Field Investigation of Dowel and Tie Bar Placement

Shreenath Rao, Ph.D., P.E., Laxmikanth Premkumar, P.E., and Abu Talha, Ph.D.

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16. Abstract

This report presents the results of dowel and tie bar alignment data collected using the MIT-DOWEL-SCAN and MIT-SCAN-T2 from various counties in Wisconsin. The data were analyzed using the latest version of the MagnoProof® software to calculate the various dowel alignment parameters including horizontal skew, vertical tilt, longitudinal translation, and vertical translation. These measured parameters were used to compute joint score (JS) and equivalent dowel diameter (EDD). The data showed moderate to good dowel alignment for both basket and dowel bar inserter sections with over 95 percent of dowel bars having horizontal skew and vertical tilt values between 0 and ± 1.0 inches, longitudinal translation between 0 and ± 3.0 inches, and vertical translation between 0 and ± 1.5 inches. However, approximately 28 percent of the bars with baskets and 9 percent of bars installed with dowel bar inserter (DBI) had JS values more than 30. The relatively high JS translates to only 70 percent and 55 percent of joints with JS less than critical joint score ($JS_{CRITICAL}$) and joint score trigger ($JS_{TRIGGER}$), respectively. According to the American Concrete Pavement Association (ACPA) guide specification, a JS higher than $JS_{CRITICAL}$ or $JS_{TRIGGER}$ indicates higher potential for locking of joints. Chi-squared tests were performed to determine any relationship between JS and spalling, slab cracking, and longitudinal translation. Results did not indicate any relationship between JS and spalling or cracking for any of the sections, suggesting that other factors may have a stronger effect on spalling and transverse cracking that JS. In two counties, the results indicated a relationship between JS and longitudinal translation. Although JS and longitudinal translation are independent metrics, the relationship between the two in these two counties suggest the contractor experienced challenges with dowel bar placement during paving. The chi-squared results were also confirmed by performing a logistic regression analysis that included JS, pavement age, and slab thickness as the independent parameters with spalling and cracking as the dependent parameters. EDD ranged from 1.6 percent to 20.5 percent equivalent reduction in dowel diameter as compared with actual dowel diameter. AASHTOWare® Pavement ME Design (PMED) was used to evaluate the impact of dowel misalignment on pavement performance. Results from the PMED runs using EDD as compared to actual dowel diameter showed increased roughness and faulting over the life of the pavement caused by the equivalent reduction in dowel diameter due to misalignment. However, slab cracking was not affected by change in dowel diameter. Based on the literature review and analysis of data, the report includes recommendations for acceptable tolerance limits for dowel and tie bar alignments and appropriate thresholds to achieve long-term satisfactory joint performance and practical installation of bars, along with inspection procedures to confirm proper bar installation in the field.

17. Key Words
Dowel bar misalignment, dowel bar alignment, MIT-SCAN, MIT-SCAN-T, MIT-DOWEL-SCAN, MIT-SCAN-T2, equivalent dowel diameter, dowel bar specifications, joint score, horizontal skew, vertical tilt, longitudinal translation, vertical deviation, dowel bar, tie bar, IRI, spalling, smoothness, faulting, joint lockup.

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Executive Summary

This report presents the results of dowel and tie bar alignment data collected using the MIT-DOWEL-SCAN and MIT-SCAN-T2 from various counties in Wisconsin. The goals of the study were to (1) investigate and quantify the dowel and tie bar placement from representative concrete pavements in Wisconsin, (2) document dowel and tie bar misalignments and relate how these misalignments impact pavement performance, (3) review the acceptable tolerance limits for dowel and tie bar alignments and recommend appropriate thresholds to achieve long-term satisfactory joint performance and practical installation of bars, and (4) provide appropriate inspection procedures to confirm proper bar installation in the field.

In total, 1,293 joints were evaluated by the research team across twelve sites in six counties which included 12,862 dowel bars after the data was passed through the initial filtering process. In addition, MIT-DOWEL-SCAN testing was performed on 20 joints in Chippewa County STH 178 SB to evaluate the alignment of tie bars. The data set also included additional MIT-DOWEL-SCAN data provided by Wisconsin Department of Transportation (WisDOT), which included of 386 joint consisting of 3,954 dowel bars.

The data were analyzed using the latest version of the MagnoProof® software to calculate the various dowel alignment parameters including horizontal skew, vertical tilt, longitudinal translation, and vertical translation. These measured parameters were used to compute joint scores (JSs) and equivalent dowel diameters (EDDs) for every joint tested by the research team along with other joints whose dowel alignment and pavement performance data were provided by WisDOT.

In terms of current WisDOT specifications, 80 percent of basket bars and 90 percent of dowel bar inserter (DBI) bars had horizontal skew within WisDOT specifications of between 0 and ± 0.5 inches. 66 percent and 73 percent of basket and DBI dowel bars, respectively, had vertical tilt values within WisDOT specifications of between 0 and ± 0.5 inches. 73 percent of basket bars and 88 percent of DBI bars had longitudinal translation within WisDOT specifications of between 0 and ± 2.0 inches. 86 percent of basket bars and 88 percent of DBI bars had vertical translation within WisDOT specifications of between 0 and ± 1.0 inches.

However, 94 percent of basket dowel bars and 99 percent of DBI dowel bars had horizontal skew values between 0 and ± 1.0 inches. 94 percent of basket dowel bars and 98 percent of DBI dowel bars had vertical tilt values between 0 and ± 1.0 inches. Over 95 percent of all dowel bars had longitudinal translation between 0 and ± 3.0 inches. Over 95 percent of all dowel bars had vertical translation between

0 and ± 1.5 inches. The global analysis of alignment data show that on average dowel bars installed using DBI had equal to or better alignment as compared to dowel bars installed using baskets.

Only 17 percent and 39 percent of the bars installed with baskets had JS values less than 5 and 10, respectively. By comparison, approximately 37 percent and 66 percent of the bars installed with DBI had JS values less than 5 and 10, respectively. 28 percent of the bars with baskets had JS values more than 30, whereas only 9 percent of the bars installed with DBI had JS values more than 30.

30 percent of joints analyzed had JS greater than $JS_{CRITICAL}$ and there were 69 instances of three or more consecutive joints having JS greater than $JS_{CRITICAL}$. 45 percent analyzed had JS greater than $JS_{TRIGGER}$ and there were 134 instances of three or more consecutive joints having JS greater than $JS_{TRIGGER}$.

Average EDD reductions range from less than 2 percent to greater than 20 percent. AASHTOWare® Pavement ME Design (PMED) analysis indicate an increase in International Roughness Index (IRI) and faulting when EDD is used instead of actual diameter. In instances where the EDD was significantly different from the actual dowel diameter due to higher levels of misalignment, the increase in faulting and IRI were pronounced and could impact service life of the pavement. However, slab cracking was not affected by change in dowel diameter to any significant extent.

Chi-squared tests were performed to determine any relationship between JS and spalling, slab cracking, and longitudinal translation. The results of the statistical analysis did not indicate any certain relationship between the JS and cracking or spalling within the tested sections. It does not necessarily mean that severely misaligned dowel bars do not affect the cracking or spalling rather it suggest that other factors may have stronger influence on localized distresses, such as cracking or spalling. The results of the chi-squared tests were also confirmed by performing a logistic regression analysis that included JS, pavement age, and slab thickness as the independent parameters.

MIT-DOWEL-SCAN testing was also performed to evaluate the tie bar position and alignment. However, the test was heavily influenced by external metal objects, presence of shallow and deep bars, and large translations. As a result, further processing of the data was not possible with the Magnoproof software.

The data collected by the research team and WisDOT and analyzed by the research team was used as a baseline to evaluate typical levels of dowel alignment in Wisconsin for basket and DBI sections. The final section of this report provides recommendations to achieve satisfactory long-term joint performance balanced with practical installation in Wisconsin.

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Introduction

Jointed plain concrete pavements (JPCPs) typically consist of two types of joints: transverse and longitudinal. Both types of joints play a crucial role in maintaining the structural integrity and serviceability of the pavement.

Transverse joints sawed at a specified intervals in the longitudinal direction help control shrinkage cracking and allow for free longitudinal slab movements due to temperature and moisture cycles. However, transverse joints also introduce discontinuities in the pavement and potentially induce premature distresses at or near the joints.

