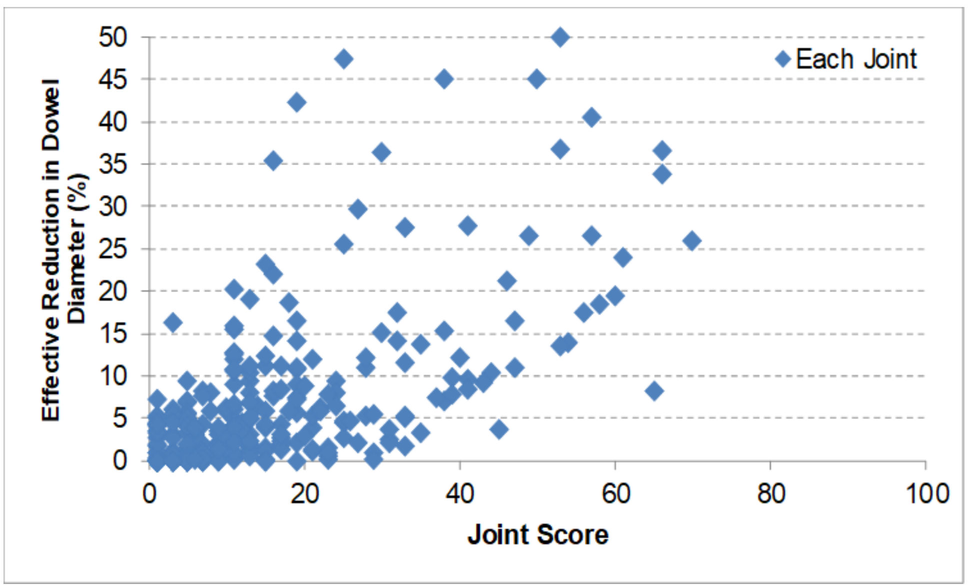


Source: FHWA.

Figure 56. Chart. Joint score distribution for LTPP test sections in Iowa.

Table 23. Joint score and equivalent dowel diameter for LTPP test sections in Iowa.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
19_0213	12	12	8.9	1.25	1.21	0.05	3.4
19_0214	14	14	8.4	1.25	1.21	0.07	3.0
19_0215	6	10	11.4	1.50	1.48	0.04	1.1
19_0216	5	5	11.4	1.50	1.46	0.08	2.7
19_0217	17	21	8.1	1.25	1.05	0.35	15.8
19_0218	15	13	8.4	1.25	1.17	0.18	6.1
19_0219	11	13	11.5	1.50	1.42	0.15	5.6
19_0220	31	25	11.5	1.50	1.31	0.29	12.8
19_0221	8	9	9.4	1.25	1.21	0.04	2.9
19_0222	25	23	8.3	1.25	1.15	0.18	8.1
19_0223	12	14	12.5	1.50	1.47	0.05	1.8
19_0224	8	9	10.0	1.50	1.47	0.05	2.0



Source: FHWA.

Figure 57. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in Iowa.

KANSAS

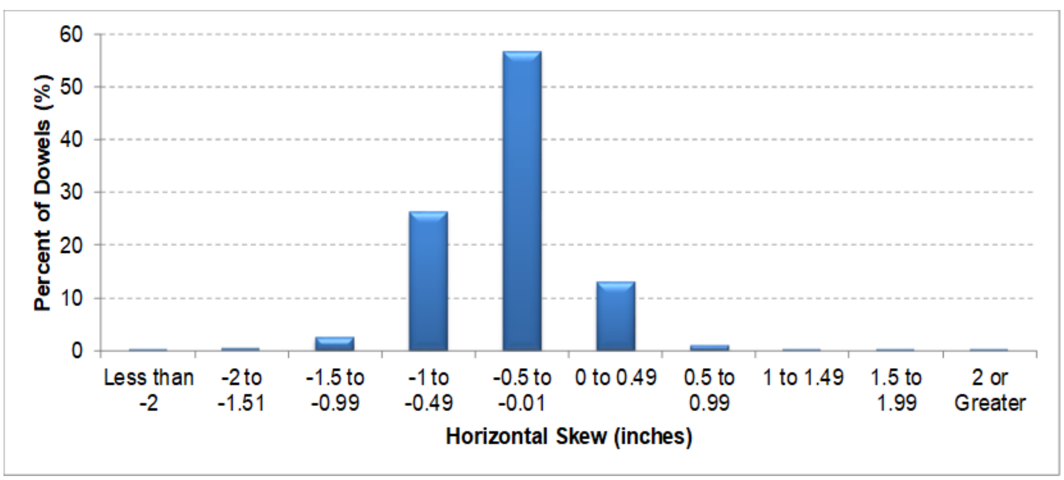
The dowel alignments of 12 SPS-2 test sections in Kansas were evaluated using an MIT scanning device as part of this study. All test sections are in the westbound direction of I–70 and were constructed in 1992. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 24. Results of the MIT scanning analysis are shown in figure 58 through figure 61 and table 25.

Table 24. Details of LTPP test sections in Kansas.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
20_0201	7.7	1.25	12/01/2015	12
20_0202	7.7	1.25	12/01/2015	14
20_0203	11.1	1.50	12/01/2015	14
20_0204	11.3	1.50	12/01/2015	12
20_0205	7.5	1.25	12/02/2015	12
20_0206	7.5	1.25	12/02/2015	14
20_0207	11.2	1.50	12/02/2015	14
20_0208	10.8	1.50	12/02/2015	12
20_0209	8.6	1.25	12/03/2015	12
20_0210	8.4	1.25	12/03/2015	14
20_0211	11.1	1.50	12/02/2015	14
20_0212	11.1	1.50	12/02/2015	12

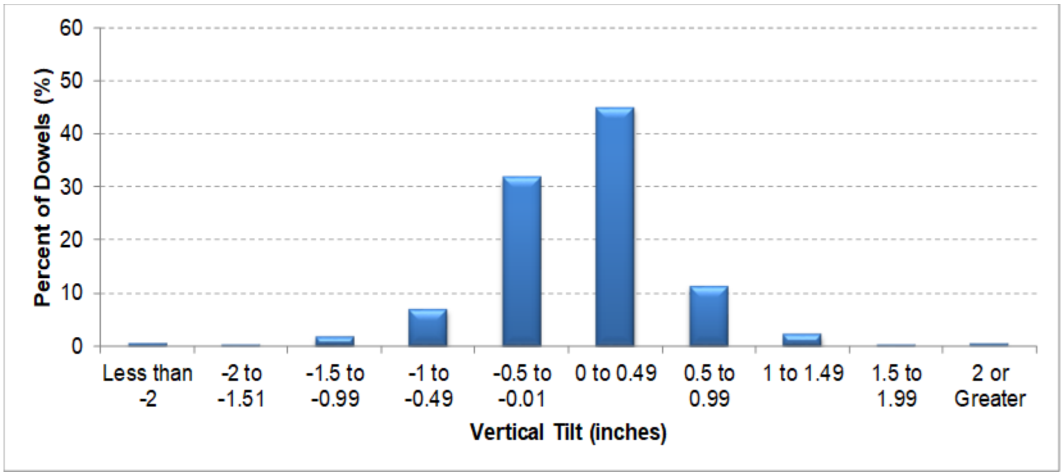
MIT scanning results from Kansas show that approximately 69, 7, and 95 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 29 percent of dowels have longitudinal translation ranging greater than 2 inches.

The joint score distribution and equivalent dowel diameter are shown in figure 62 and table 26. Approximately 47 percent of transverse joints have a joint score less than 10, while 24 percent of transverse joints have a joint score greater than 30. Figure 63 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in Kansas. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



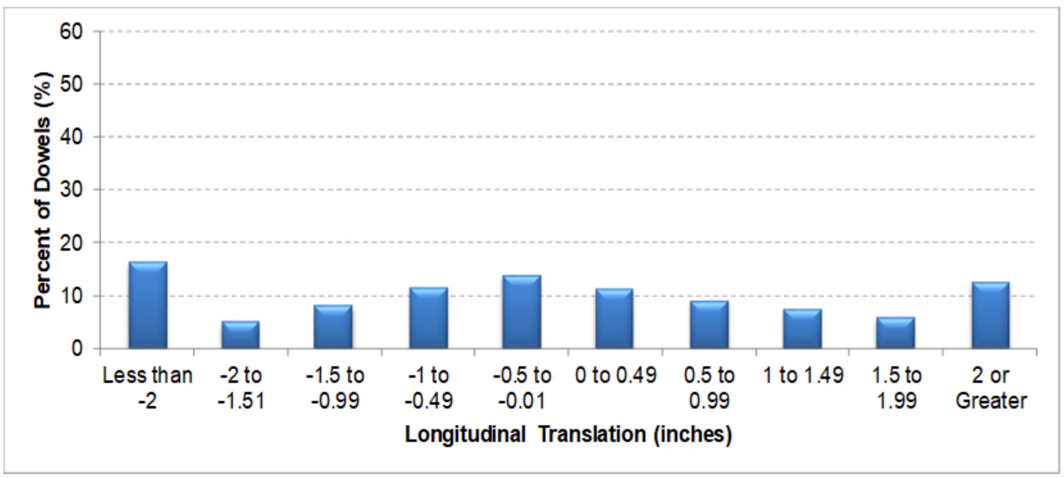
Source: FHWA.

Figure 58. Chart. Horizontal skew distribution for LTPP test sections in Kansas.



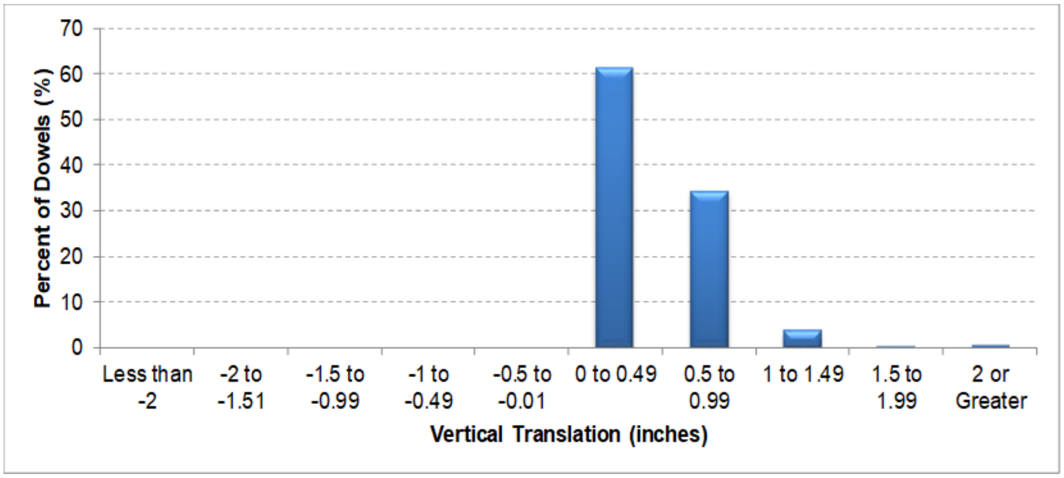
Source: FHWA.

Figure 59. Chart. Vertical tilt distribution for LTPP test sections in Kansas.



Source: FHWA.

Figure 60. Chart. Longitudinal translation distribution for LTPP test sections in Kansas.

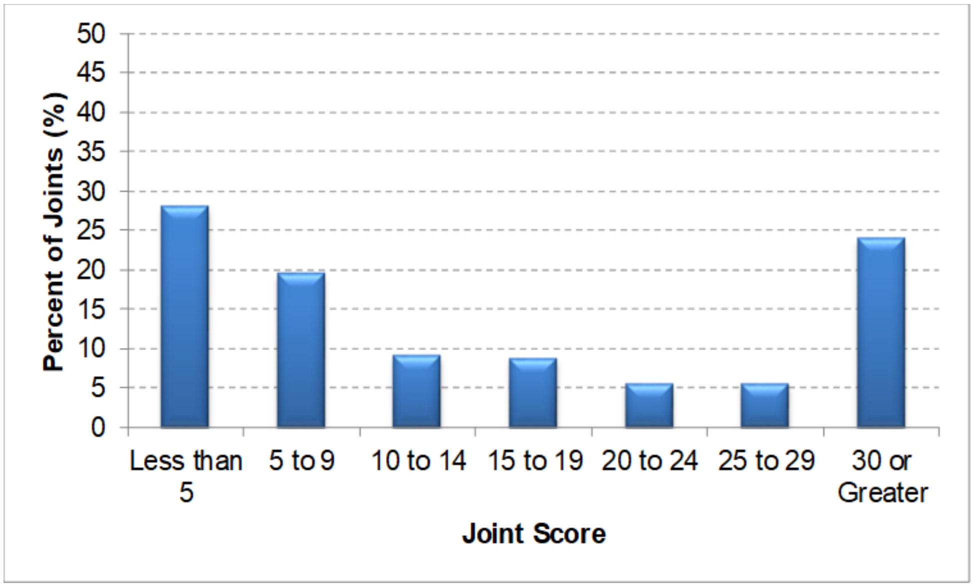


Source: FHWA.

Figure 61. Chart. Vertical translation distribution for LTPP test sections in Kansas.

Table 25. Dowel misalignment summary for LTPP test sections in Kansas.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
20_0201	0.35	0.79	0.41	0.76	1.30	1.33	0.57	0.50
20_0202	0.32	0.19	0.26	0.38	0.83	0.71	0.61	0.35
20_0203	0.38	0.42	0.22	0.19	1.12	0.81	0.36	0.20
20_0204	0.47	0.28	0.24	0.23	1.05	0.73	0.30	0.17
20_0205	0.41	0.45	0.45	0.60	1.62	1.28	0.51	0.34
20_0206	0.31	0.23	0.40	0.42	1.74	1.59	0.56	0.52
20_0207	0.47	0.37	0.60	0.76	2.48	1.70	0.56	0.32
20_0208	0.46	0.30	0.30	0.26	1.66	1.25	0.40	0.29
20_0209	0.41	0.44	0.41	0.42	2.06	3.19	0.32	0.91
20_0210	0.29	0.24	0.37	0.33	1.77	1.40	0.37	0.24
20_0211	0.42	0.27	0.39	0.29	1.67	1.30	0.51	0.33
20_0212	0.58	0.31	0.33	0.38	1.32	1.23	0.46	0.33

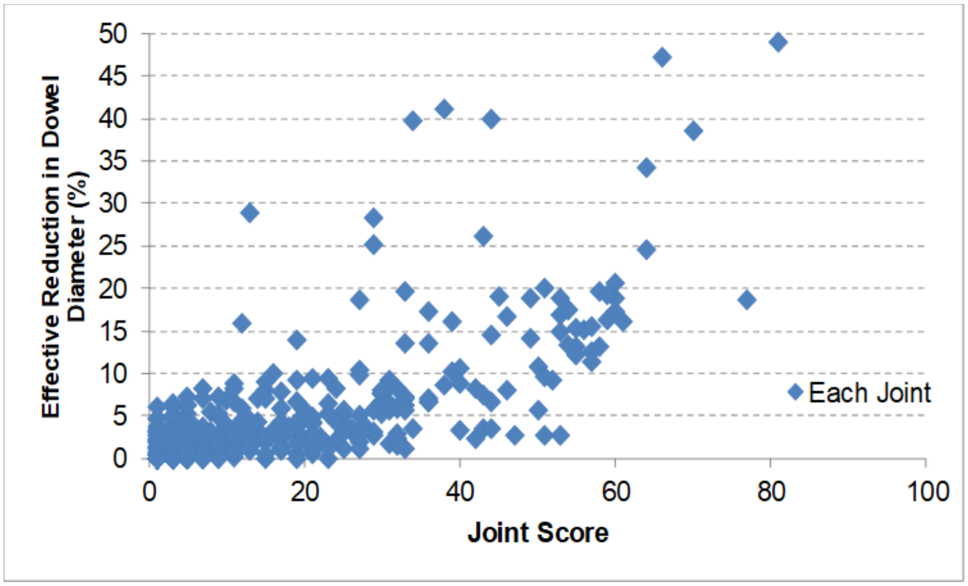


Source: FHWA.

Figure 62. Chart. Joint score distribution for LTPP test sections in Kansas.

Table 26. Chart. Joint score and equivalent dowel diameter for LTPP test sections in Kansas.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
20_0201	16	22	7.7	1.25	1.09	0.22	12.6
20_0202	7	9	7.7	1.25	1.05	0.27	15.6
20_0203	10	11	11.1	1.50	1.48	0.03	1.6
20_0204	16	16	11.3	1.50	1.48	0.04	1.5
20_0205	21	20	7.5	1.25	1.19	0.11	5.0
20_0206	17	15	7.5	1.25	1.17	0.11	6.4
20_0207	28	31	11.2	1.50	1.35	0.17	10.0
20_0208	19	17	10.8	1.50	1.46	0.05	2.9
20_0209	22	21	8.6	1.25	1.13	0.18	9.4
20_0210	16	19	8.4	1.25	1.19	0.08	4.6
20_0211	20	17	11.1	1.50	1.43	0.07	4.6
20_0212	27	18	11.1	1.50	1.43	0.15	4.4



Source: FHWA.

Figure 63. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in Kansas.

NORTH CAROLINA

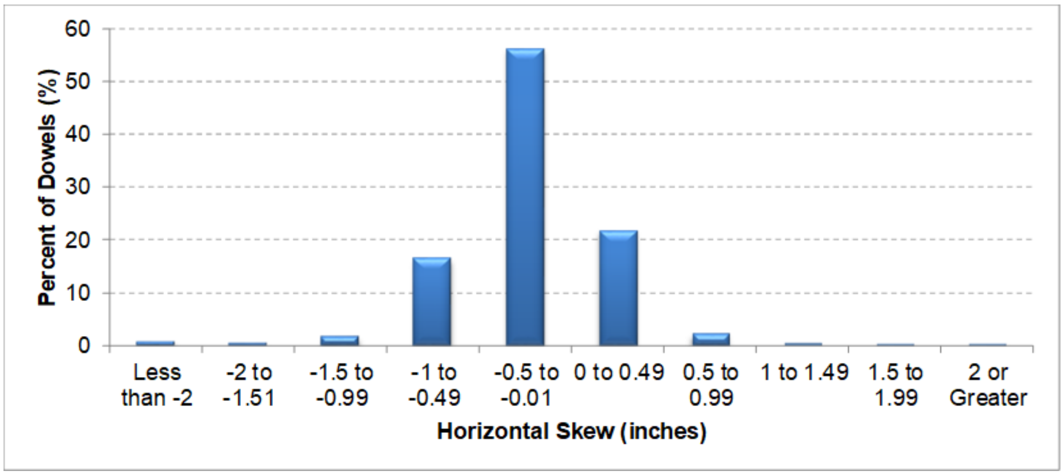
The dowel alignments of 8 SPS-2 test sections in North Carolina were evaluated using an MIT scanning device as part of this study. All test sections are in the southbound direction of US 52 and were constructed in 1992. Dowels were placed using a DBI for all test sections. Other details of the test sections are shown in table 27. Results of the MIT scanning analyses are shown in figure 64 through figure 67 and table 28.

Table 27. Details of LTPP test sections in North Carolina.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
37_0203	11.4	1.50	03/09/2015	14
37_0204	11.2	1.50	03/12/2015	12
37_0207	11.6	1.50	03/09/2015	14
37_0208	11.2	1.50	03/11/2015	12
37_0211	11.4	1.50	03/10/2015	14
37_0212	10.9	1.50	03/10/2015	12
37_0259	10.2	1.25	03/09/2015	12
37_0260	11.5	1.50	03/10/2015	14

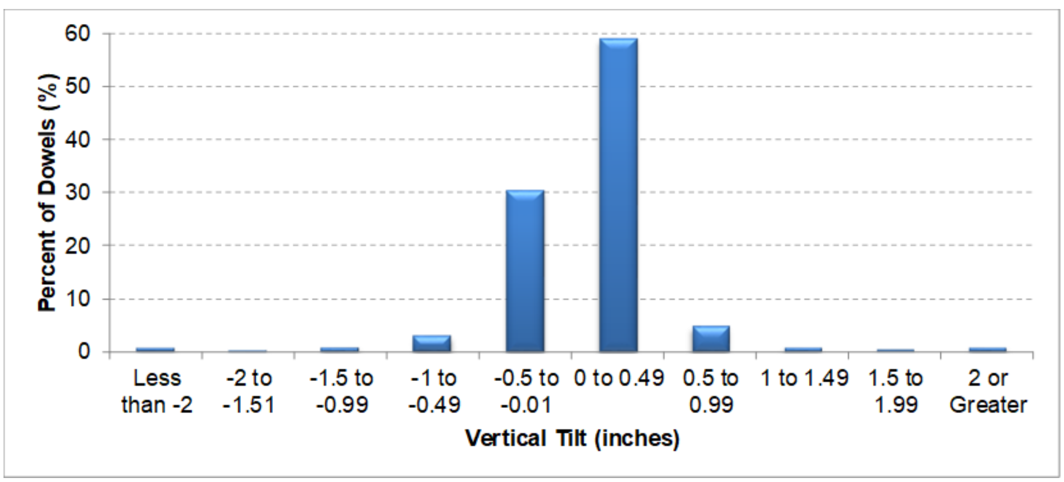
MIT scanning results from North Carolina show that approximately 78, 89, and 76 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 53 percent of dowels have longitudinal translation ranging between 0 and ±0.5 inches.