Dowel bars are placed across transverse joints in JPCP to allow for shear transfer of wheel loads between slabs while also allowing unrestricted slab expansion and contraction from changes in temperature and moisture in the concrete. There are two main methods of dowel bar installation during construction: the use of dowel basket assemblies or the dowel bar inserter (DBI). Dowel baskets are simple steel truss structures used to hold dowel bars at the specified height before concrete placement. Dowel baskets typically span a full lane width and are fabricated from thick wire. The dowel baskets are laid out and firmly anchored to the base course prior to being paved over. The DBI is a device mounted on a slipform paver. At each marked joint location, the DBI automatically inserts the dowels into the fresh concrete along the length of the joint. The DBI pushes the dowels to the proper depth and then reconsolidates the concrete around the dowels using vibrating forks. This method eliminates the need to manually lay down and anchor dowels in baskets prior to paving operations.

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 termed dowel misalignment (Tayabji 1986). Potential adverse effects of dowel misalignment have been researched in previous studies. Rao and Premkumar (2017, 2020) reported that the load-transfer efficiency (LTE) of the adjacent slabs reduces due to misalignment of the dowel bars at a joint. Similar observation was noted by Khazanovich et al. (2009). The reduction in LTE affects the long-term performance and serviceability of concrete pavement by increasing faulting and potentially corner cracking. In addition, misaligned dowel bar induces excess steel/concrete bearing stress that may cause transverse joint spalling (ACPA 2018). Excessive slab cracking has also been reported in previous studies from transverse joint lockup/restraint due to misalignment of the dowel bars (Khazanovich et al. 2009).

Longitudinal joints are used in JPCP to relieve shrinkage, curling, and warping stresses in slabs and thus control longitudinal cracking. Longitudinal joints often also serve as construction joints to accommodate paving operations.

To hold adjacent slabs together across the longitudinal joints, tie bars, typically 30-inch-long #5 epoxy-coated deformed steel bars, are used across longitudinal joints. Tie bars are mechanically installed or inserted by hand using a tie bar inserter attachment during slipform paving. Other options include drilling and epoxying tie bars into hardened concrete or using multiple piece tie bars that can be threaded together following paving one or more lanes but before paving the adjacent lane(s). Field experience has shown that longitudinal joints can separate over time if tie bars are not adequately designed and installed (Mallela et al. 2011). Separation of longitudinal joints increases the risk of transverse slab cracking due to reduced edge support and loss of transverse joint load transfer due to increased corner deflections. Longitudinal joints that open too wide could become safety hazards, particularly to motorcyclists. As in the case of dowel bars, optimal functioning of tie bars can only be attained if they are properly installed.

In contrast to dowel bars, very little research has been performed and there is a scarcity of information available in the literature about the performance impacts of tie bar misalignment. Tie bars only minimally affect functionality and performance of the pavement itself, as their sole purpose is to prevent the longitudinal joint from separating. An exception is when the tie bars are severely misaligned, resulting in issues such as steel pushing out through the surface of the concrete, which could be a safety hazard to motorists, or insufficient embedment in one of the two adjoining slabs, which could lead to opening of the longitudinal joint. Some states have tolerance limits for translation (e.g. ±3 inches) and minimum cover requirements for tie bars. However, most states do not have tolerance limits for horizontal skew, vertical tilt, and vertical deviation of tie bars. Presumably, this is because the primary function of tie bars is to lock the longitudinal joint and any amount of tilt or skew will further help lock the joint.

Considering the potential negative impact of dowel and tie bar misalignment on pavement performance, it is important to investigate any dowel and/or tie bar misalignment and determine if the alignment is within tolerance limits. In addition, an investigation is needed to inspect joint and pavement condition and establish any potential relationship with dowel and/or tie bar misalignment, which may help better understand the impact of misalignment on pavement performance. The objectives of this study are to:

1. Investigate and quantify dowel and tie bar placement in Wisconsin roadways,
2. Recommend practical tolerance limits for dowel and tie bar alignments to achieve long-term joint performance,
3. Document the relationship between dowel and tie bar misalignment and joint performance, and
4. Develop field inspection procedures for proper bar installation.

The results of this research study addressing these objectives are detailed in the following sections of this report.

Literature and Agency Review

Dowel Misalignment Categories and Causes

Dowel bars placed across transverse joints play an important role in the performance of JPCP by transferring load across these joints while allowing for longitudinal slab movement. For transverse joints to perform as designed, dowel bars should be in their respective positions or properly aligned. Dowel bar misalignments can be grouped into five categories (Tayabji 1986), illustrated in Figure 1:

- Horizontal translation,
- Longitudinal translation (side shift),
- Horizontal skew (rotation),
- Vertical translation (depth), and
- Vertical tilt (rotation).

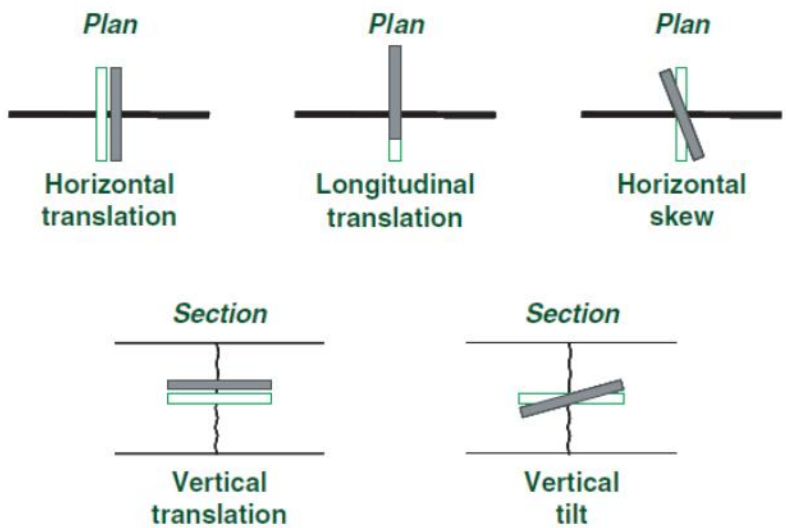


Figure 1. Types of dowel bar misalignment (after Tayabji 1986).

There are several reasons why dowel bars can get misaligned during construction. These reasons may be related to materials, equipment, or workmanship (Tayabji 1986).

When using dowel baskets, factors that may result in dowel misalignment include:

- Insufficient basket rigidity,
- Poor quality control during basket fabrication, e.g., loose welds or improper heights,
- Damage during basket transportation and placement,

- Improper basket anchoring, and
- Inaccurate placement of saw cuts over the basket.

The following factors may result in dowel misalignment when using a DBI for insertion:

- Improper or poorly tuned DBI operation (technical problems),
- Poor strike-off after dowel placement,
- Insufficient consolidation (vibration) after dowel placement,
- Inaccurate placement of saw cuts over the inserted dowels,
- Improper concrete mix design or fluctuating consistency or density, e.g., segregated mix or excessive slump.

Based on a study of 60 pavement sections in 17 U.S. states allowing for a broad range of design, construction, climate, and traffic variables, Rao et al. (2009) determined that the following specification tolerances are easily constructible, but also have no significant effect on pavement performance:

- Horizontal skew or vertical tilt: <0.5 inches over an 18-inch dowel
- Longitudinal translation: ± 2 inches over an 18-inch dowel
- Vertical translation: ± 0.5 inches for pavements 12 inches or less in thickness. Note that this dataset only included pavements that were less than 12 inches in thickness.

Agency Guidelines

Guidelines for allowable dowel misalignment vary from agency to agency. Despite more than 30 years of research, no consensus exists on dowel bar tolerances. Due to a lack of information on what levels of misalignments impact pavement performance, and because dowel misalignments are just one of many interacting factors that affect pavement performance, most agencies set conservative tolerances on dowel bar alignment. Many U.S. states have adopted limits on dowel rotation (horizontal skew and vertical tilt), recommended by the Federal Highway Administration (FHWA) of ¼ inches per foot of dowel bar length or two percent (FHWA 2007). These specifications were developed based on limited data from field and laboratory performance studies.

However, many agencies have also begun reevaluating and relaxing decades old dowel bar tolerance limits based on more recent studies. An overview of the most current tolerances in use, following a national survey of state standard construction and materials specifications, is presented in Table 1.

Table 1. Current dowel bar tolerances from various agencies.