The joint score distribution and equivalent dowel diameter are shown in figure 68 and table 29. Approximately 62 percent of transverse joints have a joint score less than 10, while 9 percent of transverse joints have a joint score greater than 30. Figure 69 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in North Carolina. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



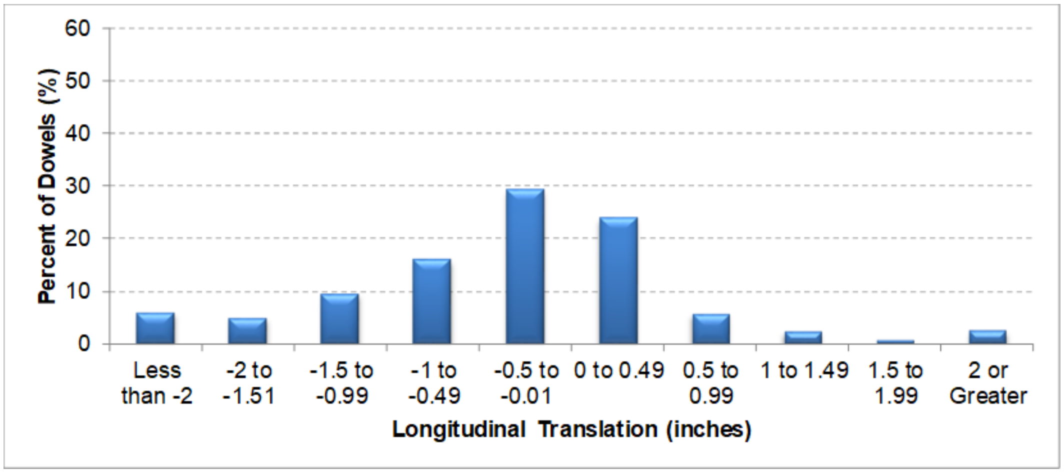
Source: FHWA.

Figure 64. Chart. Horizontal skew distribution for LTPP test sections in North Carolina.



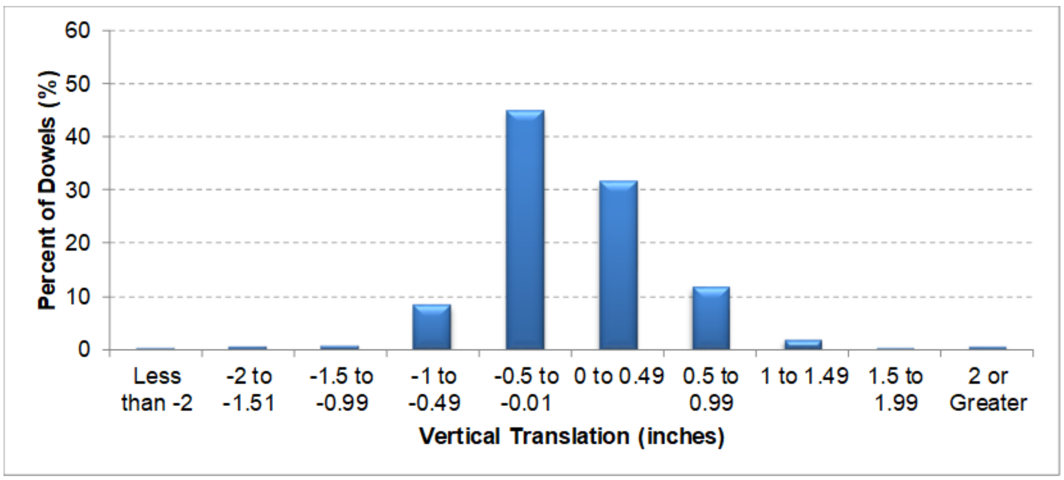
Source: FHWA.

Figure 65. Chart. Vertical tilt distribution for LTPP test sections in North Carolina.



Source: FHWA.

Figure 66. Chart. Longitudinal translation distribution for LTPP test sections in North Carolina.

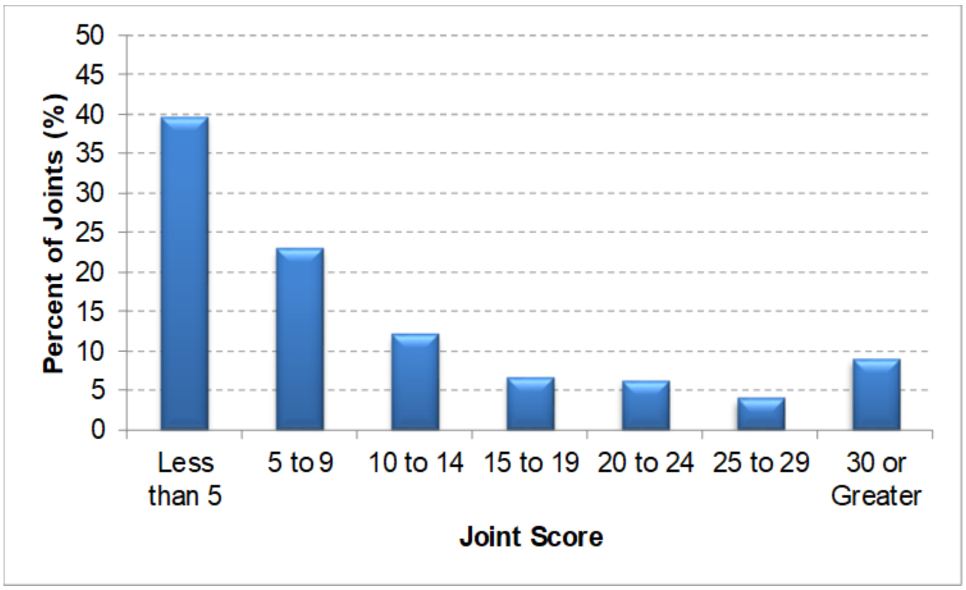


Source: FHWA.

Figure 67. Chart. Vertical translation distribution for LTPP test sections in North Carolina.

Table 28. Dowel misalignment summary for LTPP test sections in North Carolina.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
37_0203	0.41	0.24	0.23	0.21	1.04	0.91	0.44	0.39
37_0204	0.58	0.40	0.32	0.43	1.69	4.09	0.30	0.48
37_0207	0.35	0.43	0.35	0.82	0.59	0.88	0.41	0.43
37_0208	0.28	1.03	0.40	0.77	0.78	1.06	0.31	0.38
37_0211	0.35	0.38	0.24	0.54	0.64	0.93	0.45	1.96
37_0212	0.26	0.19	0.20	0.18	0.52	0.42	0.17	0.13
37_0259	0.30	0.25	0.26	0.28	0.29	0.52	0.69	0.23
37_0260	0.40	0.83	0.43	0.84	0.71	1.06	0.32	0.35

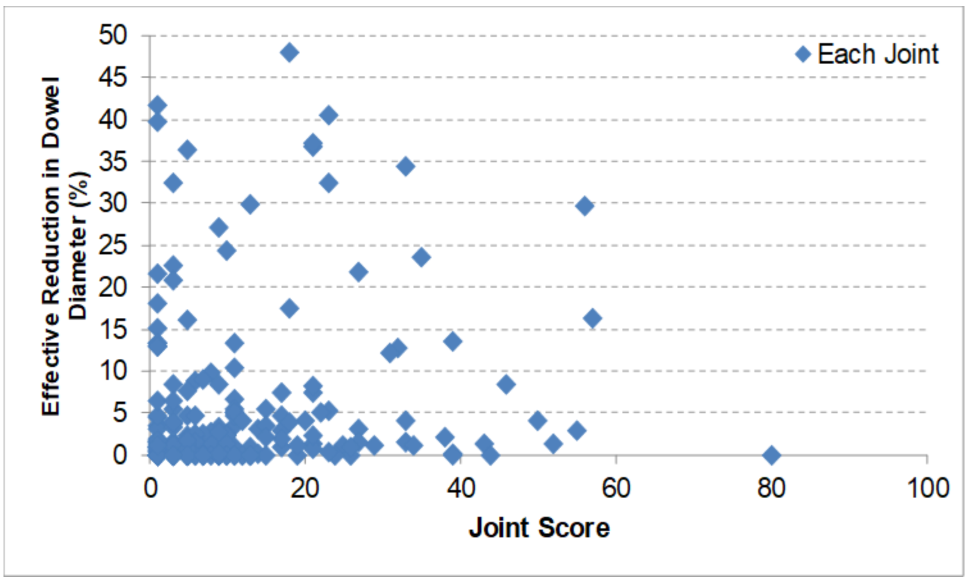


Source: FHWA.

Figure 68. Chart. Joint score distribution for LTPP test sections in North Carolina.

Table 29. Joint score and equivalent dowel diameter for LTPP test sections in North Carolina.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
37_0203	11	11	11.4	1.50	1.45	0.06	3.1
37_0204	23	19	11.2	1.50	1.39	0.31	7.2
37_0207	12	14	11.6	1.50	1.39	0.37	7.3
37_0208	10	22	11.2	1.50	1.44	0.22	4.0
37_0211	9	9	11.4	1.50	1.42	0.27	5.3
37_0212	4	4	10.9	1.50	1.50	0.01	0.1
37_0259	7	10	10.2	1.25	1.20	0.14	3.8
37_0260	14	12	11.5	1.49	1.31	0.32	12.2



Source: FHWA.

Figure 69. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in North Carolina.

NORTH DAKOTA

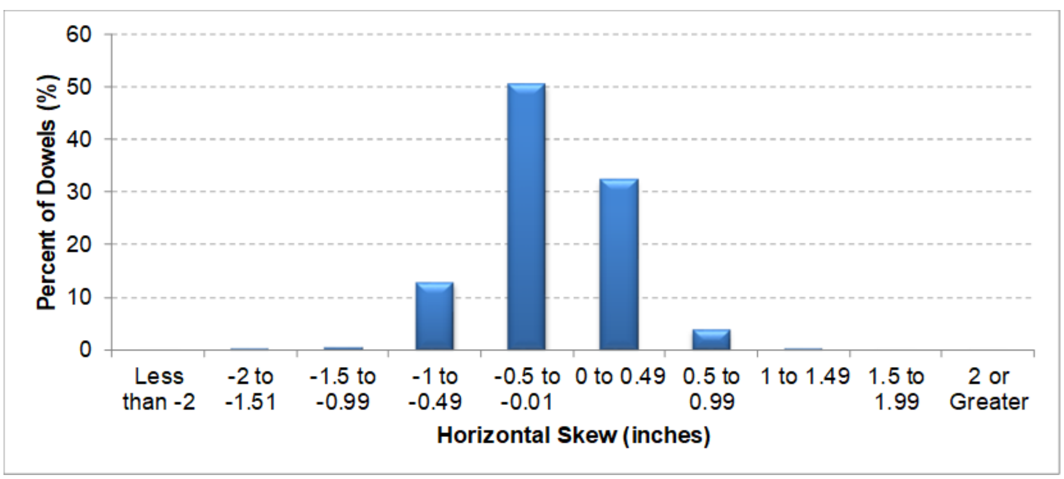
The dowel alignments of 12 SPS-2 test sections in North Dakota were evaluated using an MIT scanning device as part of this study. All test sections are in the eastbound direction of I–94 and were constructed in 1994. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 30. Results of the MIT scanning analyses are shown in figure 70 through figure 73 and table 31.

Table 30. Details of LTPP test sections in North Dakota.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
38_0213	7.9	1.25	09/22/2015	14
38_0214	8.0	1.25	09/21/2015	12
38_0215	11.1	1.50	09/21/2015	12
38_0216	11.1	1.50	09/21/2015	14
38_0217	7.9	1.25	09/23/2015	14
38_0218	7.9	1.25	09/23/2015	12
38_0219	10.8	1.50	09/24/2015	12
38_0220	11.0	1.50	09/23/2015	14
38_0221	8.1	1.25	09/30/2015	14
38_0222	8.0	1.25	09/24/2015	12
38_0223	11.1	1.50	09/24/2015	12
38_0224	11.0	1.50	09/30/2015	14

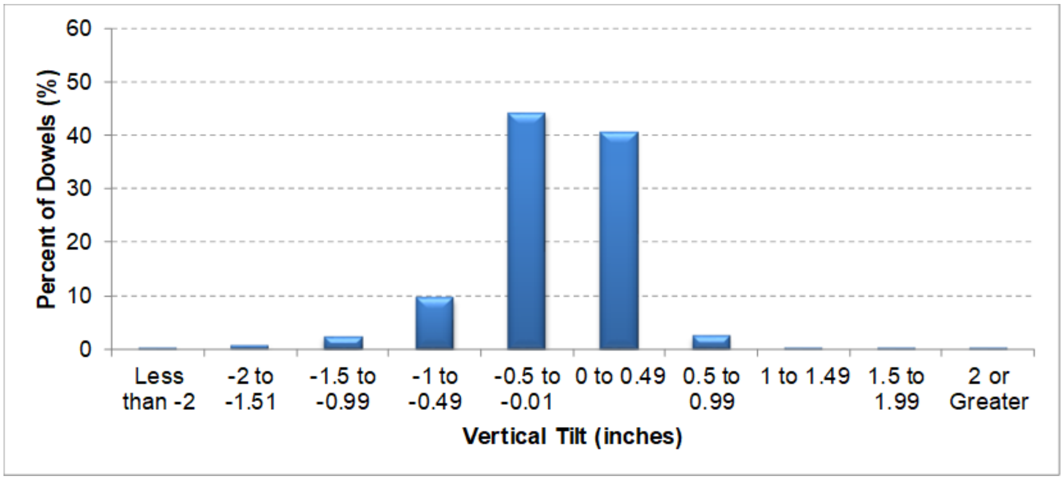
MIT scanning results from North Dakota show that approximately 82, 84, and 72 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 30 percent of dowels have longitudinal translation ranging between 0 and ±0.5 inches.

The joint score distribution and equivalent dowel diameter are shown in figure 74 and table 32. Approximately 64 percent of transverse joints have a joint score less than 10, while 7 percent of transverse joints have a joint score greater than 30. Figure 75 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in North Dakota. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



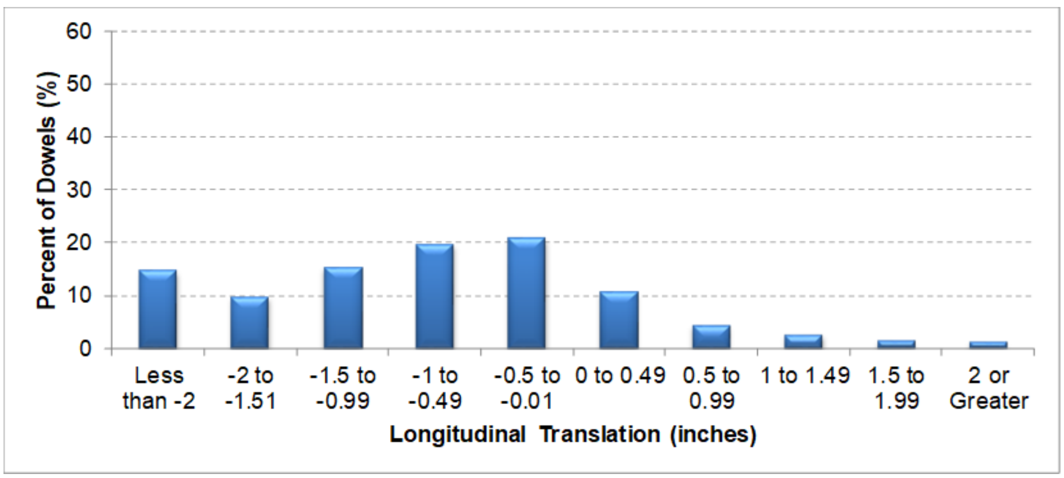
Source: FHWA.

Figure 70. Chart. Horizontal skew distribution for LTPP test sections in North Dakota.



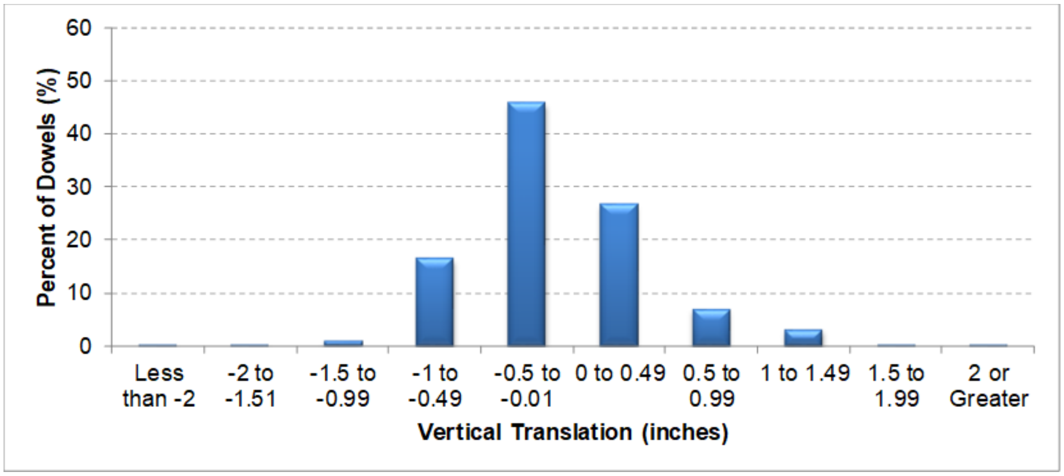
Source: FHWA.

Figure 71. Chart. Vertical tilt distribution for LTPP test sections in North Dakota.



Source: FHWA.

Figure 72. Chart. Longitudinal translation distribution for LTPP test sections in North Dakota.

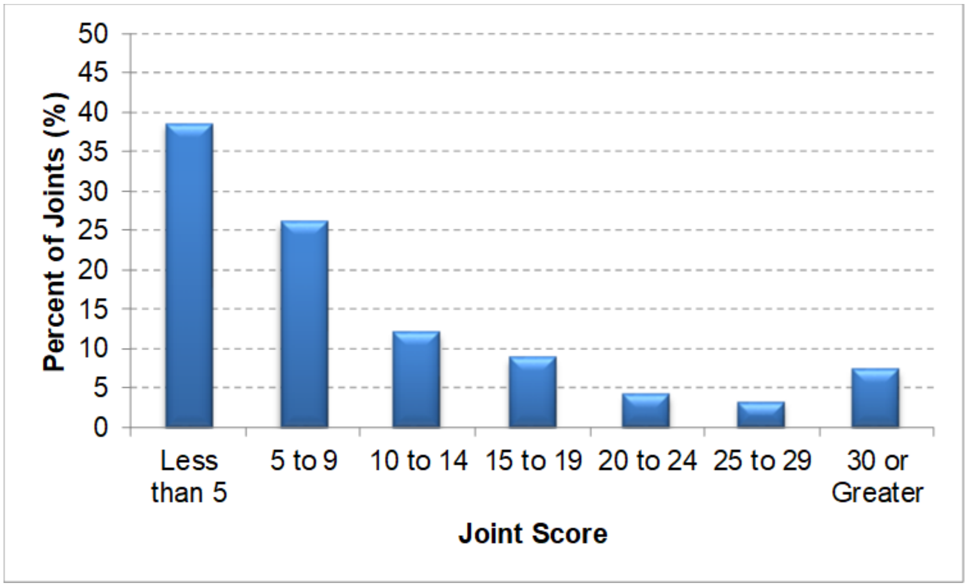


Source: FHWA.

Figure 73. Chart. Vertical translation distribution for LTPP test sections in North Dakota.