Agency	Publication Date	Vertical Tilt (inch per 18 inches)	Horizontal Skew (inch per 18 inches)	Longitudinal Translation (inch per 18 inches)	Vertical Translation[1] (inch per 18 inches)	Horizontal Translation (inch per 18 inches)
Colorado	2021	1.5	1.5	3.0	1.0	1.0
Florida	2017	0.5	0.5	2.0	1.0	N/A
Georgia	2021	0.375	0.375	1.0	1.0	1.0
Idaho	2023	See note 2.				
Illinois	2021	0.5	0.5	2.0	1.0	1.0
Iowa	2015	0.25	0.25	N/A	0.5	N/A
Kansas	2007	0.125	0.125	N/A	N/A	N/A
Kentucky	2019	0.5	0.5	3.0	1/3 slab thickness + 0.5 to 2/3 slab thickness[3]	1.0
Maryland	2019	0.5 (per 12-inch dowel)	0.5 (per 12-inch dowel)	See note 4	See note 4	N/A
Michigan	2020	0.5	0.5	2.0	N/A	N/A
Minnesota[5]	2020	0.25	0.5	N/A	N/A	N/A
Nevada	2014	0.5	0.5	2.0	1.0	1.0
New Mexico	2019	1.5	1.5	3.0	1.0 (minimum 3.0-inch cover)	2.0
New York	2019	0.25	0.25	1.0	1.0	N/A
North Carolina	2018	N/A	N/A	2.0	0.5	2.0
Ohio (acceptance)[6]	2022	0.60	0.60	2.0	1.0	2.0
Ohio (rejection)[6]	2022	1.0	1.0	4.0	1/6 slab thickness	3.0
Oregon	2021	0.188 (5°)	0.188 (5°)	N/A	0.375	N/A
Pennsylvania	2020	0.25	0.25	1.0	N/A	1.0
South Dakota	2015	0.125	N/A	0.5	0.125	N/A
Utah	2024	0.25	0.25	N/A	N/A	N/A
Washington	2024	0.5	0.5	1.0	1.0	N/A
Wisconsin	2022	0.5	0.5	2.0	1.0	1.0
Wyoming	2021	0.375	0.375	3.0	1.0	1.0

[1] Vertical translation tolerances are relative to mid-depth of the pavement slab, unless otherwise stated.
[2] Idaho DOT specification specify that dowel bars, whether placed in baskets or inserted, must have at least 6 inches of bar embedded in each slab.
[3] Measured from pavement surface to any point along the top of the dowel bar.
[4] Maryland DOT specifications indicate that the dowel bar shall be located within the middle third of the slab thickness. Minimum cover depths of 3 and 2.5 inches are required for the top and the bottom, respectively. The joint saw cut shall be in the middle third of the dowel bar length. The minimum embedment length on either side of the joint shall be 4 inches. Any missing dowel bar shall be considered misaligned.
[5] MNDOT specifications also require dowel slots to be parallel to other slots within ± 1/8 inches and a minimum of ½-inch clearance to be provided between the bottom of the dowel and the bottom of the slot.
[6] Ohio DOT also has a cover tolerance: ±0.60 inches (acceptance), ±1.0 inch (rejection).

American Concrete Pavement Association Guide Specification

Based on the findings of dowel alignment research studies and the experience of numerous North American agencies and contractors, the American Concrete Pavement Association (ACPA) has published a “Dowel Bar Alignment and Location” guide specification in 2018. This specification includes a methodology for process control testing during construction using magnetic pulse induction (MPI) equipment, as well as acceptance and rejection tolerances from a number of alignment and location parameters. ACPA’s recommended tolerances for 18-inch dowels are summarized in Table 2 (acceptance limits) and Table 3 (rejection limits) (ACPA 2018). In addition to the position of the individual dowel bars, percent within limits (PWL) is calculated for each criterion using the acceptance limits. PWL greater than or equal to 90 percent for any lot receives full payment. PWL greater than or equal to 50 percent and less than 90 percent receives a pay adjustment. Lots with PWL less than 50 percent are rejectable.

Table 2. ACPA guide specification acceptance limits (adapted from ACPA 2018).

Criterion	Lower Limit	Upper Limit
Composite Misalignment	0 inches	0.75 inches for 18-inch dowel
Longitudinal Translation	– 2 inches	2 inches
Horizontal Translation	N/A	N/A
Vertical Translation	Nominal Slab Thickness / 2 + ½ inches	Nominal Slab Thickness / 2 – ½ inches
Joint Score	0	15

Table 3. ACPA guide specification rejection limits (adapted from ACPA 2018).

Location Tolerances	Rejection Level
Composite Misalignment	> 2 inches
Longitudinal Translation	|Side Shift| > (L-8) / 2 inches (L = nominal dowel length)
Horizontal Translation	N/A
Depth	< Saw Cut Depth + ¼ inches + dowel diameter / 2 or > Slab Thickness – (2 inches + dowel diameter / 2)
Joint Score	Effective Panel Length (EPL) (due to consecutive restrained joints) > 60 feet

In addition to individual bar alignment and position parameters, the ACPA guide specification also considers additional parameters, including Composite Misalignment (CM), Joint Score (JS), and Effective Panel Length (EPL).

CM is defined as the square root of the sum of the squares of the horizontal skew and the vertical tilt for a single dowel. JS is a value that combines the impact of all misaligned dowels in a single transverse joint based on CM values for individual bars. According to ACPA (2013), JS values greater than 10 suggest a moderate risk of restraint, and JS values greater than 15 suggest a higher potential for joint lock-up. A value of the JS above which the joint has a high probability of restraining joint opening and closing to an extent that may impair long-term pavement performance is termed critical joint score ($JS_{CRITICAL}$). EPL is the effective length of the slab with one or more consecutive potentially locked-up joints.

Yu and Khazanovich (2005) developed the JS concept, calculated using the rotational misalignments of all dowels within the transverse joint. Transverse joints with a higher JS correspond to more dowels with higher levels of rotational misalignment than transverse joints with a lower JS. The JS 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 JS measure was discussed by the developers as only a quick first step toward identifying transverse joints for further investigation with regard to lockup potential, and not necessarily as a measure for acceptance by highway agencies (Yu and Tayabji 2007). Despite that stipulation, many highway agencies are adopting the JS measure in their specifications for establishing acceptance criteria primarily because of its simplicity (CDOT 2015; Gancarz et al. 2015).

The ACPA guide specification (ACPA 2018) suggests the following process control procedures:

- At the beginning of construction, the contractor places a validation section comprising of 25 to 50 transverse joints.
- Every joint is scanned using the MIT-SCAN to verify the position and alignment of the dowel bars.
- If no joints with JS exceeding the $JS_{CRITICAL}$ are found, 85 percent of the dowels meet the acceptance criteria, and no dowel bars exceeding the rejection level are found, then production paving may begin.
- During production paving, one joint for every ten joints is randomly selected and the position and alignment of the dowel bars are measured using the MIT-SCAN.
- If the position, alignment, and JS results meet the acceptance criteria and PWL is greater than or equal to 90 percent for two days of paving or a specified paving distance, then the dowel installation is under satisfactory control.
- Upon establishing control, one joint in every twenty consecutive joints is scanned.
- Should PWL fall below 90 percent, scanning of every 10^{th} joint will resume until control is re-established.
- If any misalignments exceeding the rejection criteria are found, joints on either side of the measured joint are scanned until five consecutive joints meeting the requirements are found.
- Any joints with rejectable bars require corrective action.

Dowel Misalignment and Pavement Performance

Dowel bar misalignment has been known to be a pavement performance issue for more than half a century. However, no easy means of evaluating misalignment have been available until the introduction of nondestructive equipment, such as the MIT-SCAN. Potential adverse effects of dowel misalignment include the following:

(1) reduced LTE, resulting in increased long-term faulting and, in some situations, increased corner cracking,
(2) transverse joint spalling from excessive steel/concrete bearing stresses, and
(3) slab cracking from transverse joint lockup or restraint.

In general, rotational misalignments (horizontal skew and vertical tilt), affect the free movement of joints, while translational misalignments (longitudinal and vertical) affect the effectiveness of individual dowel bars in providing load transfer. Horizontal skew and vertical tilt of dowel bars beyond tolerance limits can introduce sufficient restraint at the joint to lock the joint, i.e., restrict the joint from opening and closing. A locked transverse joint (or series of locked transverse joints) can result in random transverse cracking in pavement slabs due to increased stresses caused by an effective increase in the longitudinal length of the slab. Locking of the dowels closest to the slab edges can also lead to corner breaks. Dowel rotation can also cause excessive stresses in the area surrounding dowels, potentially causing joint spalling. Excessive stresses also result in dowel looseness, which can decrease the LTE of the joint, leading to pavement faulting (ACPA 2018).