Table 31. Dowel misalignment summary for LTPP test sections in North Dakota.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
38_0213	0.25	0.20	0.25	0.21	1.06	0.75	0.16	0.13
38_0214	0.29	0.24	0.31	0.25	1.27	1.07	0.21	0.15
38_0215	0.29	0.27	0.77	0.44	1.96	1.11	0.53	0.29
38_0216	0.22	0.17	0.29	0.48	0.95	0.77	0.30	0.28
38_0217	0.34	0.23	0.19	0.17	0.75	0.65	0.50	0.34
38_0218	0.32	0.21	0.29	0.42	1.06	0.80	0.33	0.20
38_0219	0.41	0.21	0.20	0.24	1.08	0.79	0.95	0.23
38_0220	0.23	0.15	0.18	0.16	1.06	0.96	0.58	0.74
38_0221	0.23	0.18	0.19	0.28	0.90	0.78	0.24	0.18
38_0222	0.36	0.23	0.25	0.22	0.71	0.63	0.18	0.14
38_0223	0.40	0.25	0.21	0.18	1.12	1.01	0.22	0.14
38_0224	0.20	0.15	0.31	0.27	1.37	1.19	0.31	0.25

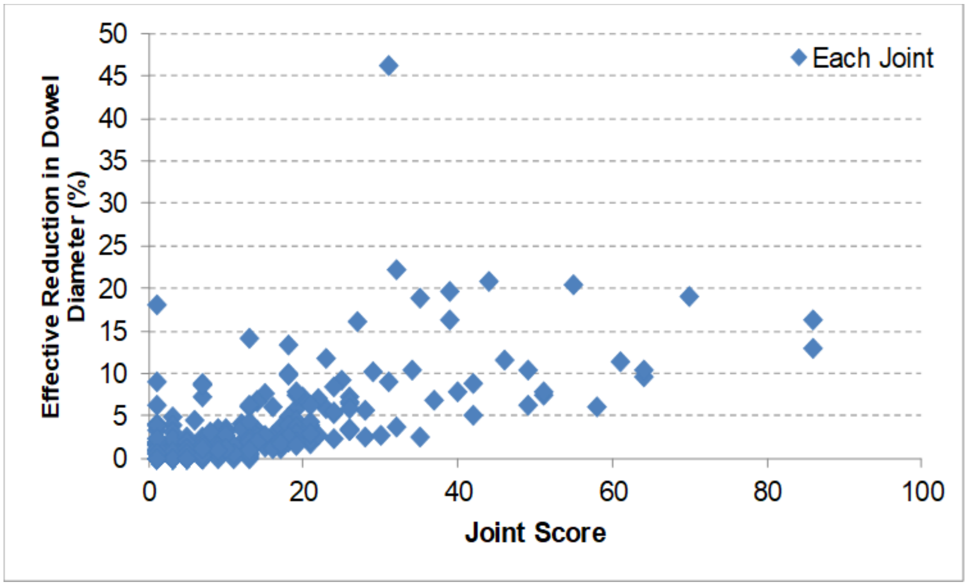


Source: FHWA.

Figure 74. Chart. Joint score distribution for LTPP test sections in North Dakota.

Table 32. Joint score and equivalent dowel diameter for LTPP test sections in North Dakota.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
38_0213	7	8	7.9	1.25	1.24	0.13	0.9
38_0214	12	12	8.0	1.25	1.22	0.05	2.7
38_0215	39	23	11.1	1.50	1.38	0.10	7.8
38_0216	6	6	11.1	1.50	1.48	0.04	1.6
38_0217	7	6	7.9	1.25	1.22	0.04	2.8
38_0218	10	9	7.9	1.25	1.21	0.13	3.6
38_0219	9	7	10.8	1.50	1.48	0.03	1.7
38_0220	3	5	11.0	1.50	1.47	0.05	1.7
38_0221	4	4	8.1	1.25	1.24	0.02	0.6
38_0222	11	7	8.0	1.25	1.24	0.01	0.5
38_0223	12	9	11.1	1.50	1.48	0.05	1.5
38_0224	9	13	11.0	1.50	1.47	0.07	2.3



Source: FHWA.

Figure 75. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in North Dakota.

SOUTH DAKOTA

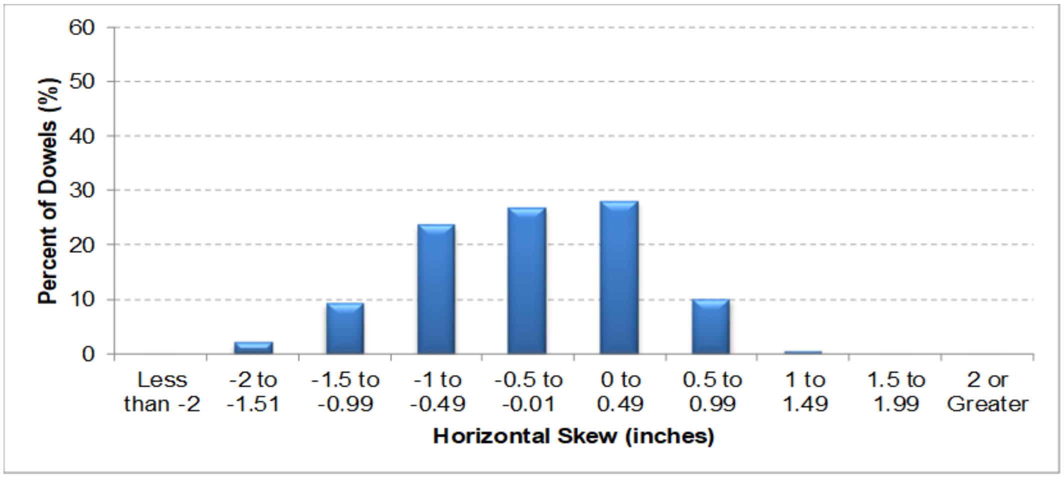
The dowel alignment of one GPS-3 test section in South Dakota was evaluated using an MIT scanning device as part of this study. The test section is in the eastbound direction of US 14 and was constructed in 1988. Dowels were placed using dowel baskets. Other details of the test section are shown in table 33. Results of the MIT scan analysis are shown in figure 76 through figure 79 and table 34.

Table 33. Details of the LTPP test section in South Dakota.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
46_3052	9.0	1.25	10/07/2015	12

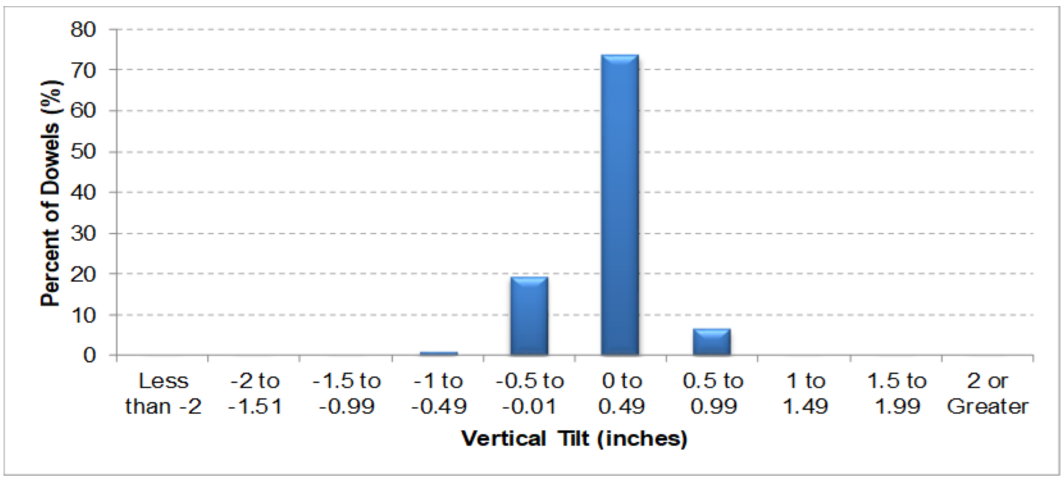
MIT scanning results from South Dakota show that approximately 55, 93, and 97 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. Approximately 90 percent of dowels have longitudinal translation (absolute) less than 1.0 inch.

The joint score distribution and equivalent dowel diameter are shown in figure 80 and table 35. Approximately 8 percent of transverse joints have a joint score less than 10, and 8 percent of transverse joints have a joint score greater than 30. Figure 81 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in South Dakota. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



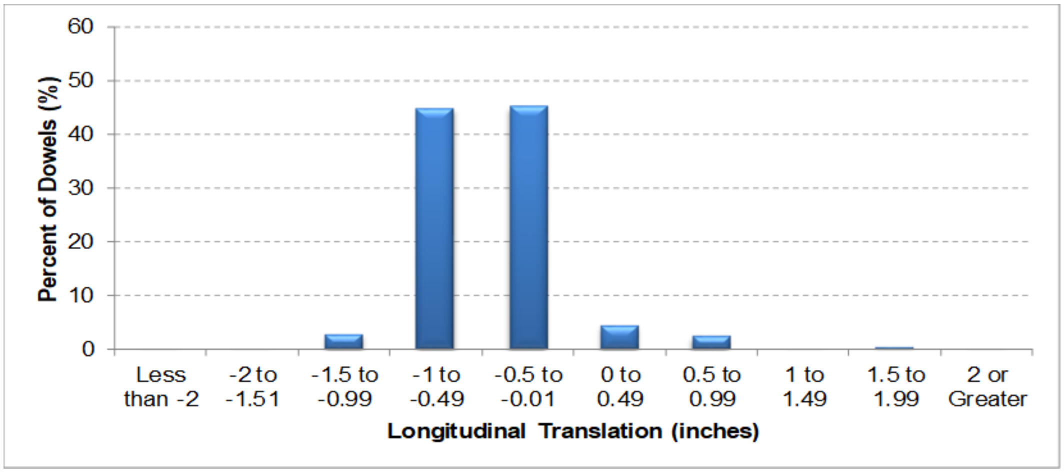
Source: FHWA.

Figure 76. Chart. Horizontal skew distribution for the LTPP test section in South Dakota.



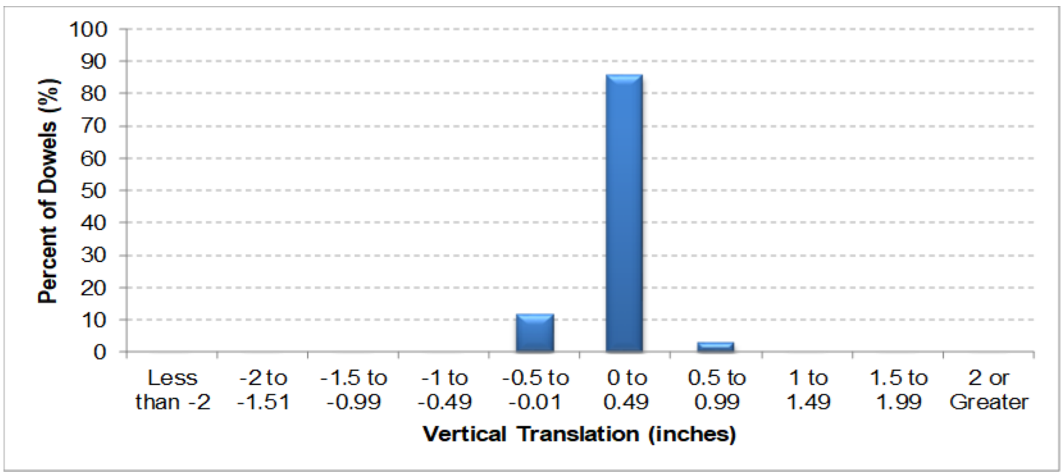
Source: FHWA.

Figure 77. Chart. Vertical tilt distribution for the LTPP test section in South Dakota.



Source: FHWA.

Figure 78. Chart. Longitudinal translation distribution for the LTPP test section in South Dakota.

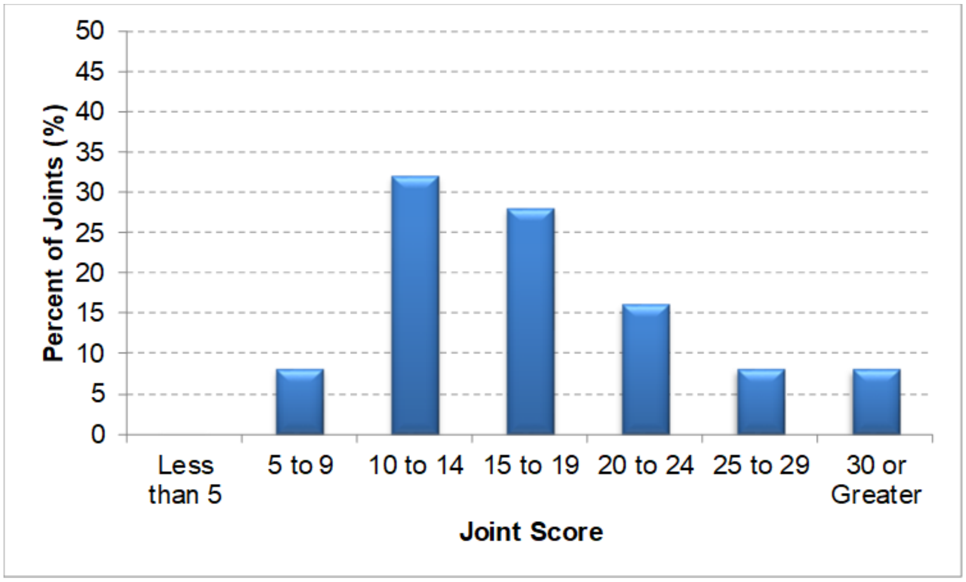


Source: FHWA.

Figure 79. Chart. Vertical translation distribution for the LTPP test section in South Dakota.

Table 34. Dowel misalignment summary for the LTPP test section in South Dakota.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
46_3052	0.53	0.37	0.23	0.16	0.20	0.26	0.19	0.13

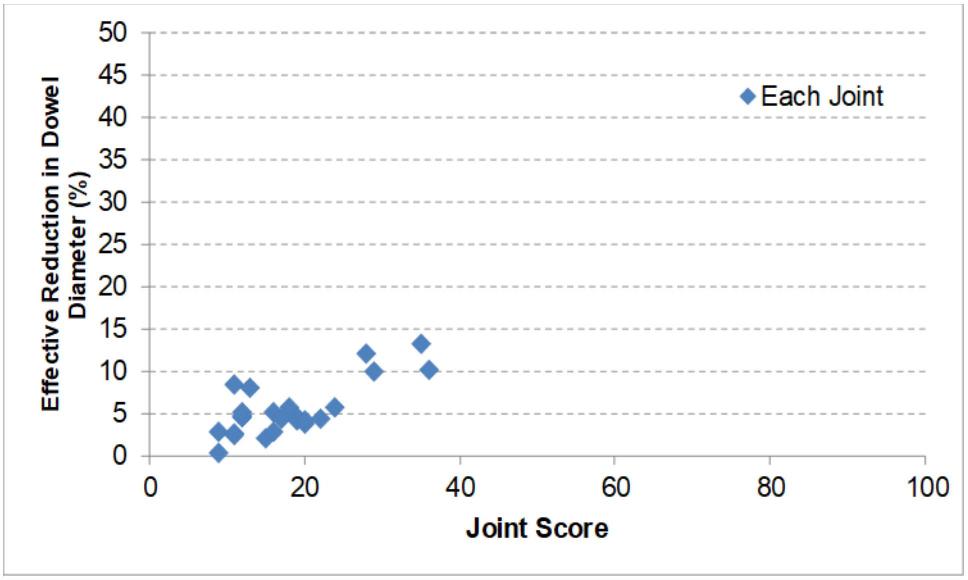


Source: FHWA.

Figure 80. Chart Joint score distribution for the LTPP test section in South Dakota.

Table 35. Joint score and equivalent dowel diameter for the LTPP test section in South Dakota.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
46_3052	18	8	9.0	1.25	1.21	0.03	3.45



Source: FHWA.

Figure 81. Chart. Joint score versus effective reduction in dowel diameter for the LTPP test section in South Dakota.

WISCONSIN

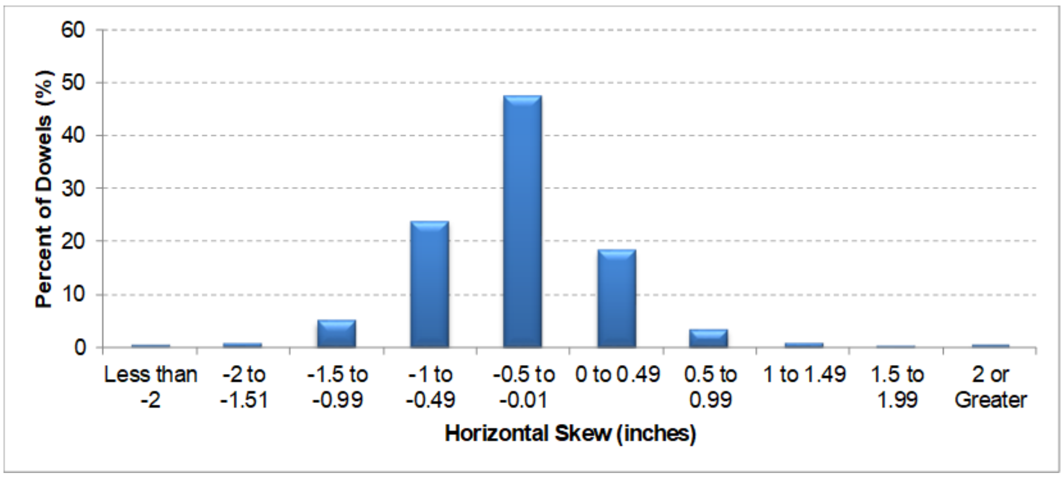
The dowel alignments of 11 SPS-2 test sections in Wisconsin were evaluated using an MIT scanning device as part of this study. All test sections are in the westbound direction of SR 29 and were constructed in 1997. Dowels were placed using dowel baskets for all test sections. Other details of the test sections are shown in table 36. Results of the MIT scanning analyses are shown in figure 82 through figure 85 and table 37.

Table 36. Details of LTPP test sections in Wisconsin.

Test Section	PCC Thickness (Inches)	Dowel Diameter (Inches)	Scan Date	Lane Width (ft)
55_0213	8.5	1.25	11/04/2015	14
55_0215	10.9	1.50	11/05/2015	12
55_0217	8.5	1.25	11/04/2015	14
55_0219	11.8	1.50	11/05/2015	12
55_0221	8.2	1.25	11/03/2015	14
55_0223	11.2	1.50	11/04/2015	12
55_0259	10.6	1.50	11/03/2015	12
55_0261	8.2	1.25	11/04/2015	12
55_0262	8.3	1.25	11/05/2015	12
55_0263	10.0	1.25	11/03/2015	12
55_0265	10.7	1.50	11/09/2015	12

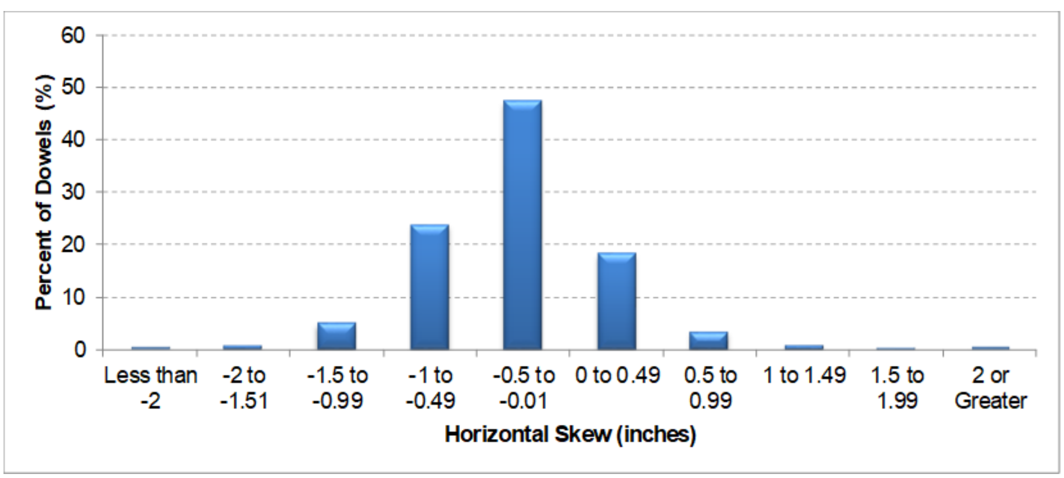
MIT scanning results from Wisconsin show that approximately 65, 79, and 66 percent of dowels have misalignments ranging between 0 and ±0.5 inches for horizontal skew, vertical tilt, and vertical translation, respectively. There is more variation in the longitudinal translation data, and approximately 39 percent of dowels have longitudinal translation ranging between 0 and ±0.5 inches.

The joint score distribution and equivalent dowel diameter are shown in figure 86 and table 38. Approximately 36 percent of transverse joints have a joint score less than 10, and 22 percent of transverse joints have a joint score greater than 30. Figure 87 shows the relationship between the joint score and effective reduction in dowel diameter for each transverse joint tested in Wisconsin. Whereas the joint score considers only vertical tilt and horizontal skew, equivalent dowel diameter considers vertical tilt, horizontal skew, vertical translation, and longitudinal translation.



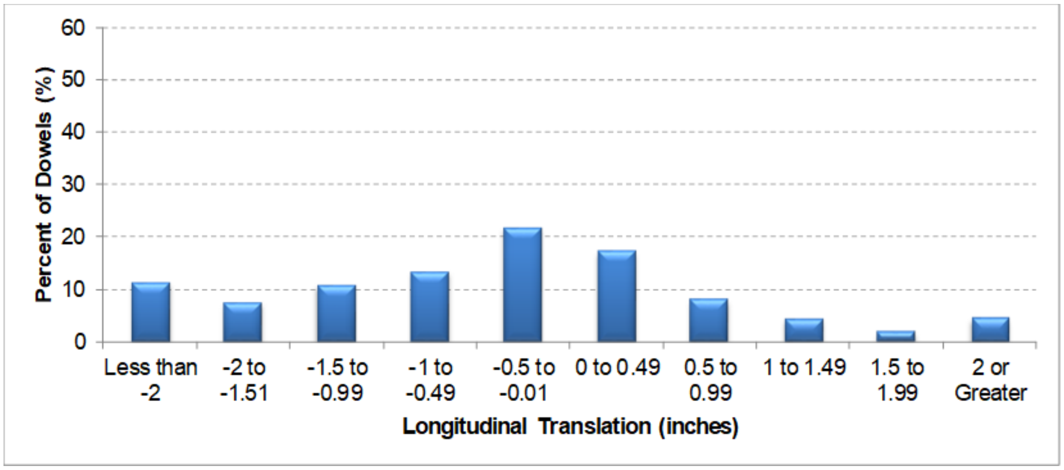
Source: FHWA.

Figure 82. Chart. Horizontal skew distribution for LTPP test sections in Wisconsin.



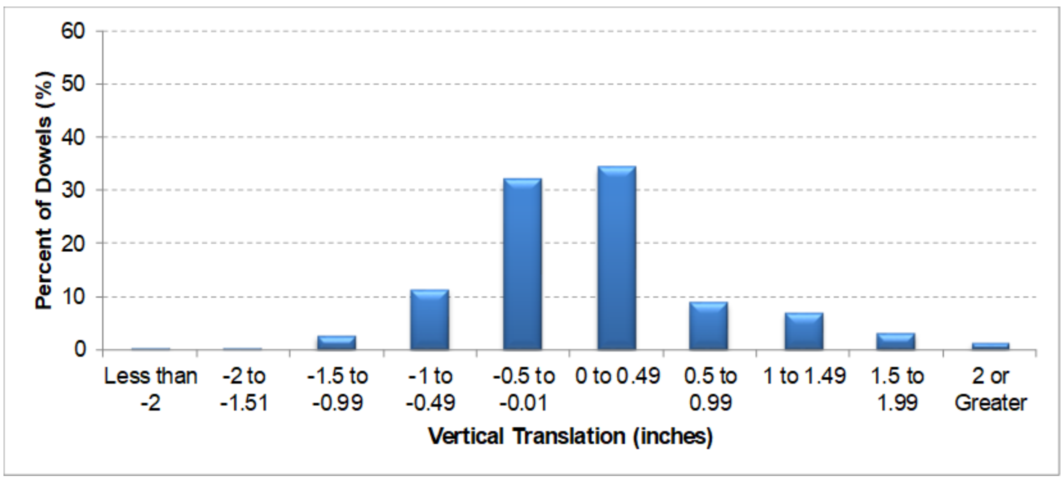
Source: FHWA.

Figure 83. Chart. Vertical tilt distribution for LTPP test sections in Wisconsin.



Source: FHWA.

Figure 84. Chart. Longitudinal translation distribution for LTPP test sections in Wisconsin.

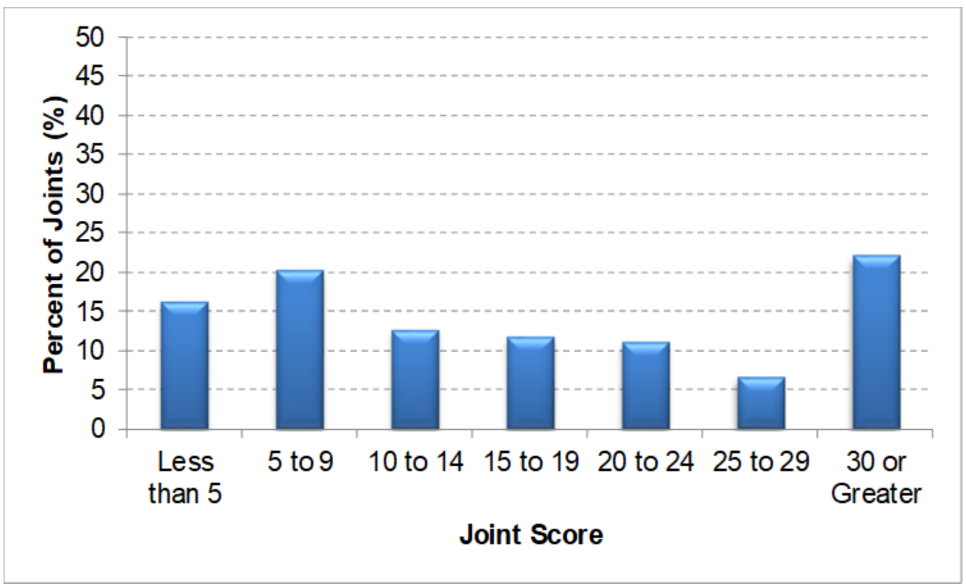


Source: FHWA.

Figure 85. Chart. Vertical translation distribution for LTPP test sections in Wisconsin.

Table 37. Dowel misalignment summary for LTPP test sections in Wisconsin.

Test Section	Average Horizontal Skew (Inches)	Horizontal Skew Standard Deviation (Inches)	Average Vertical Tilt (Inches)	Vertical Tilt Standard Deviation (Inches)	Average Longitudinal Translation (Inches)	Longitudinal Translation Standard Deviation (Inches)	Average Vertical Translation (Inches)	Vertical Translation Standard Deviation (Inches)
55_0213	0.72	0.51	0.30	0.28	0.92	1.13	0.24	0.19
55_0215	0.39	0.29	0.32	0.25	1.30	1.14	0.28	0.21
55_0217	0.49	0.31	0.34	0.79	1.00	0.88	0.82	0.26
55_0219	0.44	0.54	0.63	0.98	1.33	1.34	0.36	0.49
55_0221	0.32	0.22	0.29	0.20	0.82	0.82	0.31	0.18
55_0223	0.28	0.46	0.28	0.30	1.08	0.89	0.26	0.19
55_0259	0.40	0.34	0.31	0.23	0.87	0.71	0.27	0.22
55_0261	0.38	0.20	0.19	0.20	0.45	0.44	0.34	0.15
55_0262	0.43	0.34	0.31	0.28	1.46	1.10	0.21	0.19
55_0263	0.45	0.37	0.25	0.21	0.64	0.57	1.16	0.40
55_0265	0.64	1.00	1.07	1.13	2.12	2.09	1.25	0.73

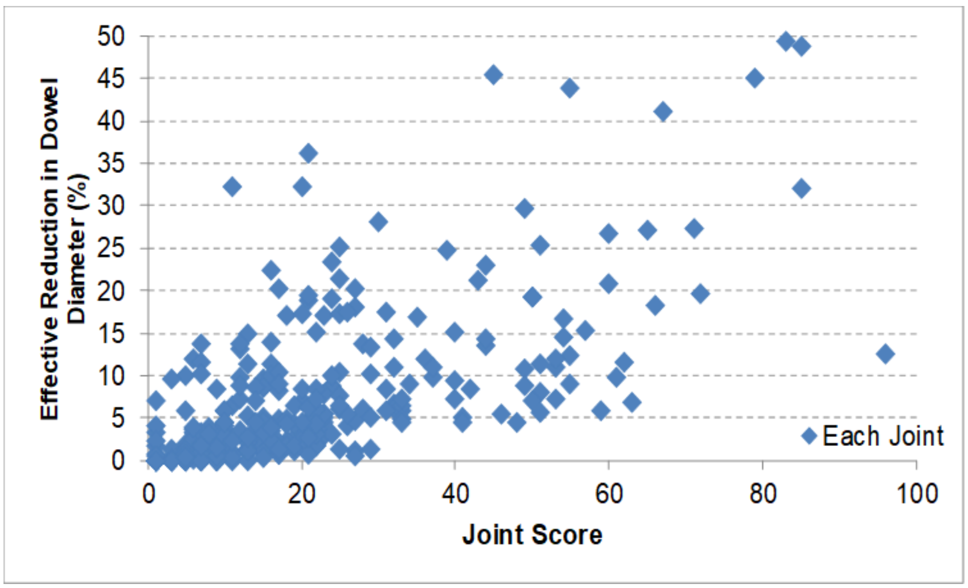


Source: FHWA.

Figure 86. Chart. Joint score distribution for LTPP test sections in Wisconsin.

Table 38. Joint score and equivalent dowel diameter for LTPP test sections in Wisconsin.

Test Section	Average Joint Score	Joint Score Standard Deviation	Average PCC Thickness (Inches)	Actual Dowel Diameter (Inches)	Average Equivalent Dowel Diameter (Inches)	Equivalent Dowel Diameter Standard Deviation (Inches)	Effective Reduction in Dowel Diameter (Percent)
55_0213	35	24	8.5	1.25	1.17	0.23	6.8
55_0215	17	12	10.9	1.50	1.45	0.09	3.4
55_0217	20	15	8.5	1.25	0.99	0.33	20.6
55_0219	27	29	11.8	1.50	1.37	0.29	8.6
55_0221	9	9	8.2	1.25	1.24	0.02	1.0
55_0223	10	11	11.2	1.50	1.48	0.03	1.6
55_0259	17	15	10.6	1.50	1.47	0.02	2.0
55_0261	8	8	8.2	1.25	1.24	0.01	0.4
55_0262	20	12	8.3	1.25	1.20	0.05	4.3
55_0263	17	8	10.0	1.25	1.05	0.06	16.3
55_0265	57	27	10.7	1.50	1.18	0.29	21.6



Source: FHWA.

Figure 87. Chart. Joint score versus effective reduction in dowel diameter for LTPP test sections in Wisconsin.

CHAPTER 6. JOINT SCORE ANALYSES

The chi-square test of independence was used to determine any potential relationship between the joint score and cracking/spalling for the LTPP test sections. The chi-square test of independence is considered an appropriate statistical test for analysis of any two categorical variables. The presence and absence of cracking or spalling for each slab was determined by evaluating available LTPP distress maps and data from the LTPP database. Joint score data were divided into three categories for analysis, as shown in table 39.

Table 39. Joint score category.

Joint Score	Category
≤12	Low
12 < joint score ≤ 30	Medium
>30	High

The following null and alternative hypotheses, respectively, were assumed:

- H_0—joint score and cracking/spalling are independent.
- H_A—joint score and cracking/spalling are dependent.

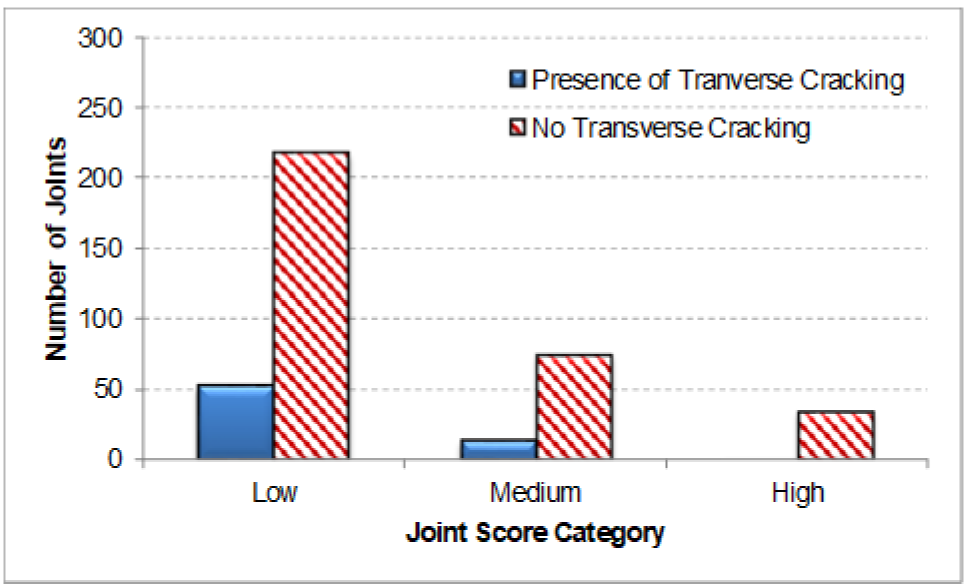
The null hypothesis was rejected if the calculated probability (*p*-value) was less than 0.05. For the LTPP test sections analyzed, rejection of H_0 implied that the joint score was related to the presence of cracking/spalling. Summary results of the analyses are shown in table 40. The *p*-value is broken down by State because each State represents a site with one GPS-3 test section or multiple SPS-2 test sections. Thus, breaking down *p*-values by State are a way to control for traffic, climate, and subgrade while maintaining a large enough sample size for the analyses. This analysis is not appropriate using the full dataset as the conditions (i.e., traffic, climate, and subgrade) change substantially from one location to another. While there are many factors responsible for cracking and spalling in PCC pavement, if the joint score has an impact on spalling or cracking at any specific site, it can be expected to show up in the analyses results shown in table 40 provided a sufficiently large sample size (i.e., number of transverse joints) is used. Figure 87 through figure 109 show the number of transverse joints exhibiting cracking/spalling compared to the total number of transverse joints for each of the three joint score categories.

Summary results of the LTPP test sections analyzed shown in table 40 indicate no definitive relationship between the joint score and transverse cracking or spalling of PCC slabs, except for three instances. Arizona and Arkansas have a *p*-value of less than 0.05, indicating a relationship between the joint score and slab cracking. Similarly, Iowa has a *p*-value of less than 0.05, indicating a relationship between the joint score and spalling. These results suggest other factors have a stronger effect on transverse cracking and spalling, but there may be some project-specific situations where dowel alignment (as measured using the joint score) has some influence on transverse cracking and spalling. Thus, dowel alignment may be a contributing factor, but not necessarily the primary factor, for these distresses. More detailed analyses of the data may be required to identify other contributing factors. LTPP test sections in North Carolina, South Dakota, and Wisconsin did not exhibit any slab cracking and were eliminated from the cracking statistical analyses.

Table 40. Summary results of statistical analyses.

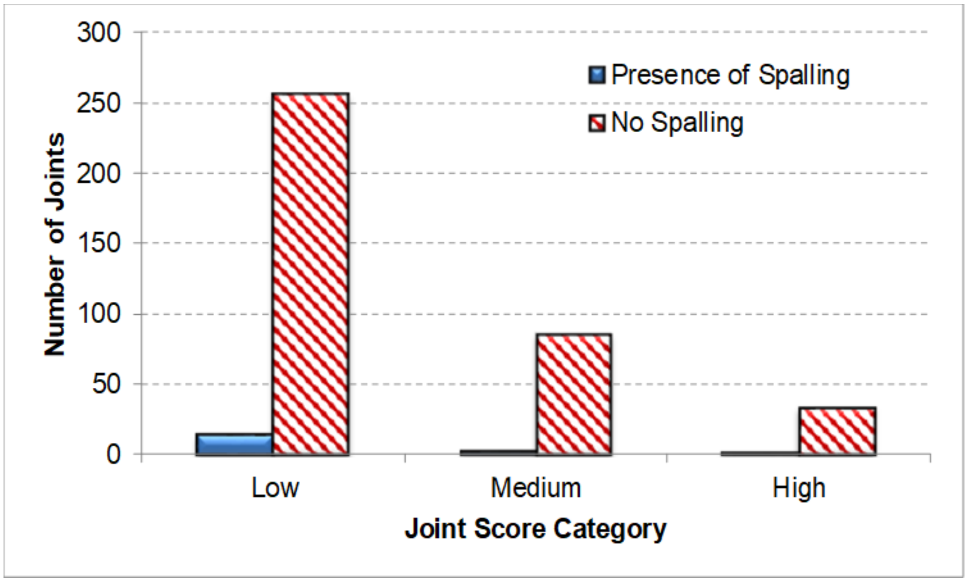
State	Number of Transverse Joints for Analyses	Cracking *p*-Value	Spalling *p*-Value
Arizona	390	0.015*	0.470
Arkansas	357	0.035*	0.823
California	388	0.769	0.589
Colorado	386	0.128	0.682
Delaware	449	0.425	0.750
Iowa	387	0.782	0.001*
Kansas	390	0.126	0.192
North Carolina	248	N/A	0.191
North Dakota	383	0.653	0.451
South Dakota	25	N/A	0.052
Wisconsin	346	N/A	0.097

*Significant at $p = 0.05$.
N/A = not applicable.



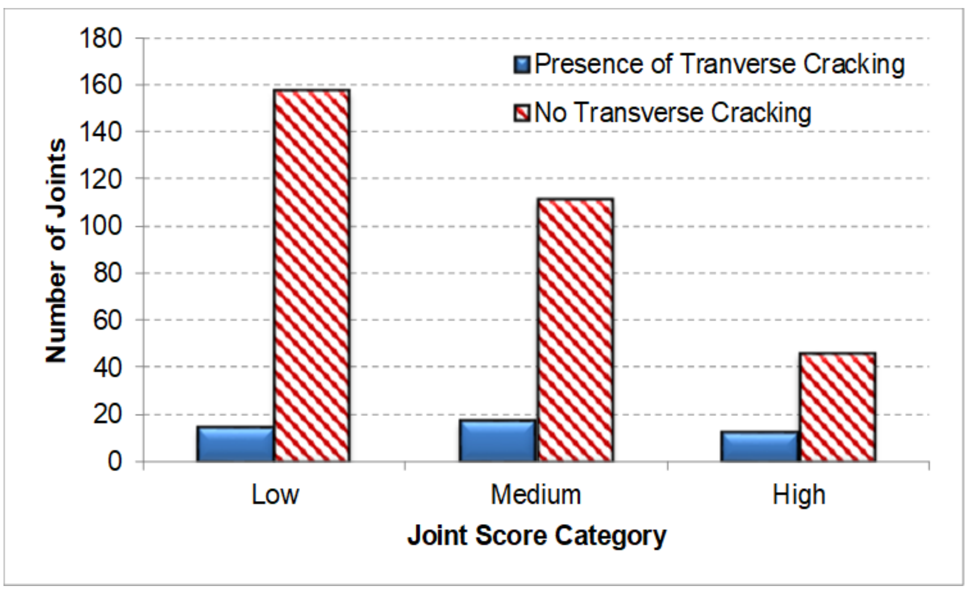
Source: FHWA.

Figure 88. Chart. Joint score and presence of cracking for LTPP test sections in Arizona.



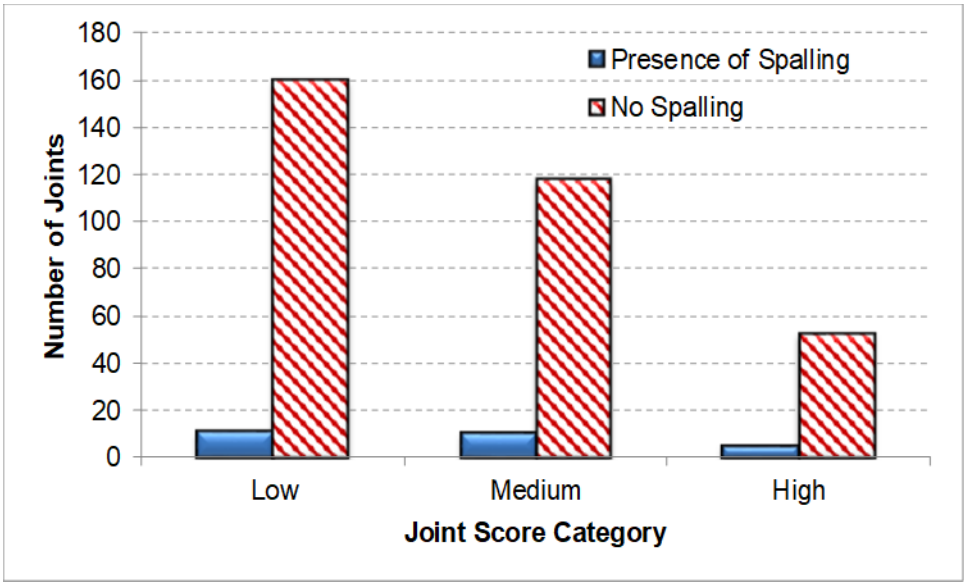
Source: FHWA.