Load transfer is influenced by the embedment length of the dowel bars. If the embedment length is not sufficient due to longitudinal translational misalignment, higher bearing stresses develop in the concrete around the dowel bars. Under repeated traffic loadings, dowel looseness or joint spalling may develop. The resulting consequences are diminished LTE and faulting (ACPA 2018).

Dowels are ideally placed at mid-depth of the slab. Bars that are too shallow or too deep due to vertical translational misalignment may not have sufficient concrete cover. Insufficient cover can cause higher concrete stresses, resulting in spalling or dowel punchouts, and diminished LTE. Adequate cover is also necessary for preventing dowel bar corrosion. Very shallow dowel bars also risk being cut during the joint saw cutting operation (ACPA 2018).

However, not all dowel misalignment necessarily results in development of pavement distresses such as slab cracking and spalling. A critical degree of misalignment is needed for performance to be affected. Rotational misalignments should not exceed critical levels to where the joint may lock, or the concrete may spall. Longitudinal and vertical translational misalignment should be limited such that an acceptable degree of load transfer is provided. Variation in depth should be limited to provide the minimum level of cover (top and bottom). Horizontal translation is often disregarded as a misalignment parameter because improper positioning of dowels at regular spacing (typically 12 inches center to center) along the transverse joint has been found to rarely occur and not considered a key factor affecting transverse joint performance.

While perfect alignment of every dowel bar is desirable, practical limitations in construction processes exist. Some degree of misalignment is acceptable as the detrimental effects of misalignment are not likely to occur. To control distresses due to excessive dowel bar misalignment and facilitate good long-term performance of concrete pavements, dowel bar alignment tolerance limits are specified by agencies. Dowel bar tolerances must consider the critical levels of misalignment, i.e., the level likely to cause distress, but also the practical limitations of equipment, workmanship, and concrete mix properties.

In National Cooperative Highway Research Program (NCHRP) Report 637: Guidelines for Dowel Alignment in Concrete Pavements, 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.

Khazanovich et al. (2009) 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 (EDD) calculated using this procedure can be used in mechanistic–empirical pavement design procedures, such as those used with AASHTOWare® Pavement ME Design (PMED) software, to model the long-term performance of the pavement, primarily LTE and faulting, and the resulting International Roughness Index (IRI), but was shown to have minimal effect on transverse joint locking and slab cracking.

The effect of dowel misalignment on concrete performance was evaluated through a comprehensive FHWA study in 2020 (Rao and Premkumar 2020). Dowel alignment testing was performed on 121 Specific Pavement Studies-2 (SPS-2), and 3 General Pavement Studies-3 (GPS-3) Long-Term Pavement Performance (LTPP) test sections all across the U.S. The dowel alignment parameters, JS and EDD, were calculated as part of the analysis. Statistical analysis was performed to determine any relationship between JS and cracking and between JS and spalling. The analysis did not indicate any definitive relationship between JS and cracking or spalling within the analysis range for most states in the U.S, although some evidence was documented relating dowel alignment to joint LTE using the EDD measure. The results from Rao and Premkumar confirmed earlier results from by Khazanovich et al. (2009).

While the importance of achieving good dowel alignment has long been recognized, the ability to assess the placement accuracy of dowel bars effectively have been limited by the lack of practical means of measuring the position and orientation of dowel bars embedded in hardened concrete. Until recently, only destructive methods such as coring and trenching were available to verify bar alignment. For this reason, the measurement of the position of dowel bars embedded in concrete was a difficult and costly task, and thus, was performed infrequently.

However, nondestructive methods have been gaining popularity in the last twenty years. These methods allow for the measurement of dowel bar position with ease and high level of accuracy. In the past two decades, highway agencies and paving contractors have increasingly used MPI also referred to as magnetic imaging tomography (MIT) scanning to evaluate dowel alignment in JPCPs.

Magnetic Imaging Tomography

Launched in the early 2000s by the German firm MIT Mess- und Prüftechnik GmbH (MIT), the MIT-SCAN revolutionized the determination of dowel bar positioning and alignment. The MIT-SCAN device emits a weak, pulsating magnetic signal and detects the induced eddy currents in the embedded dowel bars using multiple sensors on the device. Tomography technology is used to evaluate the signal measurements in both space and time. These signals contain information on the distribution of electrical conductivity and magnetic properties, which permits the determination of position, size, shape, and orientation of dowel bars and tie bars in the investigated region. Using sensitive detectors and sophisticated data analysis algorithms, the position of the dowels can be calculated with great accuracy (Yu and Khazanovich, 2005).

The original MIT-SCAN system (MIT-SCAN-2 and MIT-SCAN-2BT) consist of three main components:

- The scanner unit that emits electromagnetic pulses and detects the induced magnetic field using five sensor coils,

- An onboard computer that runs the operates the system, collects the test data, and performs the preliminary evaluation (originally wired, subsequently wireless in the Bluetooth-enabled version), and
- A glass fiber-reinforced plastic rail system that is used to guide the scanner unit along the joint.

The operator aligns the rail system along any transverse joint. After initiating the test on the computer, the operator pulls the wheeled scanner carriage along the length of the joint using a rope. Subsequently, the on-board computer, running the MagnoNorm® software, will generate the measurement results in the field for most joints without excessive misalignment. More accurate and comprehensive analysis of the data can be performed using the MagnoProof® software. Using the higher computing power of Windows-based systems, MagnoProof can calculate the positions of bars in more complicated measuring situation, e.g., greater degrees of misalignment or the influence of foreign metal. The MagnoProof software also produces graphic outputs (contour plots), which can be used to visualize the bar positions.

The MIT-SCAN works on fresh or hardened concrete. A single joint scan takes about 1 minute. Two hundred or more joints can be scanned in a workday, with up to three lanes tested in a single pass. Measurements can be performed in most weather conditions. Each MIT-SCAN is individually calibrated to each type of dowel bar that will be scanned using the device to provide very accurate results. Calibrations take into consideration bar material, diameter, and length, as well as basket geometry (only in the latest version of the MagnoProof software). While the device was designed for scanning dowel bars placed using a DBI, it can also be used to scan bars placed in dowel baskets with reasonable accuracy even if not calibrated for the specific basket. For dowel bars placed in baskets, the MIT-SCAN testing results are accurate only if the dowel bars are insulated from the basket through a coating (either paint or epoxy coating), and if the transport ties on the basket are cut or removed. Note that 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-SCAN signals as if the tie wires are cut. For dowel baskets, the results are also more sensitive to the lateral placement of the dowel basket. The best results are obtained when the basket is centered under the joint saw cut.

Numerous evaluations of the accuracy and repeatability of the MIT-SCAN have shown such devices are reliable tools for measuring dowel alignment with high accuracy (Yu and Khazanovich 2005). Studies by Hossain and Elfino (2006) and Leong et al. (2006) also confirmed the accuracy of MIT-SCAN devices.

The manufacturer's published measurement accuracy and repeatability are summarized below (Yu and Khazanovich, 2005):

- Vertical translation: ± 4 mm (0.16 inches),
- Vertical tilt / horizontal skew: ± 4 mm (0.16 inches),
- Longitudinal translation: ± 8 mm (0.31 inches),
- Repeatability: ± 2 mm (0.08 inches).

The accuracy of the results depends on the position and alignment of the dowels. MIT-SCAN 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.

The MIT-SCAN technology is susceptible to interference from foreign metal bodies. To reduce interference, care must be taken to ensure that metallic objects, e.g., vehicles, construction equipment and materials, road hardware, and steel toe shoes, are not near the scanning area. In circumstances where interference is unavoidable, the results are expected to be quantitatively unreliable, but a qualitative (visual) assessment of overall alignment may be possible. Excessive misalignment may also result in erroneous results from the computation of bar positions using the MagnoNorm or MagnoProof software.

The manufacturer, MIT, recently released the newest version, known as the MIT-DOWEL-SCAN (MIT n.d.). This system is now rail-free, which allows for faster scanning as there are no rails to assemble or move. A small laser is used to guide the scanner along the joint being scanned, which is now pushed from behind. The laser automatically maintains alignment of the scanner cart so that no steering by the operator is needed. The MIT-DOWEL-SCAN also includes 10 sensor coils for increased resolution.

Note that in this report, MIT-DOWEL-SCAN, MIT-SCAN-2, and MIT-SCAN-2BT are used when referring to specific models of the dowel alignment testing device. MIT-SCAN is used broadly when referring to any of the three dowel alignment testing devices. MIT-SCAN-T2 and MIT-SCAN-T3 are used when referring to specific models of the thickness testing device. MIT-SCAN-T is use broadly when referring to any of the two thickness testing devices.

The MIT-SCAN methodology has been detailed in ASTM standard E3013, *Standard Test Method for Evaluating Concrete Pavement Dowel Bar Alignment Using Magnetic Pulse Induction*.

Researchers found MIT-SCAN 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 FHWA Concrete Pavement Technology Program to initiate a loan program encouraging the implementation of MIT technology. FHWA identified MIT-SCAN devices as practical, implementation-ready products with the potential to improve the quality of concrete pavements (FHWA 2005).

Ground Penetrating Radar

Other nondestructive methods for evaluating dowel alignment in JPCP include Ground Penetrating Radar (GPR) and Cover Meters (FHWA 2005). GPR is one of the most widely used nondestructive testing tools to evaluate pavement subsurface conditions. GPR transmits electromagnetic signals into the ground and then captures the energy that is reflected back to the surface. The GPR signal can respond to the variations of electrical properties of subsurface materials by analyzing the dielectric constants and electrical conductivities of the materials. The reflected signals are used to map the subsurface features by measuring the amplitude and the travel of the reflected electromagnetic energy. This capability makes GPR a viable candidate to locate the position of dowel bars within pavement structure. Figure 2 shows an example of a cross-sectional scan of a joint using ground-coupled equipment. The dowel bars result in hyperbola-shaped signals.

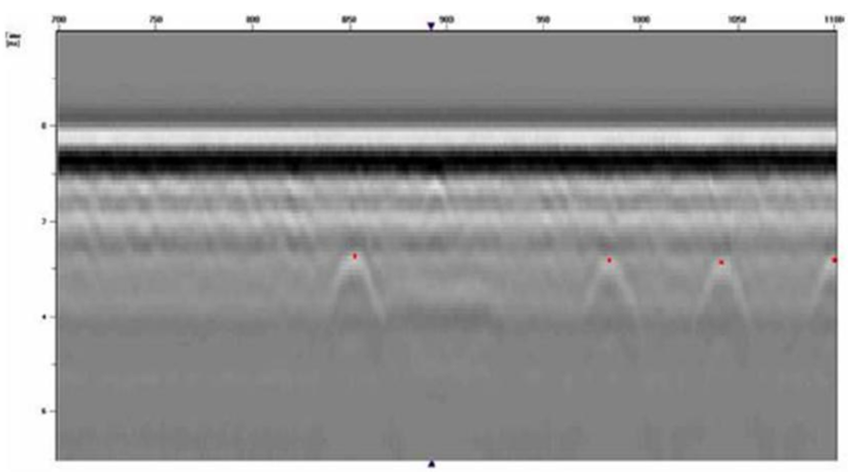


Figure 2. A typical GPR scan of doweled concrete pavement.

A limited number of studies have been conducted to use GPR data to evaluate dowel bar alignment. For example, the Missouri Department of Transportation (MoDOT 2003) conducted a study to estimate the horizontal skew, vertical tilt, transverse translation, and longitudinal translation of dowels installed with baskets and DBI. The GPR unit which contained a 1.5 GHz ground-coupled antenna was used in this study to provide high resolution data. The results of the study indicated that the vertical and the lateral alignment of the dowel bar can be measured accurately within 3 mm (0.1 inches) and 10 mm (0.4 inches), respectively. More recently, the Kentucky Transportation Center (Rister et al. 2013, Silva et al. 2013, Amer-Yahia and Majidzadeh 2014) led an effort to measure the position of dowel bars and tie bars with GPR. Similar to the previous study, results indicated that GPR can be successfully used to measure the depth and the alignment of the dowel bars. In addition, the alignment of tie bars was also evaluated in both studies from GPR scans. The researchers found GPR scans to be very effective in detecting and measuring the alignment and depth of both tie bars and dowel bars in concrete pavement. GPR technology was reported to be more efficient compared to available techniques that rely on magnetic field in measuring the alignment of dowels in presence of baskets since the results of GPR scans are not affected by the presence of foreign metal (Yu and Khazanovich 2005). However, GPR scans are highly sensitive to the dielectric constant of concrete which may vary with moisture content, temperature and the GPR antenna frequency. Therefore, this method cannot be used on fresh concrete or when the surface of concrete pavement is wet. However, as compared to the MIT-SCAN, GPR analysis requires higher level of experience and expertise to properly interpret the results.

Cover Meter

Cover meters, similar to the MIT-SCAN, emit electromagnetic pulses and detect the rebound magnetic field induced by metal objects. Cover meters were mainly developed to locate reinforcement in concrete structure and determining the depth of concrete cover. The alignment of dowel bars cannot be obtained directly using a cover meter. The cover meter measures the horizontal distance to the dowel bar from the concrete surface based on the intensity of the magnetic field. This information can be used to further measure the alignment of the dowel bar. The steps involve finding out the ends of the dowel bars based on the abrupt signal drops. Once the ends are identified, the horizontal alignment is obtained from the deviations of the two ends and the vertical alignment is obtained by measuring the depths from the two ends (Young and Holle 2005). Unlike GPR and MIT-SCAN, this process is very time consuming and not practical to measure the alignment and location of all bars of a pavement section.

Ontario Ministry of Transportation Specification

One agency that does not use JS, but rather uses lots and sublots along with statistical sampling for verifying dowel alignment, is the Ontario Ministry of Transportation (MTO). The MTO adopted use of the MIT-SCAN for quality control in 2006 with an update to their concrete paving specification (Lane and Kazmierowski, 2008). Before 2017, the dowel bar alignment was a contractor’s responsibility, but in 2017, it became an MTO quality assurance activity. MTO evaluates four parameters as part of the dowel bar alignment verification: vertical translation, longitudinal translation, horizontal skew and vertical tilt. A specification limit and a rejection limit are established for each parameter (OPSS 2018). Current limits are shown in Table 4 and Table 5.

Table 4. Ontario specification limits for dowel bar alignment (adapted from OPSS 2018).

Quality Characteristic		Lower Limit (inches)	Upper Limit (inches)
Horizontal Skew		– 0.6	+ 0.6
Vertical Tilt		– 0.6	+ 0.6
Longitudinal Translation		– 2.0	+ 2.0
Vertical Translation	Slab Thickness < 8.5 inches	Mid-depth – 6	Mid-depth + 6
	Slab Thickness 8.5 to 9 inches	Mid-depth – 0.5	Mid-depth + 0.6
	Slab Thickness ≥ 9 inches	Mid-depth – 0.6	Mid-depth + 1.0

Table 5. Ontario rejection criteria for dowel bar alignment (adapted from OPSS 2018).

Quality Characteristic		Lower Limit (inches)	Upper Limit (inches)
Horizontal Skew		– 1.5	+ 1.5
Vertical Tilt		– 1.5	+ 1.5
Longitudinal Translation		– 3.0	+ 3.0
Vertical Translation	Slab Thickness <8.5 inches	Mid-depth – 0.4	Mid-depth + 0.4
	Slab Thickness 8.5 to 9.0 inches	Mid-depth – 0.7	Mid-depth + 0.9
	Slab Thickness 9.0 to 10.2 inches	Mid-depth – 1.0	Mid-depth + 1.4
	Slab Thickness ≥ 10.2 inches	Mid-depth – 1.0	Mid-depth + 1.6

The total quantity of concrete pavement placed on the contract is considered a lot. Each transverse joint is considered a sublot. Acceptance of the dowel bar alignment for the lot is based on the mean and standard deviation of the lot measurements for each quality characteristic. The dowel bar closest to the longitudinal joint is removed from the analysis due to potential interference of the longitudinal tie bar.

The PWL for the lot is calculated for each quality characteristic using the specification limits. If the lot PWL is greater than or equal to 90 percent, the lot is acceptable. If the lot PWL is less than 90 percent and greater than or equal to 50 percent, the lot is accepted with a price adjustment. If the lot PWL is less than 50 percent, the lot is rejectable and subject to repair and reassessment.

At the commencement of paving, the first joint is chipped out after being evaluated with the MIT-SCAN. The Contract Administrator inspects the joint and measures and records the dowel positions and alignments of all the dowel bars. These measurements are compared to the MIT-SCAN results to verify accuracy.

During paving, one joint for every ten joints is randomly selected and the position and alignment of the dowel bars are measured using the MIT-SCAN by the Owner's representative. If the position and alignment of any of the dowel bars is found to be rejectable, joints on either side of the unacceptable joint are scanned, until five consecutive joints on each side are found with no rejectable bars. Any joints with rejectable bars are removed and replaced.