Figure 89. Chart. Joint score and presence of spalling for LTPP test sections in Arizona.



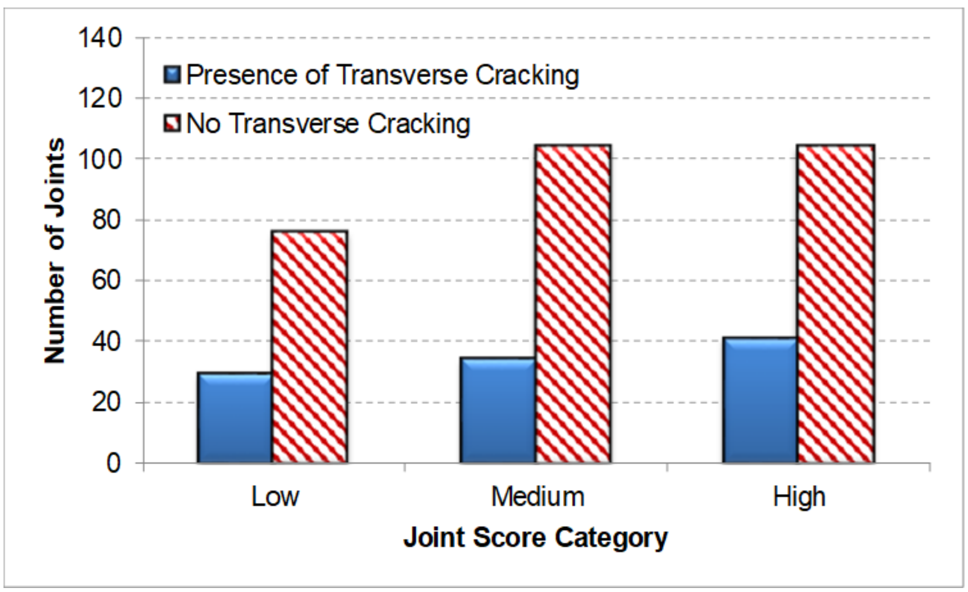
Source: FHWA.

Figure 90. Chart. Joint score and presence of cracking for LTPP test sections in Arkansas.



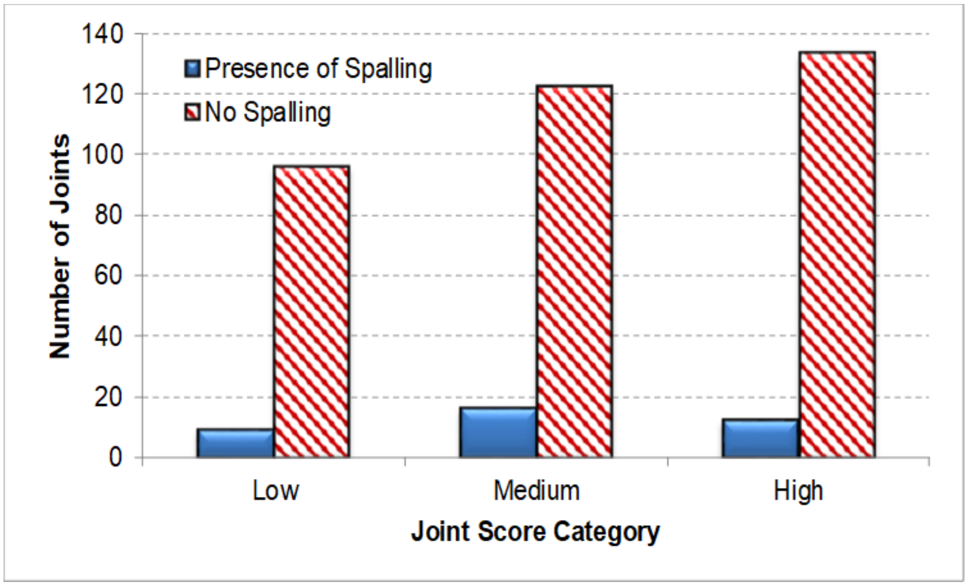
Source: FHWA.

Figure 91. Chart. Joint score and presence of spalling for LTPP test sections in Arkansas.



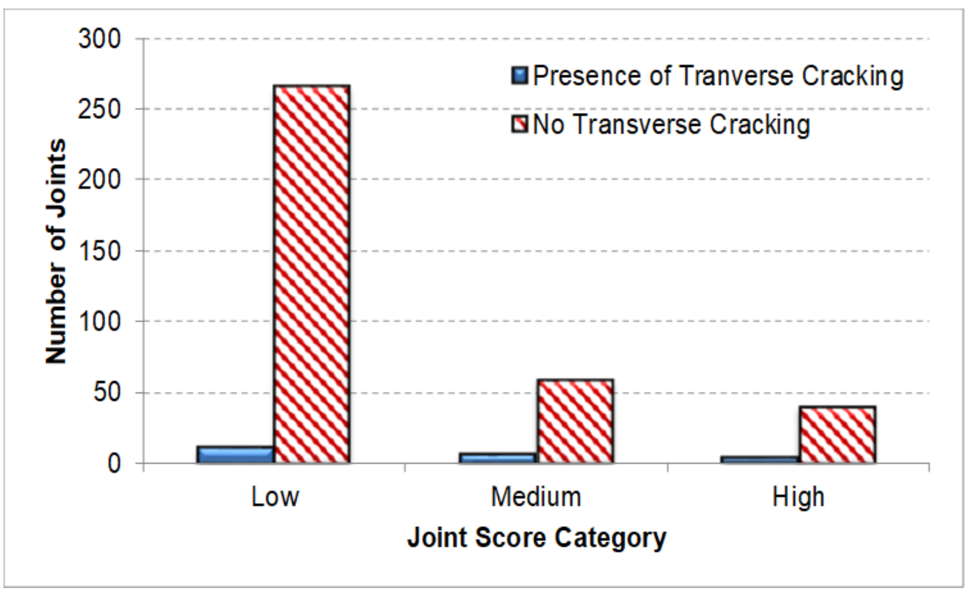
Source: FHWA.

Figure 92. Chart. Joint score and presence of cracking for LTPP test sections in California.



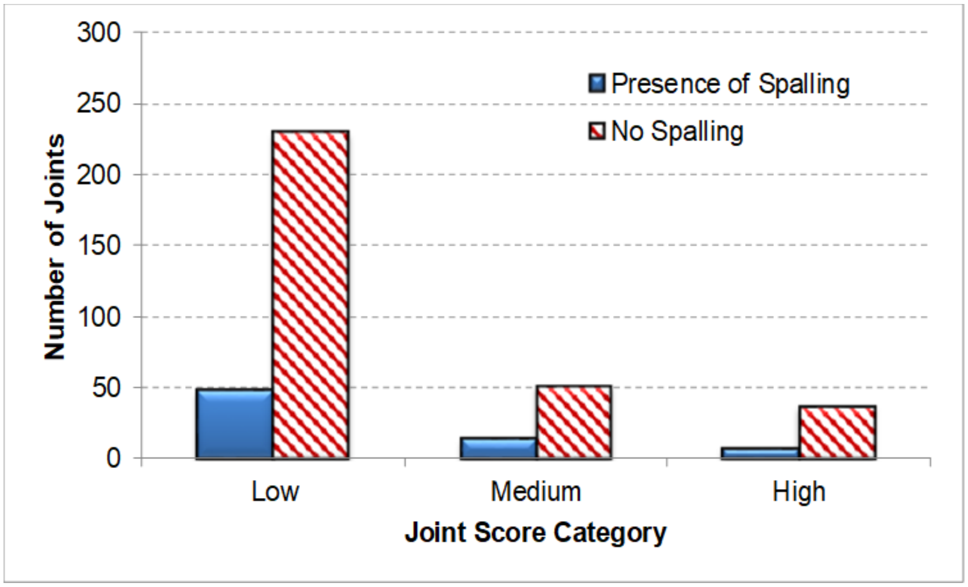
Source: FHWA.

Figure 93. Chart. Joint score and presence of spalling for LTPP test sections in California.



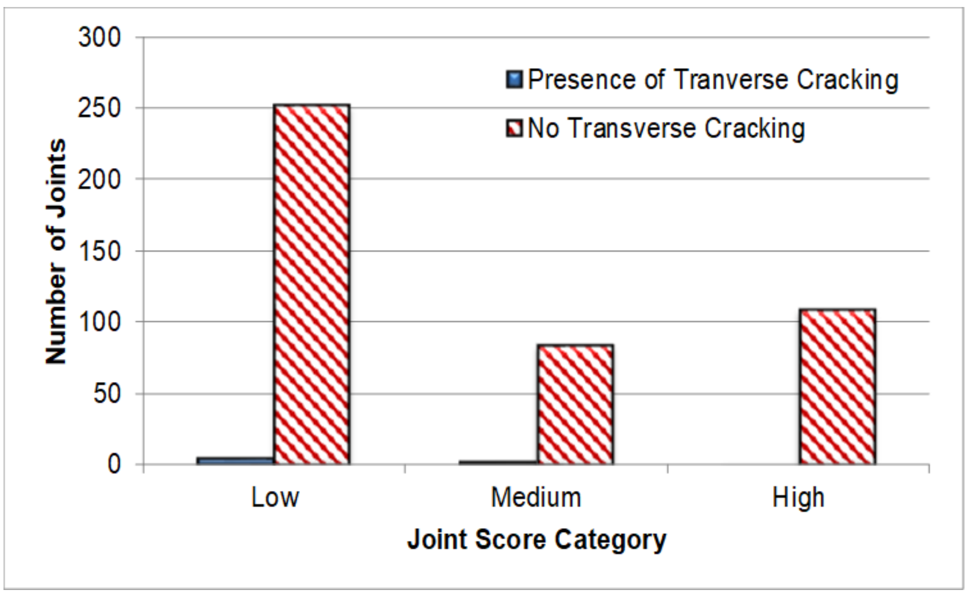
Source: FHWA.

Figure 94. Chart. Joint score and presence of cracking for LTPP test sections in Colorado.



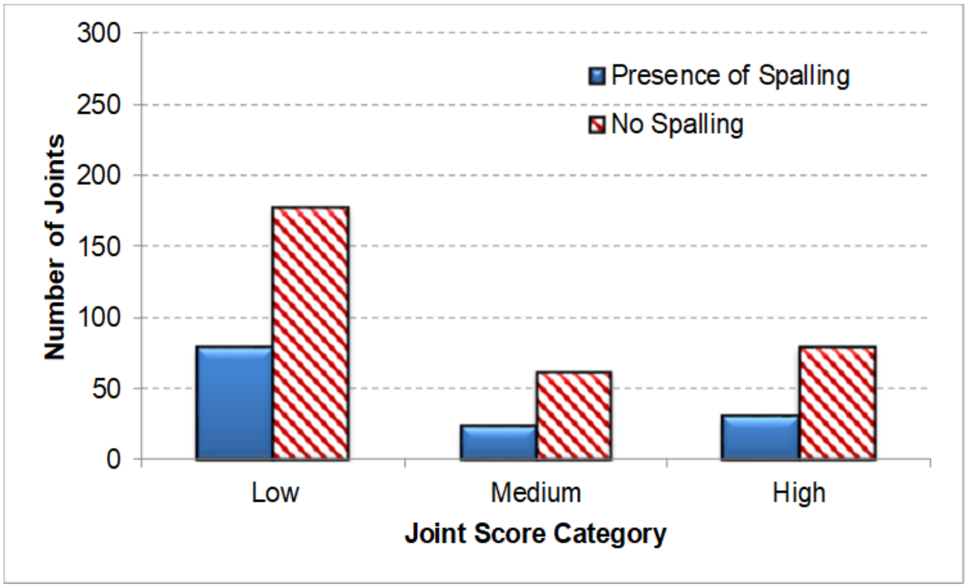
Source: FHWA.

Figure 95. Chart. Joint score and presence of spalling for LTPP test sections in Colorado.



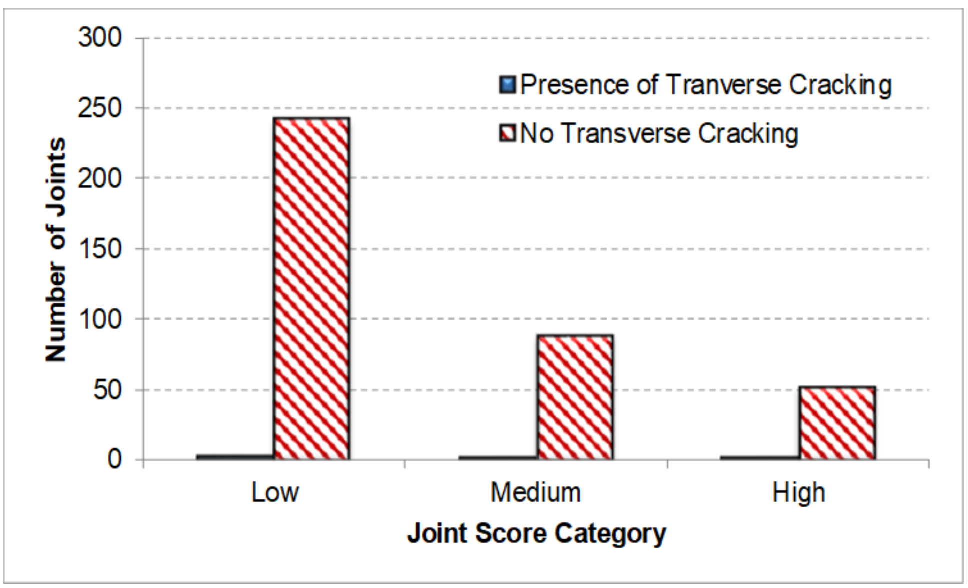
Source: FHWA.

Figure 96. Chart. Joint score and presence of cracking for LTPP test sections in Delaware.



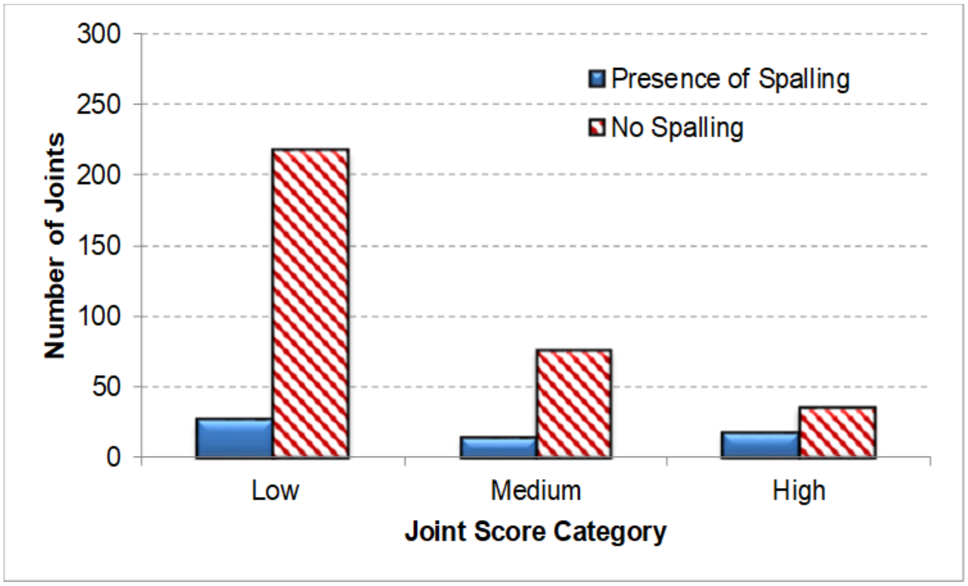
Source: FHWA.

Figure 97. Chart. Joint score and presence of spalling for LTPP test sections in Delaware.



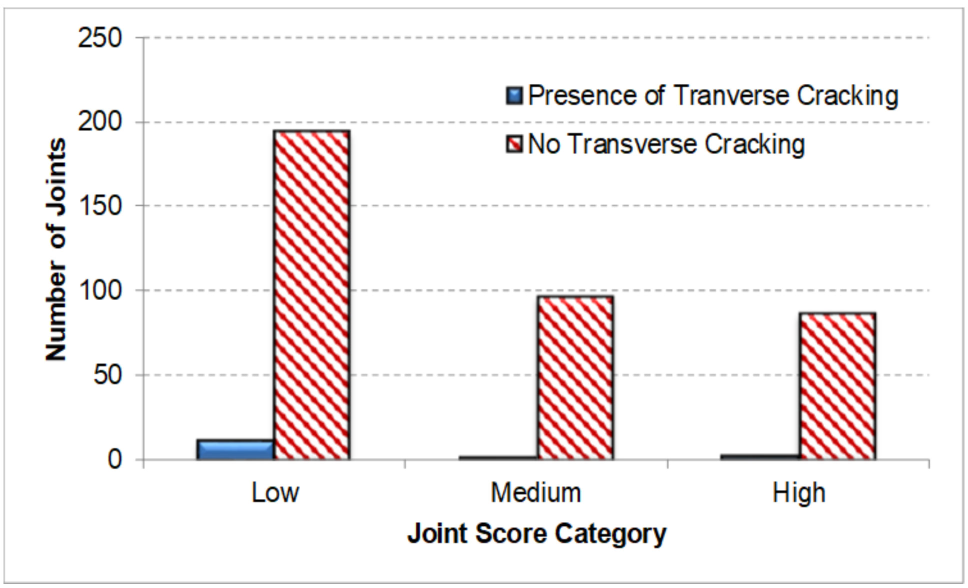
Source: FHWA.

Figure 98. Chart. Joint score and presence of cracking for LTPP test sections in Iowa.



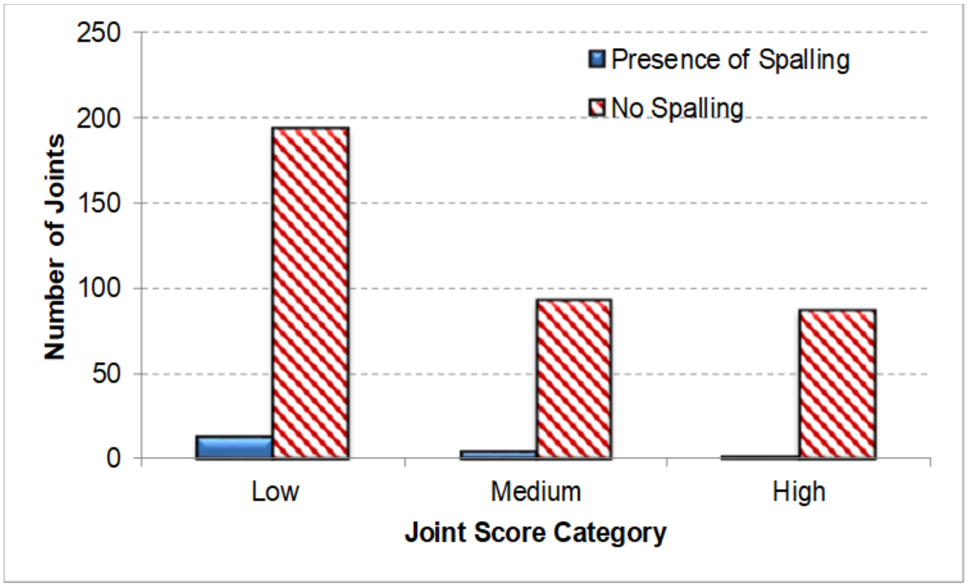
Source: FHWA.

Figure 99. Chart. Joint score and presence of spalling for LTPP test sections in Iowa.



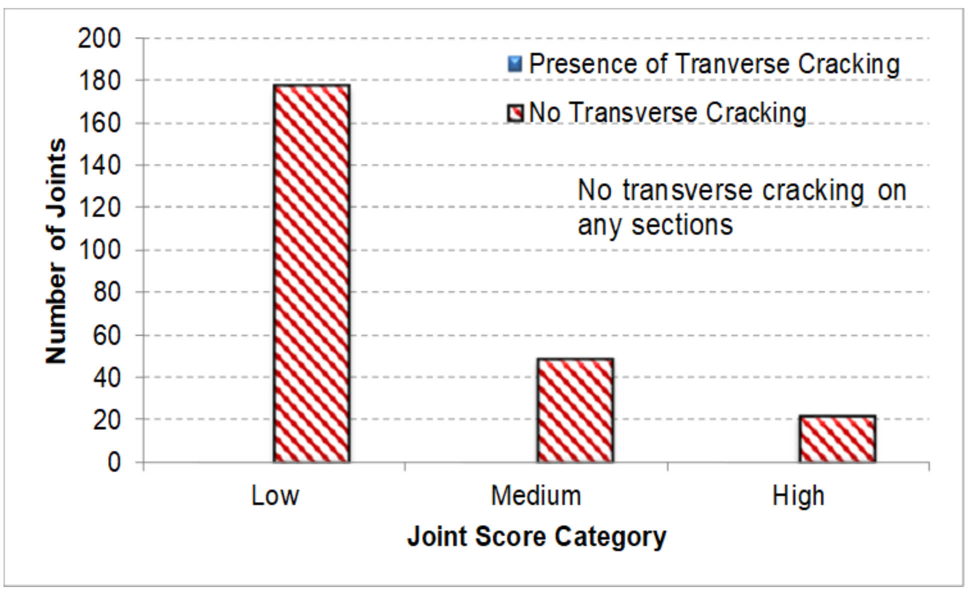
Source: FHWA.

Figure 100. Chart. Joint score and presence of cracking for LTPP test sections in Kansas.



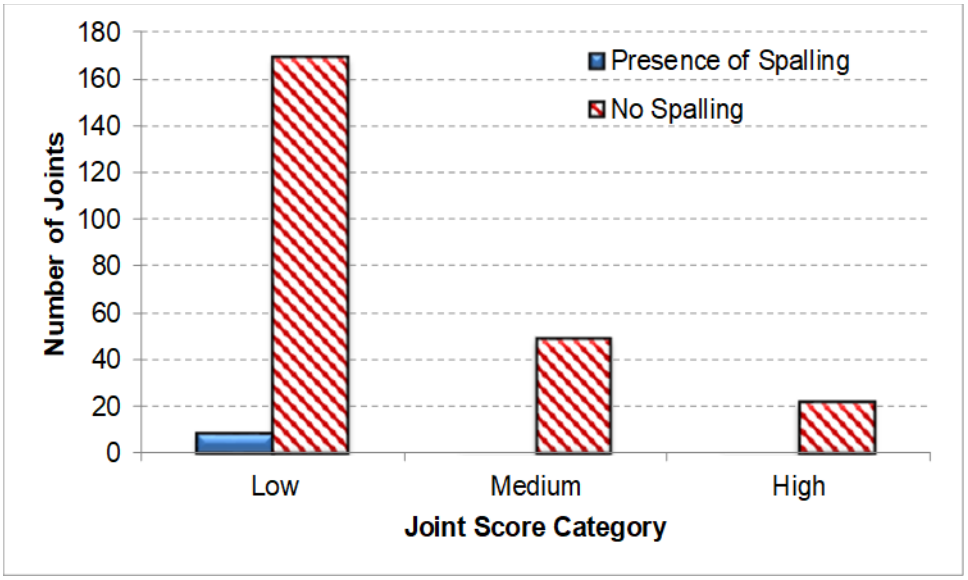
Source: FHWA.

Figure 101. Chart. Joint score and presence of spalling for LTPP test sections in Kansas.



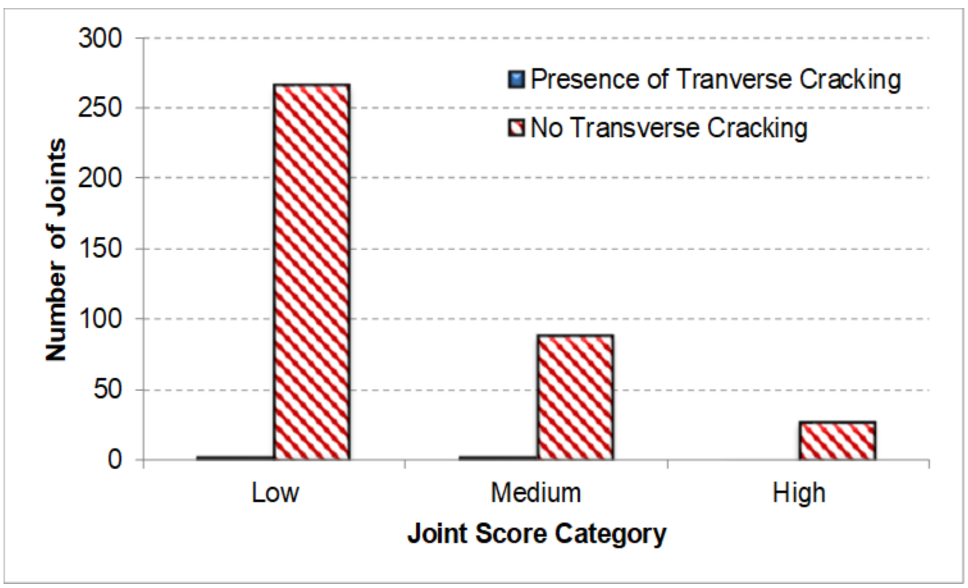
Source: FHWA.

Figure 102. Chart. Joint score and presence of cracking for LTPP test sections in North Carolina.



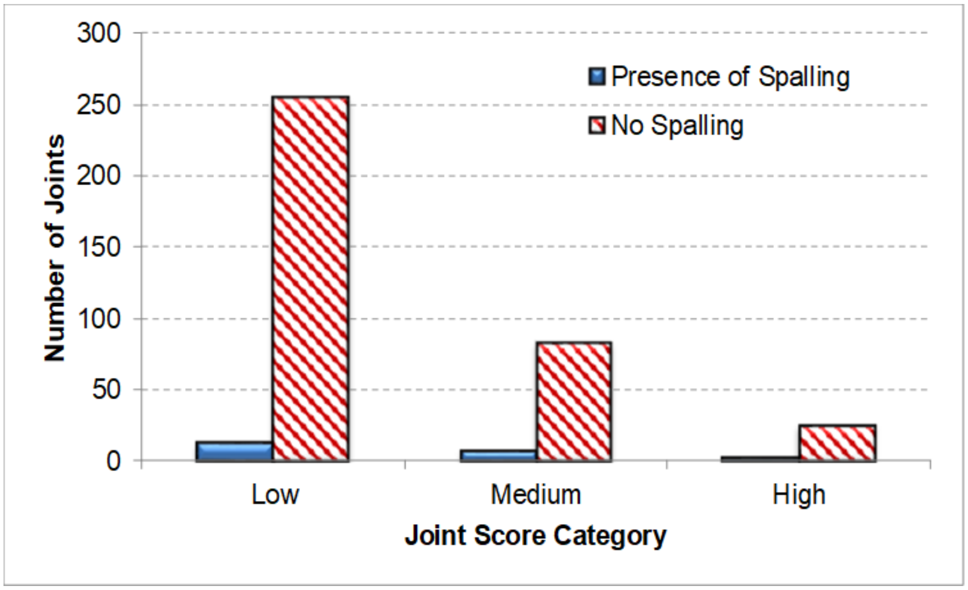
Source: FHWA.

Figure 103. Chart. Joint score and presence of spalling for LTPP test sections in North Carolina.



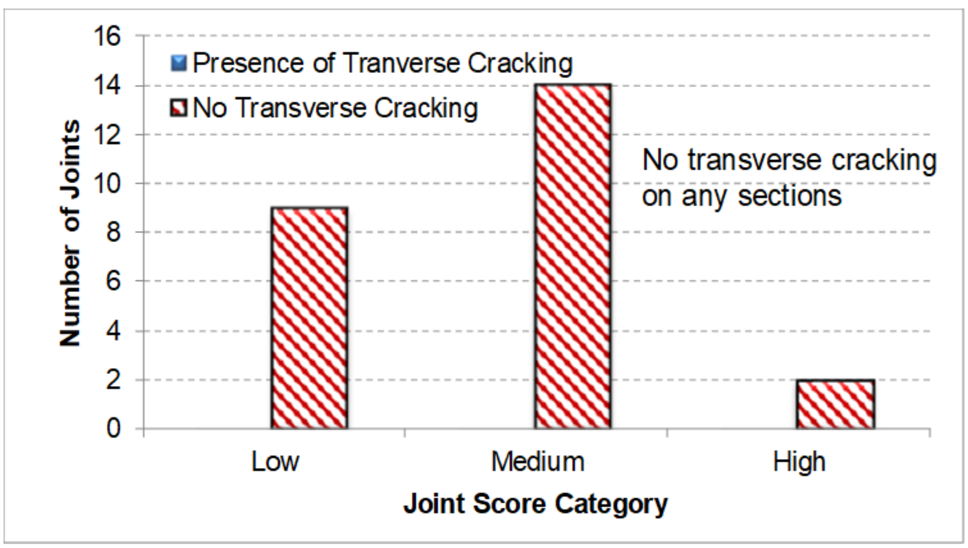
Source: FHWA.

Figure 104. Chart. Joint score and presence of cracking for LTPP test sections in North Dakota.



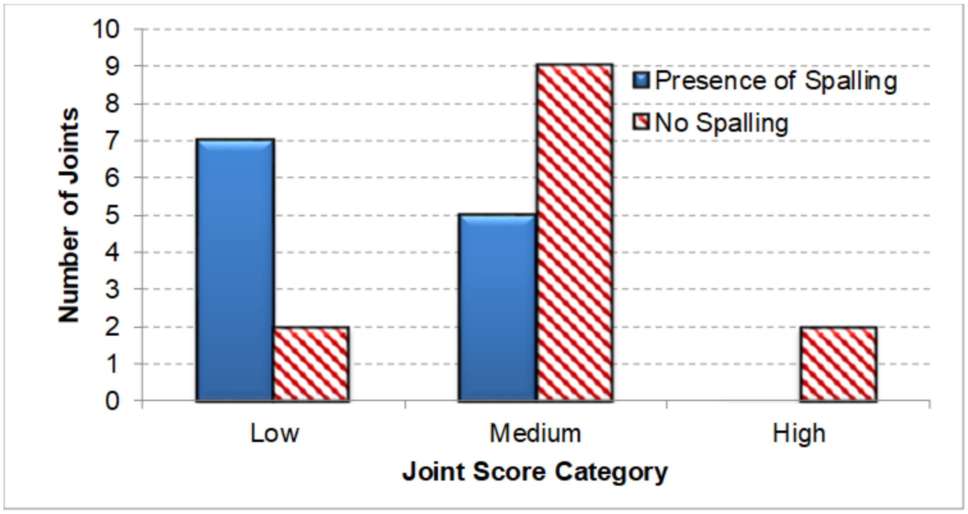
Source: FHWA.

Figure 105. Chart. Joint score and presence of spalling for LTPP test sections in North Dakota.



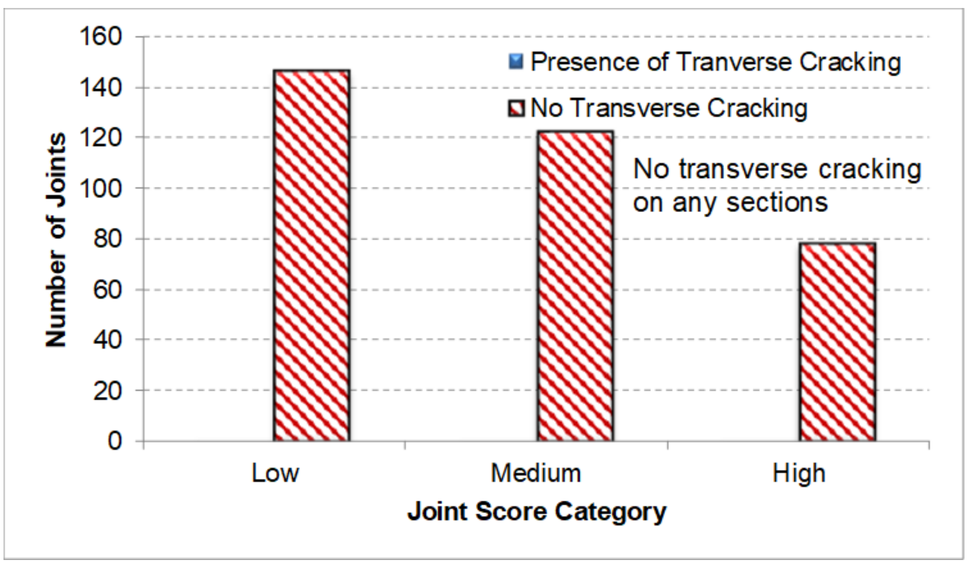
Source: FHWA.

Figure 106. Chart. Joint score and presence of cracking for the LTPP test section in South Dakota.



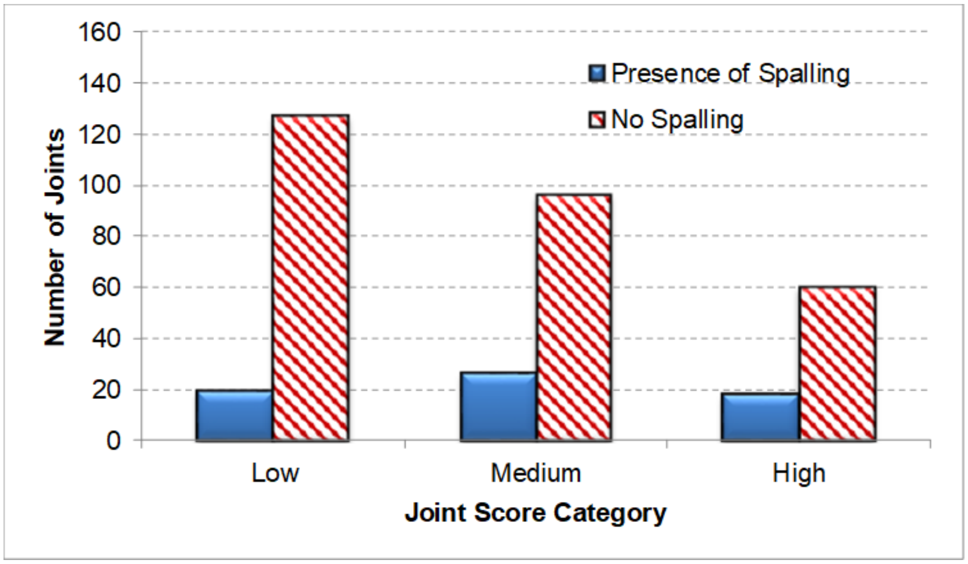
Source: FHWA.

Figure 107. Chart. Joint score and presence of spalling for the LTPP test section in South Dakota.



Source: FHWA.

Figure 108. Chart. Joint score and presence of cracking for LTPP test sections in Wisconsin.



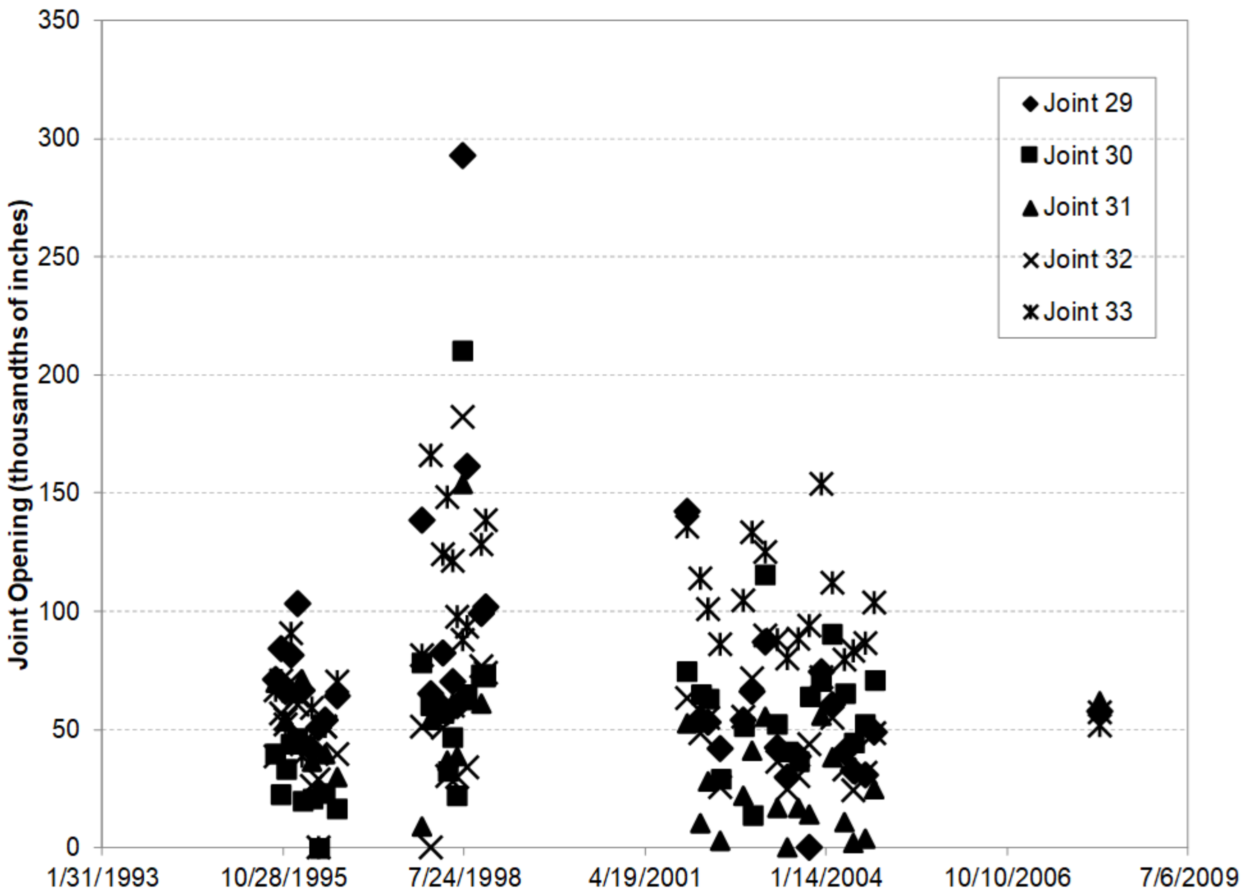
Source: FHWA.

Figure 109. Chart. Joint score and presence of spalling for LTPP test sections in Wisconsin.

CHAPTER 7. JOINT-OPENING ANALYSES

Arizona LTPP test section 4_0215, which was selected for MIT scanning and analysis, was part of the LTPP Seasonal Monitoring Program (SMP). Joint-opening data for five transverse joints on Arizona LTPP test section 4_0215 (i.e., joint 29 through joint 33) collected over approximately 13 yr were extracted from the LTPP database for analysis. Joint-opening data for Arizona LTPP test section 4_0215 are shown in figure 110. Each datapoint represents the average gage reading of three locations (i.e., pavement edge, middle of lane, and inside lane edge) relative to the smallest average gage reading at the transverse joint. A similar analysis was performed for Arizona LTPP test section 4_0215 in NCHRP Report 637 for joint-opening data measured over 10 yr.

Figure 110 shows that all transverse joints opened and closed over the analysis period due to thermal expansion and contraction of the PCC slabs and were not inhibited from doing so by misaligned dowels. Table 41 shows the maximum joint opening, average horizontal skew, average vertical tilt, average longitudinal translation, joint score, and effective reduction in dowel diameter for the five transverse joints from Arizona LTPP test section 4_0215. Data in table 41 do not indicate any correlation between dowel misalignment and joint opening for joint 29 through joint 33. The sample size presented in figure 110 and table 41 is limited, and analysis of other joint-opening data is needed to further understand the effect of dowel misalignment on joint opening and the potential for joint lockup.



Source: FHWA.

Figure 110. Chart. Joint-opening data from five instrumented transverse joints at Arizona LTPP test section 4_0215.

Table 41. Maximum joint opening, dowel alignment data, and joint score for five instrumented transverse joints with joint-opening data at Arizona LTPP test section 4_0215.

Transverse Joint Number	Maximum Joint Opening (Thousandths of Inches)	Average Horizontal Skew (Inches)	Average Vertical Tilt (Inches)	Average Longitudinal Translation (Inches)	Joint Score	Effective Reduction in Dowel Diameter (Percent)
29	293	0.18	0.36	1.33	1	3.5
30	210	0.36	0.15	0.29	1	0.0
31	154	0.09	0.29	2.12	1	2.7
32	182	0.21	0.42	0.86	14	3.0
33	166	0.21	0.37	1.37	7	0.3

CHAPTER 8. AASHTOWARE PAVEMENT ME DESIGN ANALYSES USING EQUIVALENT DOWEL DIAMETER

To identify any relationship between the equivalent dowel diameter and LTPP field distress data, analyses were conducted using data from all test sections. Pavement distress information was extracted from the LTPP database and compared with predicted performance from AASHTOWare Pavement ME Design using both the actual and computed equivalent dowel diameter. The goal of these analyses was to consider the effects of dowel misalignment through the use of the equivalent dowel diameter in terms of performance criteria, such as faulting and cracking, in the context of other compounding factors (e.g., climate, traffic, materials, support conditions), which allows data from all sections to be used together as the impact of these factors is considered in AASHTOWare Pavement ME Design performance models.