Field Investigation

To evaluate the position and alignment of dowel and tie bars in Wisconsin, the research team conducted MIT-DOWEL-SCAN and MIT-SCAN-T2 testing at select concrete pavement locations in the state. Additional MIT-DOWEL-SCAN data was provided by WisDOT to supplement the analysis. The steps involved in site selection and field-testing process is detailed in this section.

Site Selection

Twelve test sites from six different counties in Wisconsin were chosen to carry out the MIT-DOWEL-SCAN testing. Information related to the project sites were obtained from WisDOT's Pavement Management Information System (PMIS) database provided by members of the Project Oversight Committee (POC). The sites were chosen based on the following considerations:

- Severity of pavement distress,
- Class of highway: Interstate, state highway, or local street,
- Dowel bar installation method (i.e., DBI or basket),
- Pavement thickness (which also relates to dowel bar diameter),
- Pavement shoulder type and width,
- Date and time of the construction,
- Dowel bar diameter, spacing, and offset,
- Tie bar diameter and spacing,
- Pavement foundation,
- Pavement lane numbers,
- Ability to close the traffic lane safely to conduct testing, and
- Site location.

In total, 1,293 joints were evaluated using the MIT-DOWEL-SCAN, which included 12,862 dowel bars after the data was passed through the initial filtering process. In addition, MIT-DOWEL-SCAN testing was performed on 20 joints in Chippewa County STH 178 SB to evaluate the alignment of tie bars. The data set also included the additional MIT-DOWEL-SCAN data provided by WisDOT, which included of 386 joints consisting of 3,954 dowel bars. The general description of the selected sites for this study is presented in Table 6 and the locations are shown in Figure 3.

Table 6. Description of the MIT-DOWEL-SCAN test sections.

County	Direction	Route	Baskets / DBI	Number of Joints Tested	Shoulder / Centerline Testing[1]	PCC Thickness (inch)	Dowel Diameter (inch)	AADT[2]	Pavement Surface Age
Chippewa	SB	178	Baskets	120	Y	8.85	1.25	8,100	21
Chippewa	NB	178	Baskets	105	Y	8.85	1.25	8,100	21
Eau Claire	NB	93	Baskets	110	N	8.0	1.25	13,740	20
Eau Claire	NB	53	DBI	120	N	9.5	1.25	37,550	16
Wood	EB	10	DBI	110	N	10.0	1.5	8,300	10
Wood	WB	10	DBI	98	N	10.0	1.5	8,300	10
Fond du Lac	NB	151	DBI	100	N	10.0	1.5	16,210	17
Fond du Lac	SB	151	DBI	90	N	10.0	1.5	16,210	17
Jefferson	WB	12	Baskets	115	N	9.0	1.25	12,700	19
Jefferson	EB	12	Baskets	105	N	9.0	1.25	12,700	19
Rock	NB	51	Baskets	110	N	9.0	1.25	10,630	12
Rock	WB	51	Baskets	110	N	9.0	1.25	10,630	12

[1]Using MIT-DOWEL-SCAN. MIT-SCAN-T2 testing was performed on all sections.
[2]AADT = Average annual daily traffic.

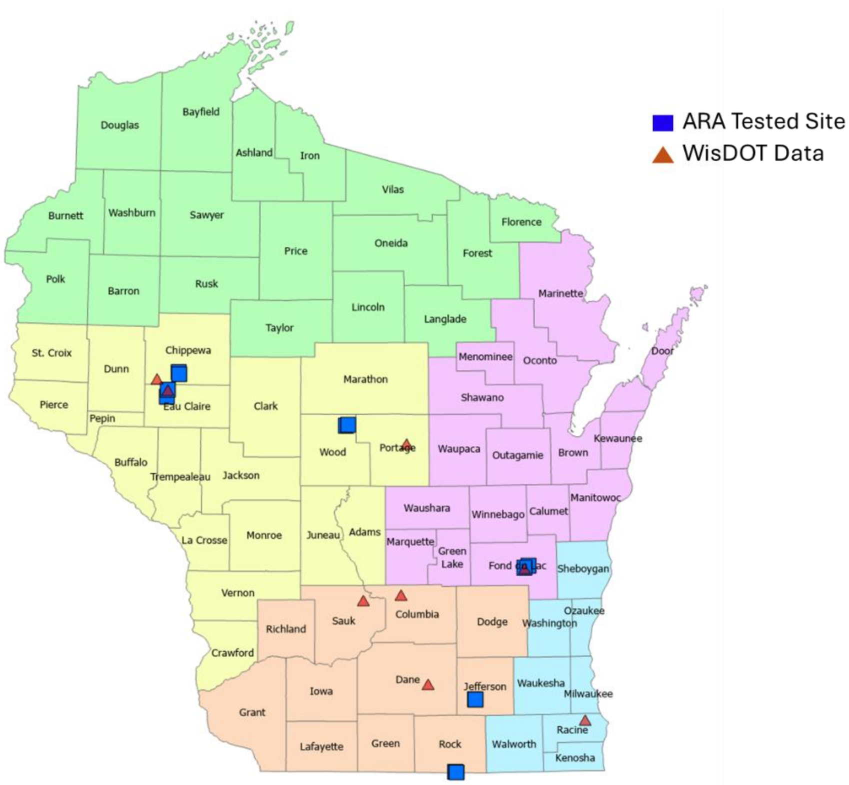


Figure 3. Location of the research and WisDOT sections (location of the WisDOT sections is approximate).

MIT-DOWEL-SCAN Testing

In recent years, transportation agencies have increasingly used the MIT-SCAN for evaluation of dowel bar alignment in JPCP for its accuracy and reliability. For the MIT-DOWEL-SCAN, the measuring process involves entering the pavement information into the unit and then pushing the unit along the joint. A snapshot of field crew testing a joint with the MIT-DOWEL-SCAN in shown in Figure 4. The data analysis process is performed using the MagnoProof software provided with the device. The latest version of this software is version 6, which was used for this project.

For this study, a two-person crew was deployed for field testing. Testing was restricted to the outer lane for all sections. Lane closure of the traffic lane was provided by the individual counties in Wisconsin. Notes taken during testing were documented through daily test logs. Each day upon completion of field data collection, the data files were saved on a local server and uploaded to a secure server for backup purposes.

Figure 4. MIT-DOWEL-SCAN testing in Chippewa County on STH 178 NB.

MIT-SCAN-T2 Testing

In addition to dowel bar testing using MIT-DOWEL-SCAN, MIT-SCAN-T2 testing was conducted on randomly selected centerline joints at all test sections, to evaluate any abnormalities in location and position of tie bars, as shown in Figure 5. MIT-SCAN-T2 was used to perform this testing rather than MIT-DOWEL-SCAN because the lane closures did not allow for testing of the centerline longitudinal joint adjacent to the open traffic lane.

MIT-SCAN-T2 is a nondestructive testing device that is designed to measure the thickness of the pavement by placing reflector metal plates on top of the base course prior to concrete paving operations. MIT-SCAN-T2 emits magnetic pulse and the rebound of the pulse induced by the metallic object is captured. The intensity of the rebound pulse is then used to calculate the depth to the metallic object (i.e., metal plates for thickness measurement) from the pavement surface. The MIT-SCAN-T2 was used to assess the approximate location and alignment of the tie bar. Testing involved locating the ends of the tie bars across the centerline of the slabs and estimating any misalignment based on the output signal displayed on the unit at the time of testing. Field observations are documented in Table 7.

Figure 5. MIT-SCAN-T2 testing to locate tie bar in Chippewa County STH 178 NB.

Table 7. Field notes from MIT-SCAN-T2 testing.

Section	Field notes
Chippewa STH 178 NB	Tested Joints 1-50 and 75-105. One location found at Joint 82 with one potential shallow tie bar, however not definitive.
Chippewa STH 178 SB	Tested Joints 1-30, 70-105 with no abnormalities noted.
Eau Claire STH 53	Significant tie bar misalignment observed in Joints 58, 95, and 97.
Eau Claire STH 93	No abnormalities noted.
Fond Du Lac US 151 EB	No abnormalities noted.
Fond Du Lac US 151 WB	No tie bars found in Joints 10 and 11.
Jefferson US12 WB	Checked tie bars for the curb/gutter and no noticeable misalignment was found.
Jefferson US12 EB	Horizontal and vertical misalignment under overpass between joints 61 and 88.
Rock US 51 NB	No tie bars found from joints 111 to 115.
Rock US 51 WB	Potential tie bar horizontal misalignment in centerline between joints 66 and 71.
Wood US 10 EB	No abnormalities noted.
Wood US 10 WB	No abnormalities noted.