Default global calibration coefficients and actual relevant site information available in the LTPP database (e.g., subgrade, materials, traffic, and climate) for each test section were used to develop the AASHTOWare Pavement ME Design files for the analyses. Although some States developed local calibration coefficients, they were not used for consistency between all LTPP test sections analyzed. Results of the analyses for various test sections are shown in table 42 through table 52. The AASHTOWare Pavement ME Design runs were executed from the actual construction month to the field-data-collection month as shown in table 42 through table 52. Table 53, figure 111, and figure 112 summarize the results of the analyses.

The results of the analyses show that using the average equivalent, instead of actual, dowel diameter produces a reduced bias of the in-service LTE as modeled using AASHTOWare Pavement ME Design. This result is consistent for both 1.25- and 1.5-inch-diameter dowels, and the effect is stronger when LTE is greater than 60 percent. Figure 111 shows that, when the actual dowel diameter is used, AASHTOWare Pavement ME Design generally models higher LTE than is observed in the field; some of this bias is removed when the average equivalent dowel diameter is used. For LTE, table 53 shows lower mean residuals when comparing as-predicted distresses versus actual distresses using the average equivalent, as opposed to actual, dowel diameter. Thus, using the equivalent dowel diameter is a less-biased estimator of long-term pavement LTE as modeled using AASHTOWare Pavement ME Design than using the actual dowel diameter.

The results of the analyses are reversed when evaluating faulting. The results of faulting analyses show that using the average equivalent, instead of actual, dowel diameter produces a greater bias of faulting as modeled using AASHTOWare Pavement ME Design. Figure 112 shows that when the actual dowel diameter is used, AASHTOWare Pavement ME Design models are generally unbiased; some bias (i.e., asymmetry) is introduced when the average equivalent dowel diameter is used. For faulting, table 53 shows lower mean residuals when comparing as-predicted distresses versus actual distresses using the actual, as opposed to average equivalent dowel diameter. Thus, using the actual dowel diameter is a less-biased estimator of faulting as modeled using AASHTOWare Pavement ME Design than using the average equivalent dowel diameter.

The two results of the analyses seem contradictory because faulting correlates with LTE. However, the results make sense when the following two factors are considered:

- Faulting correlates with LTE, but low LTE does not always correspond to high faulting.
- Factors such as traffic, support conditions, climate, and age all affect faulting independent of LTE.

The results of the analyses also show the effect of calibration on the faulting models in AASHTOWare Pavement ME Design, which was calibrated using LTPP test sections. As such, the research team for the current study hypothesize that dowel misalignment in LTPP test sections is accounted for in the calibration. The calibration process for faulting may have removed some of the bias in faulting models but not necessarily in LTE models because LTE models are not calibrated with field-measured LTE data.

Taken together, the data suggest that dowel misalignment affects long-term LTE of a concrete pavement because using the average equivalent, instead of actual, dowel diameter reduces bias in the AASHTOWare Pavement ME Design LTE model. This result is consistent with the lab results conducted in NCHRP Report 637. However, figure 111 and figure 112 exhibit a considerable amount of scatter in LTE and faulting modeled using AASHTOWare Pavement ME Design versus actual LTE and faulting. The remaining bias and scatter suggests that the two models (i.e., the equivalent dowel diameter model from NCHRP Report 637 and the LTE model in AASHTOWare Pavement ME Design) can be improved using the data collected as part of this study. More thorough analyses and adjustments to the models may be warranted to improve the equivalent dowel diameter model and the LTE model in AASHTOWare Pavement ME Design, which is beyond the scope of this study.

Analyses of LTE and faulting as independent variables with the joint score and average equivalent dowel diameter as dependent variables were not undertaken in this study. LTE and faulting are significantly impacted by other parameters (e.g., traffic, dowel size, base type, subgrade type, climate, PCC thickness, and age of pavement). For example, a test section experiencing 5 million trucks over 20 yr will have lower LTE and far more faulting than a test section experiencing 200,000 trucks over 20 yr with the same extent of misalignment. Likewise, a test section with—a heavy clay subgrade and an aggregate base will have lower LTE and more faulting than a test section with a sandy gravel subgrade and a treated base for the same average joint score. These types of analyses have to be performed on a section-by-section basis by comparing the well-aligned transverse joints within a test section to the poorly aligned transverse joints within the same test section. However, there is too much inherent variability between slabs and transverse joints within any test section to perform this analysis on a section-by-section basis. These analyses for each test section were also beyond the scope of this study. As such, in this study, a 500-foot LTPP test section was analyzed as a single unit and AASHTOWare Pavement ME Design used to account for the effects of other variables by comparing LTE and faulting using the actual and average equivalent dowel diameter to the pavement age.

Temperature affects the field-measured LTE but is not considered in the LTE generated by AASHTOWare Pavement ME Design using the actual and average equivalent dowel diameter. The LTE generated using AASHTOWare Pavement ME Design represents an average LTE at the pavement age (corresponding to the date of field data collection) rather than a temperature-dependent LTE affected by daily opening and closing of transverse joints due to temperature cycling. Because the temperature dependence of LTE cannot be modeled in AASHTOWare Pavement ME Design, it is not considered in analyses. It is assumed that, because of the large number of transverse joints analyzed in this study, the temperature effects on transverse joint LTE average out.

Table 42. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in Arizona.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (12/2014)	Predicted faulting (Inches) (12/2014)	Predicted Slabs Cracked (Percent) (12/2014)	Actual LTE (Percent) (12/2014)	Actual Faulting (Inches) (12/2014)	Actual Slabs Cracked (Percent) (12/2014)
213	1.23 (equivalent)	90.1	0.002	51.04	66	0.027	0.0
	1.25 (actual)	90.7	0.001	51.04	66	0.027	0.0
214	1.17 (equivalent)	86.1	0.804	3.42	61	0.051	3.0
	1.25 (actual)	89.7	0.498	3.42	61	0.051	3.0
215	1.37 (equivalent)	87.8	0.297	5.28	73	0.023	0.0
	1.50 (actual)	91.6	0.161	5.28	73	0.023	0.0
216	1.43 (equivalent)	89.1	0.032	0.00	57	0.011	0.0
	1.50 (actual)	91.0	0.017	0.00	57	0.011	0.0
217	1.24 (equivalent)	91.6	0.026	99.92	53	0.012	63.6
	1.25 (actual)	91.8	0.024	99.92	53	0.012	63.6
218	1.17 (equivalent)	87.9	0.926	99.93	83	0.009	51.5
	1.25 (actual)	91.1	0.624	99.93	83	0.009	51.5
219	1.42(equivalent)	92.1	0.152	99.48	48	0.007	57.5
	1.50 (actual)	93.6	0.127	99.48	48	0.007	57.5
220	1.44 (equivalent)	91.1	0.011	0.00	82	0.006	0.0
	1.50 (actual)	92.4	0.006	0.00	82	0.006	0.0
221	1.22 (equivalent)	90.6	0.000	1.42	38	0.021	0.0
	1.25 (actual)	91.5	0.000	1.42	38	0.021	0.0
222	1.15 (equivalent)	85.5	0.511	0.10	39	0.012	21.2
	1.25 (actual)	90.4	0.245	0.10	39	0.012	21.2
223	1.37 (equivalent)	88.9	0.191	0.08	54	0.013	0.0
	1.50 (actual)	92.4	0.093	0.08	54	0.013	0.0
224	1.40 (equivalent)	91.0	0.008	0.00	57	0.004	0.0
	1.50 (actual)	93.1	0.003	0.00	57	0.004	0.0

Table 43. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in Arkansas.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (08/2013)	Predicted Faulting (Inches) (08/2013)	Predicted Slabs Cracked (Percent) (08/2013)	Actual LTE (Percent) (08/2013)	Actual Faulting (Inches) (08/2013)	Actual Slabs Cracked (Percent) (08/2013)
214	1.14 (equivalent)	85.1	0.166	32.02	67	0.10	3.03
	1.25 (actual)	90.6	0.097	32.02	67	0.10	3.03
215	1.40 (equivalent)	95.0	0.012	0.01	93	0.14	0.00
	1.50 (actual)	95.0	0.009	0.01	93	0.14	0.00
216	1.42 (equivalent)	89.7	0.002	0.00	51	0.04	0.00
	1.50 (actual)	91.7	0.001	0.00	51	0.04	0.00
217	1.15 (equivalent)	89.4	0.002	11.40	52	0.02	24.20
	1.25 (actual)	92.8	0.000	11.40	52	0.02	24.20
218	0.97 (equivalent)	53.7	1.030	96.23	44	0.01	100.00
	1.25 (actual)	91.8	0.121	96.23	44	0.01	100.00
219	1.41 (equivalent)	94.1	0.006	0.01	32	0.01	0.00
	1.50 (actual)	95.0	0.005	0.01	32	0.01	0.00
220	1.39 (equivalent)	95.0	0.001	0.00	84	0.02	0.00
	1.50 (actual)	95.0	0.001	0.00	84	0.02	0.00
221	1.22 (equivalent)	95.0	0.000	1.05	81	0.05	6.06
	1.25 (actual)	95.0	0.000	1.05	81	0.05	6.06
222	1.18 (equivalent)	89.6	0.129	30.62	84	0.09	0.00
	1.25 (actual)	91.9	0.103	30.62	84	0.09	0.00
223	1.41 (equivalent)	95.0	0.007	0.06	91	0.02	0.00
	1.50 (actual)	95.0	0.006	0.06	91	0.02	0.00
224	1.47 (equivalent)	94.7	0.001	0.00	39	0.04	0.00
	1.50 (actual)	95.0	0.001	0.00	39	0.04	0.00

Table 44. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sites in Colorado.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (09/2013)	Predicted Faulting (Inches) (09/2014)	Predicted Slabs Cracked (Percent) (09/2014)	Actual LTE (Percent) (09/2013)	Actual Faulting (Inches) (09/2014)	Actual Slabs Cracked (Percent) (09/2014)
213	1.24 (equivalent)	91.0	0.005	0.70	79	0.0	0.0
	1.25 (actual)	91.3	0.004	0.70	79	0.0	0.0
214	1.22 (equivalent)	89.5	0.042	0.00	80	0.0	3.0
	1.25 (actual)	90.5	0.038	0.00	80	0.0	3.0
215	1.45 (equivalent)	95.0	0.011	0.00	88	0.0	0.0
	1.50 (actual)	95.0	0.009	0.00	88	0.0	0.0
216	1.48 (equivalent)	93.6	0.002	0.00	95	0.0	18.1
	1.50 (actual)	94.0	0.001	0.00	95	0.0	18.1
217	1.09 (equivalent)	83.3	0.008	0.00	88	0.1	21.2
	1.25 (actual)	92.9	0.000	0.00	88	0.1	21.2
218	1.05 (equivalent)	84.9	0.173	12.74	78	0.0	9.1
	1.25 (actual)	93.6	0.098	12.74	78	0.0	9.1
219	1.32 (equivalent)	95.0	0.012	0.00	89	0.0	0.0
	1.50 (actual)	95.0	0.009	0.00	89	0.0	0.0
220	1.48 (equivalent)	95.0	0.000	0.00	91	0.1	0.0
	1.50 (actual)	95.0	0.000	0.00	91	0.1	0.0
221	1.19 (equivalent)	90.4	0.000	0.17	92	0.0	0.0
	1.25 (actual)	92.5	0.000	0.17	92	0.0	0.0
222	1.24 (equivalent)	90.6	0.022	0.00	89	0.0	0.0
	1.25 (actual)	90.9	0.021	0.00	89	0.0	0.0
223	1.47 (equivalent)	93.2	0.009	0.00	28	0.0	12.1
	1.50 (actual)	93.7	0.009	0.00	28	0.0	12.1
224	1.43 (equivalent)	91.0	0.001	0.00	95	0.0	0.0
	1.50 (actual)	92.6	0.001	0.00	95	0.0	0.0

Table 45. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in California.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (10/2014)	Predicted Faulting (Inches) (10/2014)	Predicted Slabs Cracked (Percent) (10/2014)	Actual LTE (Percent) (10/2014)	Actual Faulting (Inches) (10/2014)	Actual Slabs Cracked (Percent) (10/2014)
201	1.14 (equivalent)	84.1	0.061	53.11	78	0.01	75.75
	1.50 (actual)	94.4	0.007	53.11	78	0.01	75.75
202	0.80 (equivalent)	43.7	0.193	8.50	87	0.01	81.80
	1.25 (actual)	90.9	0.000	8.50	87	0.01	81.80
203	1.22 (equivalent)	67.9	0.015	1.21	83	0.01	0.00
	1.50 (actual)	90.9	0.000	1.21	83	0.01	0.00
204	1.00 (equivalent)	44.0	0.169	0.05	94	0.02	0.00
	1.25 (actual)	77.1	0.037	0.05	94	0.02	0.00
205	1.29 (equivalent)	92.5	0.004	0.00	79	0.03	69.69
	1.50 (actual)	95.0	0.001	0.00	79	0.03	69.69
206	0.79 (equivalent)	51.2	0.067	0.00	88	0.00	69.69
	1.25 (actual)	92.0	0.000	0.00	88	0.00	69.69
207	1.31(equivalent)	87.3	0.000	0.00	72	0.04	9.09
	1.50 (actual)	93.4	0.000	0.00	72	0.04	9.09
208	1.03 (equivalent)	52.0	0.092	0.00	74	0.03	6.06
	1.25 (actual)	82.9	0.013	0.00	74	0.03	6.06
209	1.29 (equivalent)	91.9	0.011	25.22	85	0.03	3.03
	1.50 (actual)	95.0	0.003	25.22	85	0.03	3.03
210	1.05 (equivalent)	67.1	0.035	1.24	88	0.01	0.00
	1.25 (actual)	91.5	0.000	1.24	88	0.01	0.00
211	1.21 (equivalent)	53.0	0.023	0.04	87	0.02	0.00
	1.50 (actual)	91.1	0.000	0.04	87	0.02	0.00
212	0.96 (equivalent)	51.0	0.115	0.03	96	0.00	0.00
	1.25 (actual)	79.9	0.024	0.03	96	0.00	0.00

Table 46. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test section in Delaware.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (05/2012)	Predicted Faulting (Inches) (05/2012)	Predicted Slabs Cracked (Percent) (05/2012)	Actual LTE (Percent) (05/2012)	Actual Faulting (Inches) (05/2012)	Actual Slabs Cracked (Percent) (05/2012)
201	1.07 (equivalent)	90.1	0.026	0.01	88	0.0	0.0
	1.25 (actual)	93.3	0.009	0.01	88	0.0	0.0
202	1.19 (equivalent)	89.8	0.001	0.00	85	0.0	0.0
	1.25 (actual)	91.5	0.001	0.00	85	0.0	0.0
203	1.49 (equivalent)	92.1	0.000	0.00	88	0.0	0.0
	1.50 (actual)	92.3	0.000	0.00	88	0.0	0.0
204	1.48 (equivalent)	91.2	0.005	0.00	87	0.0	0.0
	1.50 (actual)	91.6	0.004	0.00	87	0.0	0.0
205	1.22 (equivalent)	88.9	0.005	0.00	80	0.0	12.1
	1.25 (actual)	90.1	0.004	0.00	80	0.0	12.1
206	1.10 (equivalent)	90.4	0.000	0.00	85	0.0	0.0
	1.25 (actual)	94.0	0.000	0.00	85	0.0	0.0
207	1.47 (equivalent)	94.2	0.000	0.00	90	0.0	3.0
	1.50 (actual)	94.5	0.000	0.00	90	0.0	3.0
208	1.42 (equivalent)	91.0	0.001	0.00	91	0.0	0.0
	1.50 (actual)	92.4	0.001	0.00	91	0.0	0.0
209	1.14 (equivalent)	87.5	0.010	0.00	83	0.0	0.0
	1.25 (actual)	91.8	0.006	0.00	83	0.0	0.0
210	1.23 (equivalent)	93.4	0.000	0.00	81	0.0	0.0
	1.25 (actual)	93.8	0.000	0.00	81	0.0	0.0
211	1.48 (equivalent)	93.0	0.000	0.00	70	0.0	0.0
	1.50 (actual)	93.3	0.000	0.00	70	0.0	0.0
212	1.47 (equivalent)	90.4	0.002	0.00	74	0.0	0.0
	1.50 (actual)	91.2	0.002	0.00	74	0.0	0.0
259	1.41 (equivalent)	90.8	0.007	0.00	71	0.0	0.0
	1.50 (actual)	92.7	0.006	0.00	71	0.0	0.0
260	0.30 (equivalent)	46.1	0.055	0.00	77	0.0	0.0
	1.25 (actual)	83.8	0.010	0.00	77	0.0	0.0

Table 47. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in Iowa.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (11/2014)	Predicted Faulting (Inches) (11/2014)	Predicted Slabs Cracked (Percent) (11/2014)	Actual LTE (Percent) (11/2014)	Actual Faulting (Inches) (11/2014)	Actual Slabs Cracked (Percent) (11/2014)
213	1.21 (equivalent)	89.9	0.000	0.01	73	0.0	0.0
	1.25 (actual)	91.2	0.000	0.01	73	0.0	0.0
214	1.21 (equivalent)	88.9	0.025	0.01	83	0.0	6.1
	1.25 (actual)	90.2	0.022	0.01	83	0.0	6.1
215	1.48 (equivalent)	90.9	0.009	0.00	89	0.0	0.0
	1.50 (actual)	91.4	0.008	0.00	89	0.0	0.0
216	1.46 (equivalent)	90.3	0.012	0.00	88	0.0	0.0
	1.50 (actual)	95.0	0.011	0.00	88	0.0	0.0
217	1.05 (equivalent)	87.2	0.002	0.07	82	0.0	0.0
	1.25 (actual)	93.9	0.002	0.07	82	0.0	0.0
218	1.17 (equivalent)	89.7	0.009	0.00	67	0.0	6.1
	1.25 (actual)	92.1	0.007	0.00	67	0.0	6.1
219	1.42 (equivalent)	94.3	0.000	0.00	86	0.0	0.0
	1.50 (actual)	95.0	0.000	0.00	86	0.0	0.0
220	1.31 (equivalent)	91.6	0.000	0.00	79	0.0	0.0
	1.50 (actual)	94.2	0.000	0.00	79	0.0	0.0
221	1.21 (equivalent)	92.0	0.000	0.00	83	0.0	0.0
	1.25 (actual)	92.9	0.000	0.00	83	0.0	0.0
222	1.15 (equivalent)	88.7	0.014	0.00	87	0.0	0.0
	1.25 (actual)	92.0	0.010	0.00	87	0.0	0.0
223	1.47 (equivalent)	90.6	0.003	0.00	88	0.0	0.0
	1.50 (actual)	91.4	0.003	0.00	88	0.0	0.0
224	1.47 (equivalent)	94.6	0.000	0.00	85	0.0	0.0
	1.50 (actual)	94.8	0.000	0.00	85	0.0	0.0

Table 48. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in Kansas.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (09/2012)	Predicted Faulting (Inches) (09/2012)	Predicted Slabs Cracked (Percent) (09/2012)	Actual LTE (Percent) (09/2012)	Actual Faulting (Inches) (09/2012)	Actual Slabs Cracked (Percent) (09/2012)
201	1.09 (equivalent)	84.9	0.136	45.32	95	0.0	15.2
	1.25 (actual)	91.9	0.077	45.32	95	0.0	15.2
202	1.05 (equivalent)	81.3	0.055	13.42	86	0.0	24.2
	1.25 (actual)	92.2	0.000	13.42	86	0.0	24.2
203	1.48 (equivalent)	91.6	0.002	0.00	82	0.0	0.0
	1.50 (actual)	92.0	0.002	0.00	82	0.0	0.0
204	1.48 (equivalent)	90.4	0.072	0.01	71	0.0	3.0
	1.50 (actual)	90.9	0.069	0.01	71	0.0	3.0
205	1.19 (equivalent)	91.8	0.035	9.50	70	0.0	0.0
	1.25 (actual)	93.2	0.027	9.50	70	0.0	0.0
206	1.17 (equivalent)	91.0	0.000	0.45	86	0.0	0.0
	1.25 (actual)	93.4	0.000	0.45	86	0.0	0.0
207	1.35 (equivalent)	91.5	0.002	0.00	89	0.0	0.0
	1.50 (actual)	94.7	0.000	0.00	89	0.0	0.0
208	1.46 (equivalent)	92.2	0.034	0.00	87	0.0	0.0
	1.50 (actual)	92.9	0.030	0.00	87	0.0	0.0
209	1.13 (equivalent)	84.2	0.087	0.28	84	0.0	0.0
	1.25 (actual)	90.7	0.052	0.28	84	0.0	0.0
210	1.19 (equivalent)	88.6	0.004	0.03	86	0.0	0.0
	1.25 (actual)	91.1	0.000	0.03	86	0.0	0.0
211	1.43 (equivalent)	91.5	0.002	0.00	86	0.0	0.0
	1.50 (actual)	93.0	0.001	0.00	86	0.0	0.0
212	1.43 (equivalent)	90.7	0.050	0.00	92	0.0	0.0
	1.50 (actual)	92.3	0.041	0.00	92	0.0	0.0

Table 49. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in North Carolina.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (10/2012)	Predicted Faulting (Inches) (10/2012)	Predicted Slabs Cracked (Percent) (10/2012)	Actual LTE (Percent) (10/2012)	Actual Faulting (Inches) (10/2012)	Actual Slabs Cracked (Percent) (10/2012)
203	1.45 (equivalent)	90.1	0.000	0.0	76	0.0	0.0
	1.50 (actual)	91.3	0.000	0.0	76	0.0	0.0
204	1.39 (equivalent)	87.6	0.013	0.0	89	0.0	0.0
	1.50 (actual)	90.9	0.009	0.0	89	0.0	0.0
207	1.39 (equivalent)	91.0	0.000	0.0	96	0.0	0.0
	1.50 (actual)	93.6	0.000	0.0	96	0.0	0.0
208	1.44 (equivalent)	91.1	0.004	0.0	32	0.0	0.0
	1.50 (actual)	92.5	0.003	0.0	32	0.0	0.0
211	1.42 (equivalent)	90.3	0.001	0.0	66	0.0	0.0
	1.50 (actual)	92.3	0.001	0.0	66	0.0	0.0
212	1.50 (equivalent)	92.5	0.004	0.0	59	0.0	0.0
	1.50 (actual)	92.5	0.004	0.0	59	0.0	0.0
259	1.20 (equivalent)	80.6	0.017	0.0	56	0.0	0.0
	1.25 (actual)	85.4	0.011	0.0	56	0.0	0.0
260	1.31 (equivalent)	87.2	0.001	0.0	84	0.0	0.0
	1.50 (actual)	92.4	0.000	0.0	84	0.0	0.0

Table 50. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in North Dakota.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (08/2012)	Predicted Faulting (Inches) (08/2012)	Predicted Slabs Cracked (Percent) (08/2012)	Actual LTE (Percent) (08/2012)	Actual Faulting (Inches) (08/2012)	Actual Slabs Cracked (Percent) (08/2012)
213	1.24 (equivalent)	94.4	0.000	5.86	80	0.0	0.0
	1.25 (actual)	94.5	0.000	5.75	80	0.0	0.0
214	1.22 (equivalent)	91.0	0.055	1.00	89	0.0	0.0
	1.25 (actual)	91.8	0.051	0.98	89	0.0	0.0
215	1.38 (equivalent)	95.0	0.023	0.00	92	0.0	0.0
	1.50 (actual)	95.0	0.022	0.00	92	0.0	0.0
216	1.48 (equivalent)	95.0	0.000	0.00	96	0.0	0.0
	1.50 (actual)	93.9	0.000	0.00	96	0.0	0.0
217	1.22 (equivalent)	94.7	0.000	0.00	73	0.0	9.1
	1.25 (actual)	95.0	0.000	0.00	73	0.0	9.1
218	1.21 (equivalent)	93.7	0.021	0.00	87	0.0	0.0
	1.25 (actual)	94.4	0.020	0.00	87	0.0	0.0
219	1.48 (equivalent)	95.0	0.016	0.00	91	0.1	0.0
	1.50 (actual)	95.0	0.016	0.00	91	0.1	0.0
220	1.47 (equivalent)	95.0	0.000	0.00	85	0.0	0.0
	1.50 (actual)	95.0	0.000	0.00	85	0.0	0.0
221	1.24 (equivalent)	93.7	0.000	0.00	83	0.0	0.0
	1.25 (actual)	93.8	0.000	0.00	83	0.0	0.0
222	1.24 (equivalent)	92.0	0.026	0.01	90	0.0	0.0
	1.25 (actual)	92.2	0.025	0.01	90	0.0	0.0
223	1.48 (equivalent)	95.0	0.017	0.00	91	0.0	0.0
	1.50 (actual)	95.0	0.017	0.00	91	0.0	0.0
224	1.47 (equivalent)	94.1	0.000	0.00	92	0.0	0.0
	1.50 (actual)	94.4	0.000	0.00	92	0.0	0.0

Table 51. Comparison of AASHTOWare Pavement ME Design analysis results with actual LTPP distress data using the average equivalent and actual dowel diameter for the LTPP test section in South Dakota.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (05/2011)	Predicted Faulting (Inches) (05/2011)	Predicted Slabs Cracked (Percent) (05/2011)	Actual LTE (Percent) (05/2011)	Actual Faulting (Inches) (05/2011)	Actual Slabs Cracked (Percent) (05/2011)
3052	1.21 (equivalent)	90.5	0.020	0.1	92	0.0	0.0
	1.25 (actual)	91.4	0.018	0.1	92	0.0	0.0

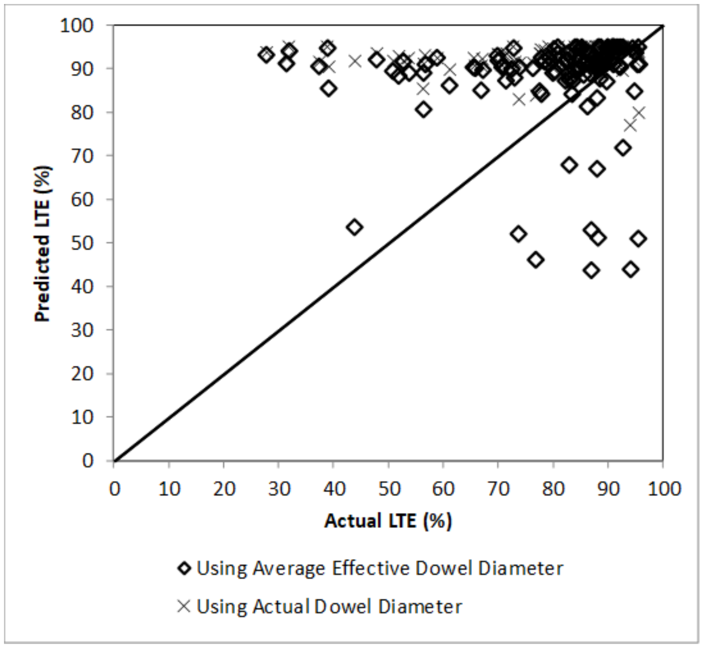
Table 52. Comparison of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter for LTPP test sections in Wisconsin.

Test Section	Dowel Diameter (Inches)	Predicted LTE (Percent) (07/2012)	Predicted Faulting (Inches) (07/2012)	Predicted Slabs Cracked (Percent) (07/2012)	Actual LTE (Percent) (07/2012)	Actual Faulting (Inches) (07/2012)	Actual Slabs Cracked (Percent) (07/2012)
213	1.17 (equivalent)	93.2	0.000	0.0	90	0.0	0.0
	1.25 (actual)	94.1	0.000	0.0	90	0.0	0.0
215	1.45 (equivalent)	95.0	0.011	0.0	92	0.0	0.0
	1.50 (actual)	95.0	0.010	0.0	92	0.0	0.0
217	0.99 (equivalent)	94.9	0.000	0.0	91	0.0	0.0
	1.25 (actual)	95.0	0.000	0.0	91	0.0	0.0
219	1.37 (equivalent)	95.0	0.006	0.0	90	0.0	0.0
	1.50 (actual)	95.0	0.006	0.0	90	0.0	0.0
221	1.24 (equivalent)	95.0	0.000	0.0	90	0.0	0.0
	1.25 (actual)	95.0	0.000	0.0	90	0.0	0.0
223	1.48 (equivalent)	95.0	0.008	0.0	84	0.0	0.0
	1.50 (actual)	95.0	0.007	0.0	84	0.0	0.0
259	1.47 (equivalent)	94.8	0.013	0.0	95	0.0	0.0
	1.50 (actual)	95.0	0.013	0.0	95	0.0	0.0
261	1.24 (equivalent)	95.0	0.003	0.0	88	0.0	0.0
	1.25 (actual)	95.0	0.003	0.0	88	0.0	0.0
262	1.20 (equivalent)	92.5	0.000	0.0	78	0.0	0.0
	1.25 (actual)	93.3	0.000	0.0	78	0.0	0.0
263	1.05 (equivalent)	71.8	0.044	0.0	93	0.0	0.0
	1.25 (actual)	89.6	0.015	0.0	93	0.0	0.0
265	1.18 (equivalent)	87.0	0.043	0.0	90	0.0	0.0
	1.50 (actual)	95.0	0.023	0.0	90	0.0	0.0

Table 53. Summary of AASHTOWare Pavement ME Design analyses results with actual LTPP distress data using the average equivalent and actual dowel diameter.

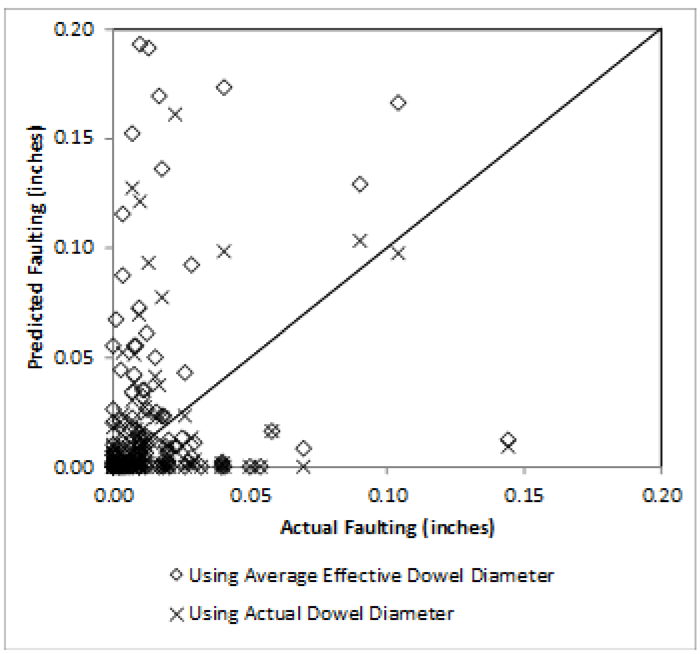
Test Sections	Distress	Mean Residual (As-Predicted Distress versus Actual Distress) Using Actual Dowel Diameter	Mean Residual (As-Predicted Distress versus Actual Distress) Using Average Equivalent Dowel Diameter
All (*N* = 117)	LTE (percent)	13.30	8.46**
	Faulting (inches)	0.01**	0.04
	Slab cracking (percent)	−0.65	−0.65
1.50-inch-diameter dowels (*N* = 61)	LTE (percent)	14.44	12.00**
	Faulting (inches)	0.00	0.00
	Slab cracking (percent)	−1.09	−1.09
1.25-inch-diameter dowels (*N* = 56)	LTE (percent)	12.07	4.62**
	Faulting (inches)	0.03**	0.08
	Slab cracking (percent)	−0.17	−0.17
Trimmed* (*N* = 101)	LTE (percent)	8.12	3.19**
	Faulting (inches)	0.01**	0.03
	Slab cracking (percent)	−1.05	−1.05
1.50-inch-diameter dowels trimmed* (*N* = 51)	LTE (percent)	7.96	5.32**
	Faulting (inches)	0.00	0.00
	Slab cracking (percent)	−1.90	−1.90
1.25-inch-diameter dowels trimmed* (*N* = 50)	LTE (percent)	8.29	1.01**
	Faulting (inches)	0.02**	0.06
	Slab cracking (percent)	−0.19	−0.19

*Trimmed test sections represent only those that have measured LTE > 60 percent.
**Lower residual value.
N = number of sections used in the analyses.



Source: FHWA.

Figure 111. Chart. Predicted and actual LTE Using AASHTOWare Pavement ME Design from the LTPP database for 117 test sections using the actual and average equivalent dowel diameter.



Source: FHWA.

Figure 112. Chart. Predicted and actual LTE Using AASHTOWare-Pavement ME Design from the LTPP database for 117 test sections using the actual and average equivalent dowel diameter.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

Dowel-alignment data were collected from 3 GPS-3 and 121 SPS-2 LTPP test sections using an MIT scanning device in various States to evaluate the effects of dowel misalignment on JPCP performance. Dowel-alignment data were analyzed using the software provided with the MIT scanning device to calculate various dowel-alignment parameters, including horizontal skew, vertical tilt, longitudinal translation, and vertical translation. In addition, the joint score and equivalent dowel diameter were calculated for every transverse joint tested. These data were uploaded to the LTPP database.

The results of the analyses indicate that approximately 50 percent of transverse joints have a joint score of less than 10 and 19 percent of transverse joints have joint scores greater than 30. The average effective reduction in dowel diameter for 1.25- and 1.5-inch-diameter dowels ranged from 0.1 to 76 percent.

Only 8 SPS-2 test sections from North Carolina had dowels placed using a DBI. Dowels for the other 116 test sections were placed using dowel baskets. Because of the small sample size of test sections with dowels placed using a DBI, placement of dowels using a DBI versus dowel baskets was not meaningful and was not compared.

Chi-square tests were performed to determine if there was a relationship between the joint score and slab cracking or spalling. Results of the statistical analyses did not indicate any definitive relationship between the joint score and transverse cracking or spalling of concrete slabs for most States—except for three instances (transverse cracking in Arizona and Arkansas and spalling in Iowa). These results suggest other factors have a stronger effect on transverse cracking and spalling but there may be some project-specific situations where dowel misalignment (as measured using the joint score) has some influence on transverse cracking and spalling. These results also suggest that dowel alignment may not be a primary factor affecting transverse cracking and spalling but may be a contributing factor exacerbating transverse cracking and spalling. Detailed analyses of the dataset were beyond the scope of this study and should be undertaken as a followup to this study.

Joint openings on five transverse joints of Arizona LTPP test section 04_0215, which was an SMP test site, were analyzed. The data did not indicate any correlation between dowel misalignment/joint score and joint opening. However, as the sample size was limited, analysis of additional SMP sites is recommended by the researchers of the current study.

The results of AASHTOWare Pavement ME Design runs using the actual and average equivalent dowel diameter show that using the average equivalent, instead of actual, dowel diameter produces a reduced bias of the in-service LTE as modeled using AASHTOWare Pavement ME Design. It is likely that using the average equivalent dowel diameter as specified in NCHRP Report 637 is a less-biased estimator of long-term pavement LTE as modeled using AASHTOWare Pavement ME Design than using actual dowel diameter. However, the results were reversed when evaluating faulting. The results of the analyses show that using the average, instead of actual, dowel diameter produces a greater bias of faulting as modeled using AASHTOWare Pavement ME Design.

The two results of the analyses seem contradictory because faulting is correlated with LTE. However, the results may make sense when considering AASHTOWare Pavement ME Design was calibrated using LTPP test sections. The researchers of the current study hypothesize that dowel misalignment in LTPP test sections is accounted for in the calibration. The calibration process for faulting may have removed some of the bias in faulting models but not necessarily in LTE models since LTE models are not calibrated with field-measured LTE data.

Taken together, the data suggest that dowel misalignment affects long-term LTE of a concrete pavement. This result is consistent with the lab results conducted in NCHRP Report 637. However, the results show considerable scatter in LTE and faulting modeled using AASHTOWare Pavement ME Design versus actual LTE and faulting. The remaining bias and scatter suggests that the two models (i.e., the equivalent dowel diameter model from NCHRP Report 637 and the LTE model in AASHTOWare Pavement ME Design) can be improved using the data collected as part of this study.

MIT scanning data collected as a part of this study provide a platform for future analyses to establish effective construction specifications based on field performance. Some potential future analyses include the following:

- Understanding the effects of the joint score and dowel misalignment on LTE.
- Reviewing, validating, and improving current joint score methodology.
- Conducting project-level analyses comparing the joint score/dowel misalignment of transverse joints adjacent to slabs exhibiting cracking/spalling and slabs not exhibiting cracking/spalling.
- Using local calibration factors for each State in AASHTOWare Pavement ME Design to better determine the use of the average equivalent dowel diameter as a measure of dowel misalignment.
- Surveying SMP sites to understand any potential correlation between the joint score/dowel misalignment and joint opening.
- Enhancing the equivalent dowel diameter and AASHTOWare Pavement ME Design LTE models.

REFERENCES

AASHTOWare® Pavement ME Design, Version 2.2. (2014). American Association of State Highway and Transportation Officials, Washington, DC.

ACPA. (2006). *Evaluating and Optimizing Dowel Bar Alignment*, Report No. SR999P, American Concrete Pavement Association, Skokie, IL.

CDOT. (2015). *Revision of Sections 105, 106, 412, 601, and 709: Conformity to the Contract of PCC Pavement and Dowel Bars and Tie Bars for Joints*, Colorado Department of Transportation, Denver, CO.

Federal Highway Administration. (2014). "Long-Term Pavement Performance Program Database Standard Data Release 28." (website) Washington, DC. Available online: https://infopave.fhwa.dot.gov/Data/StandardDataRelease, last accessed May 1, 2015.

Fowler, G. and Gulden, W. (1983). *Investigation of Location of Dowel Bars Placed by Mechanical Implantation*, Report No. DTFH-36D2-704, Federal Highway Administration, Washington, DC.

Gancarz, D.J., Tayabji, S.D., and Vavrik, W.R. (2015). "Testing of Dowel Alignment and Development of a Dowel Bar Alignment Specification for the Illinois Tollways." *Transportation Research Record*, *2504*, pp. 117–123, Transportation Research Board, Washington, D.C.

Hoerner, T.E., Darter, M.I., Khazanovich, L., Titus-Glover, L., and Smith, K.L. (2000). *Improved Prediction Models for PCC Pavement Performance-Related Specifications, Volume I: Final Report*, Report No. FHWA-RD-00-130, Federal Highway Administration, Washington, DC.

Hossain, S. and Elfino, M.K. (2006). *Field Demonstration of Magnetic Tomography Technology for Determination of Dowel Bar Position in Concrete Pavement*, Report No. FHWA/VTRC 06-R40, Virginia Transportation Research Council, Charlottesville, VA.

Khazanovich, L., Darter, M.I., Bartlett, R., and McPeak, T. (1998). *Common Characteristics of Good and Poorly Performing PCC Pavements*, Report No. FHWA-RD-97-131, Federal Highway Administration, Washington, DC.

Khazanovich, L., Hoegh, K., and Snyder, M. (2009). *Guidelines for Dowel Alignment in Concrete Pavements*, NCHRP Report 637, National Cooperative Highway Research Program, Washington, D.C.

Lechner, B. (2005). "Joint Design and Joint Performance of Plain Concrete Pavements (JPCP): Investigations and Experiences in Germany." *Proceedings, 8th International Conference on Concrete Pavements*, Colorado Springs, CO.

Leong, P., Tighe, S., Rothenburg, L., and Hein, D.K. (2006). “Finite Difference Modeling of Misaligned Dowel Bars and Their Effects on Joint Performance.” *Transportation Research Record*, *1946*(1), pp. 101–110, Transportation Research Board, Washington, DC.

Mallela, J., Rao, S., and Littleton, P. (2012). “Field Investigation of Dowel Misalignment and Potential for Joint Lock-Up.” *Proceedings 10th International Conference on Concrete Pavements*, Quebec City, Quebec, Canada.

Prabhu, M., Buch, N., Varma, A.H., and Thandaveswara, D. (2006). “Experimental Investigation of Effects of Dowel Misalignment on Joint Opening Behavior in Rigid Pavements.” *Transportation Research Record*, *1947*(1), pp. 15–27, Transportation Research Board, Washington, DC.

Rao, S., Hoegh, K, Yu, H.T., and Khazanovich, L. (2009). “Evaluation of Dowel Alignment Constructability in Portland Cement Concrete Pavements.” *Transportation Research Record*, *2098*, pp. 86–93, Transportation Research Board, Washington, DC.

Tayabji, S.D. (1986). “Dowel Placement Tolerances for Concrete Pavements.” *Transportation Research Record*, *1062*, pp. 47–54, Transportation Research Board, Washington, DC.

Yu, H.T. and Khazanovich, L. (2005). *Use of Magnetic Tomography Technology to Evaluate Dowel Placement*, Report No. FHWA-IF-06-006, Federal Highway Administration, Washington, DC.

Yu, H.T., Smith, K.D., Darter, M.I., Jiang, J., and Khazanovich, L. (1998). *Performance of Concrete Pavements, Volume III: Improving Concrete Pavement Performance*, Report No. FHWA-RD-95-111, Federal Highway Administration, Washington, DC.

Yu, H.T. and Tayabji, S.D. (2007). *Best Practices for Dowel Placement Tolerances*, Report No. FHWA-HIF-07-021, Federal Highway Administration, Washington, DC.

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