Pavement Condition Data

In addition to MIT-DOWEL-SCAN and MIT-SCAN-T2 testing, a condition survey was conducted to document the presence of spalling and cracking. The condition of the pavement, particularly the joints, was documented by capturing the photograph of the respective joint during the MIT-DOWEL-SCAN testing. The distress information such as spalling and cracking and the respective severity of the distresses were documented from the captured images and used in the post-process analysis to investigate any correlation between dowel bar misalignment and distresses at the joints. The images were tagged with field notes to ensure consistency between the image and the MIT-DOWEL-SCAN data. Figure 6 shows images of some tested joints associated with different types of distress with different severity levels.

WisDOT provided the research team with pavement performance data collected using Pathway Services for the various sections. The data set included historical distress information for each section and condition data. However, pavement condition information on a join-by-joint basis was unavailable and the research team utilized the data from field condition survey for data analysis.

Figure 6. (a) Joint spalling in Eau Claire County on STH 53, (b) joint spalling in Jefferson County on US 12 EB, (c) cracking in Jefferson County on US 12 EB, and (d) cracking in Wood County on US 10 EB.

Data Analysis

This section discusses data analysis of the dowel alignment data collected using the MIT-DOWEL-SCAN. Major tasks included:

- Analysis of raw MIT-DOWEL-SCAN files to generate misalignment data including vertical translation, longitudinal translation, horizontal skew, and vertical tilt for each bar at each joint.
- Computation of JS for each joint.
- Computation of EDD using NCHRP Report 637 methodology for each joint.
- Analysis of effect of JS on slab cracking, joint spalling, and longitudinal translation.
- Documenting the modeled distress from PMED using both actual dowel diameter and EDD for each section.

Dowel Bar Alignment Analysis

The MIT-DOWEL-SCAN data collected was analyzed using MagnoProof version 6, the latest version of the software provided with the MIT-SCAN for analysis. Unlike earlier versions, with version 6, MIT upgraded the software to analyze dowel bars installed with either baskets (with tie wires cut or uncut) or DBI. Henceforth, in this report, these are referred to as version 6 (basket uncut analysis), version 6 (basket cut analysis) and version 6 (DBI analysis).

In version 6 (basket uncut analysis and basket cut analysis), depending on the shape or type of baskets, different analysis options are available, including (a) A-shaped basket (uncut), (b) A-shaped basket (cut), and (c) U-shaped basket.

For each joint that is successfully analyzed, the output includes the positions and the depths of the bars, the rotational misalignments (horizontal, vertical, and total), and the longitudinal translations. The vertical translations are estimates and computed based on the average PCC thickness, dowel diameter, and the measured depth of the bar from the surface. A screenshot of the different type of analysis offered by the software is shown in Figure 7.

To verify the results from version 6, the research team compared the calculated misalignments of dowel bars placed by means of DBI for a few individual joints in Wisconsin, using version 6 (DBI analysis) and version 5, as shown in Figure 8. Results from both versions were comparable except for a few dowel bars. Based on these comparisons, all sections with dowels placed using DBIs were analyzed using version 6 (DBI analysis).

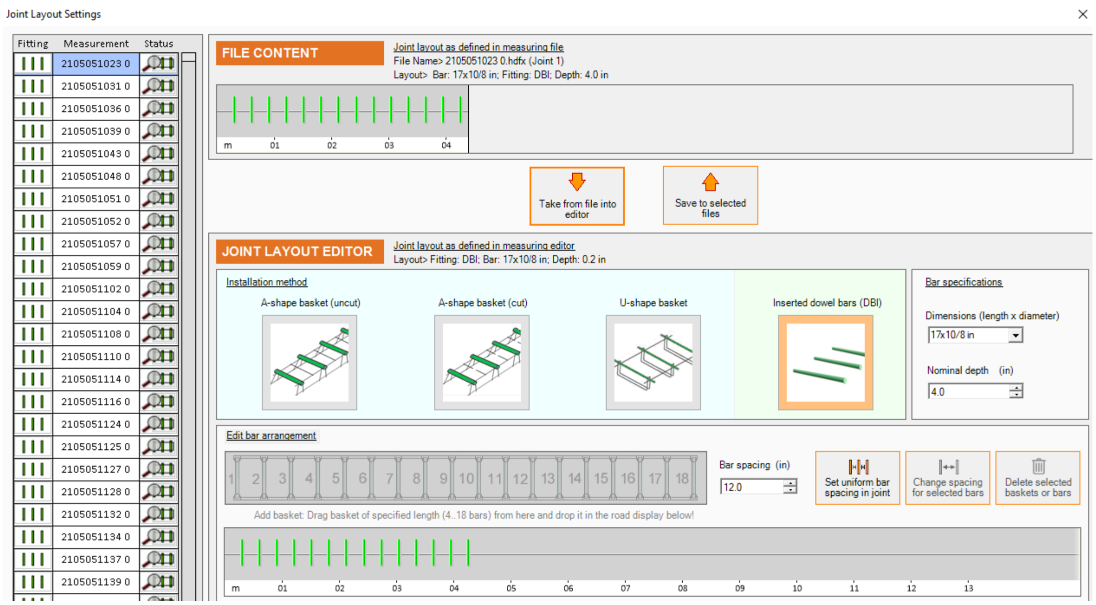
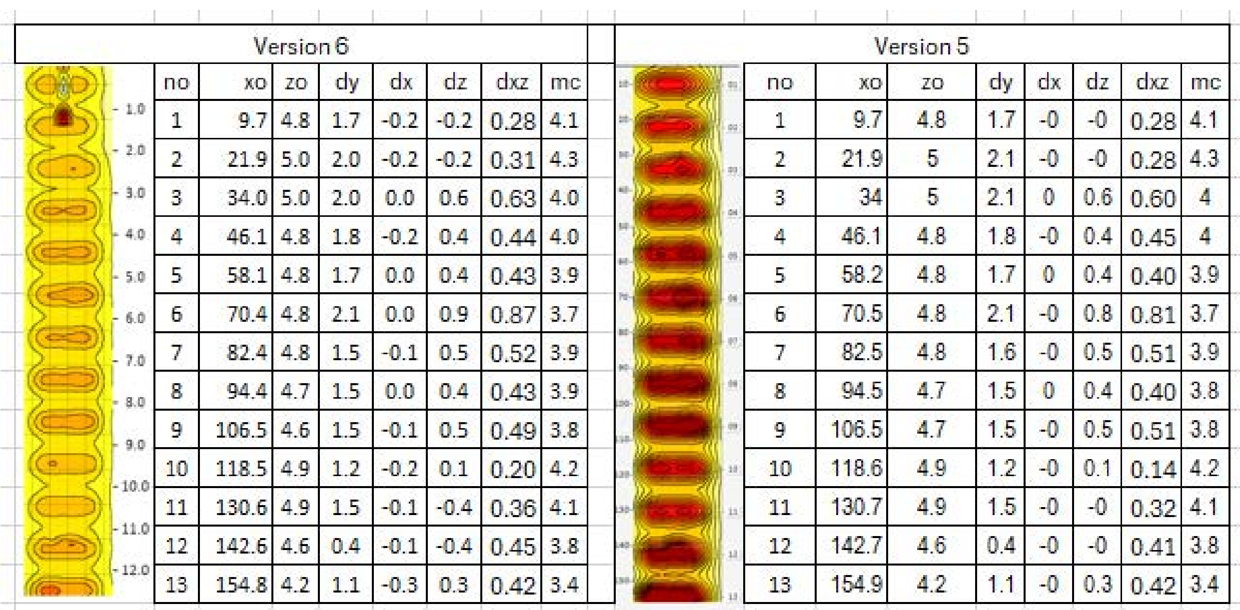


Figure 7. A screenshot of MagnoProof version 6 software showing different analysis options.



Version 6

no	xo	zo	dy	dx	dz	dxz	mc
1	9.7	4.8	1.7	-0.2	-0.2	0.28	4.1
2	21.9	5.0	2.0	-0.2	-0.2	0.31	4.3
3	34.0	5.0	2.0	0.0	0.6	0.63	4.0
4	46.1	4.8	1.8	-0.2	0.4	0.44	4.0
5	58.1	4.8	1.7	0.0	0.4	0.43	3.9
6	70.4	4.8	2.1	0.0	0.9	0.87	3.7
7	82.4	4.8	1.5	-0.1	0.5	0.52	3.9
8	94.4	4.7	1.5	0.0	0.4	0.43	3.9
9	106.5	4.6	1.5	-0.1	0.5	0.49	3.8
10	118.5	4.9	1.2	-0.2	0.1	0.20	4.2
11	130.6	4.9	1.5	-0.1	-0.4	0.36	4.1
12	142.6	4.6	0.4	-0.1	-0.4	0.45	3.8
13	154.8	4.2	1.1	-0.3	0.3	0.42	3.4

Version 5

no	xo	zo	dy	dx	dz	dxz	mc
1	9.7	4.8	1.7	-0	-0	0.28	4.1
2	21.9	5	2.1	-0	-0	0.28	4.3
3	34	5	2.1	0	0.6	0.60	4
4	46.1	4.8	1.8	-0	0.4	0.45	4
5	58.2	4.8	1.7	0	0.4	0.40	3.9
6	70.5	4.8	2.1	-0	0.8	0.81	3.7
7	82.5	4.8	1.6	-0	0.5	0.51	3.9
8	94.5	4.7	1.5	0	0.4	0.40	3.8
9	106.5	4.7	1.5	-0	0.5	0.51	3.8
10	118.6	4.9	1.2	-0	0.1	0.14	4.2
11	130.7	4.9	1.5	-0	-0	0.32	4.1
12	142.7	4.6	0.4	-0	-0	0.41	3.8
13	154.9	4.2	1.1	-0	0.3	0.42	3.4

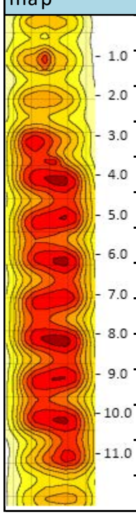
Note: x0 = distance from start of joint, z0=depth of bar center, dy = longitudinal translation, dx= horizontal skew, dz = vertical tilt, dxz = total misalignment, mc = minimum cover.

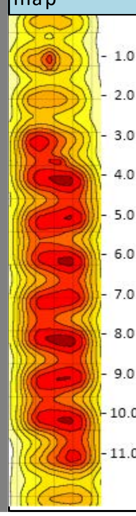
Figure 8.Comparison of calculated positions and misalignment of dowel bars using version 6 and version 5 of MagnoProof software.

To contrast the results from version 6 (basket uncut analysis) and version 6 (DBI analysis), the research team compared the calculated misalignments of dowel bars placed in baskets for a few individual joints in Wisconsin, as shown in Figure 9.

It is important to note the difference in the horizontal skew and the vertical tilt values resulting from using version 6 (basket uncut analysis) and version 6 (DBI analysis). As shown in the figure, the signal map produced by both approaches are identical and indicate that several dowel bars, particularly from bar #5 to bar #11, have relatively large horizontal skew values and vertical tilt values. This can be surmised visually by looking at the horizontal orientation of the bars relative to each other and the size of the bars, and the gradation in vertical intensities of the contour plots for the individual dowel bars. The horizontal skew values of the dowel bars ranged from 1.8 inches in the clockwise to 1.8 inches in the counterclockwise directions, as shown in the results of version 6 (DBI analysis). On the other hand, the horizontal skew values calculated by version 6 (basket uncut analysis) is reported by the software as an average value of -0.4 inches for all the bars within the joint. Likewise, the vertical tilt values calculated by version 6 (DBI analysis) ranged from 1.3 inches in the clockwise direction to 1.4 inches in the counterclockwise direction. However, the vertical tilt values calculated by version 6 (basket uncut analysis) is reported by the software as an average value of 0.0 inches for all the bars within the joint. Also, the version 6 (basket cut analysis) option did not function with the data files for this project.

Thus, the use of version 6 (basket uncut analysis and basket cut analysis) was deemed unacceptable by the research team for analysis conducted under this project since computing JS and EDD require alignment values for individual dowel bars within a joint and not averaged for all dowel bars within the joint. Therefore, analysis for all sections were conducted using version 6 (DBI analysis).

Computed bar positions using Basket (uncut)								
map	no	xo	zo	dy	dx	dz	dxz	mc
								
	1	9.1	6.1	1.3	-0.4	0.0	0.4	5.6
	2	20.9	6.1	1.1	-0.4	0.0	0.4	5.6
	3	32.8	6.1	0.8	-0.4	0.0	0.4	5.6
	4	44.6	6.1	0.5	-0.4	0.0	0.4	5.6
	5	56.4	6.1	0.3	-0.4	0.0	0.4	5.6
	6	68.2	6.1	0.0	-0.4	0.0	0.4	5.6
	7	80.0	6.1	-0.3	-0.4	0.0	0.4	5.6
	8	91.8	6.1	-0.6	-0.4	0.0	0.4	5.6
	9	103.6	6.1	-0.8	-0.4	0.0	0.4	5.6
	10	115.4	6.1	-1.1	-0.4	0.0	0.4	5.6
	11	127.2	6.1	-1.4	-0.4	0.0	0.4	5.6
	12	139.1	6.1	-1.6	-0.4	0.0	0.4	5.6
	13	150.9	6.1	-1.9	-0.4	0.0	0.4	5.6

Computed bar positions using DBI									
map	no	xo	zo	dy	dx	dz	dxz	mc	remark
									
	1	6.5	5.2	0.5	0.6	-0.3	0.6	4.5	
	2	18.4	5.1	1.0	0.2	-0.9	0.9	4.0	
	3	30.3	5.1	0.4	-0.2	-0.6	0.7	4.2	
	4	43.1	4.7	0.9	-0.5	-1.4	1.5	3.4	Un-known cause
	5	54.6	4.3	0.6	1.5	0.1	1.5	3.6	
	6	66.8	4.3	-0.7	-1.6	-0.1	1.6	3.7	Large hor. misal.
	7	78.7	4.4	0.4	1.1	0.3	1.2	3.6	
	8	90.9	4.4	-0.2	-1.8	-0.1	1.8	3.7	Large hor. misal.
	9	102.8	4.3	1.1	1.2	0.2	1.2	3.6	
	10	115.0	4.3	-0.4	-1.5	-0.1	1.5	3.7	
	11	126.5	4.3	-0.3	1.8	0.1	1.8	3.7	Very shallow bar
	12	138.6	4.6	-0.5	-1.5	1.3	2.0	3.3	
	13	151.4	4.9	-1.5	-0.4	0.1	0.4	4.3	

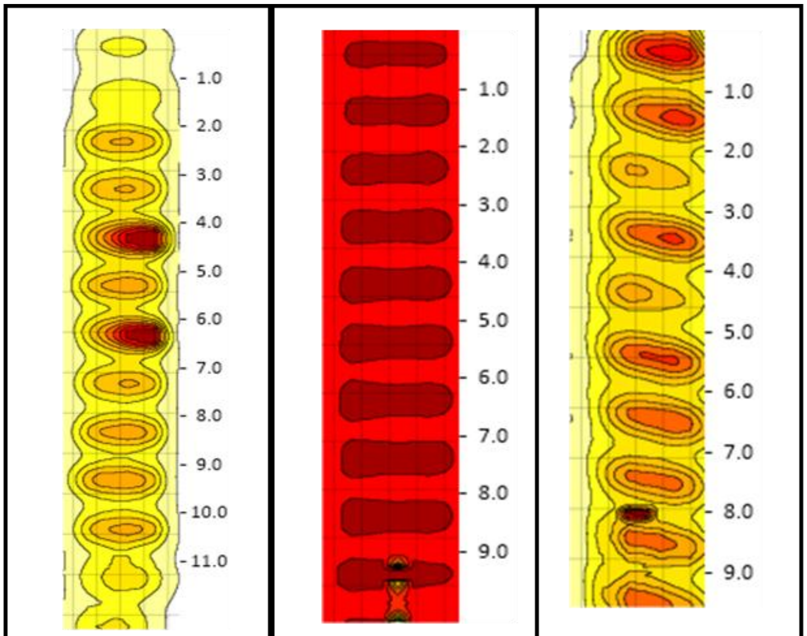
Note: x0 = distance from start of joint, z0=depth of bar center, dy = longitudinal translation, dx= horizontal skew, dz = vertical tilt, dxz = total misalignment, mc = minimum cover.

Figure 9. Results of the positions and alignment of dowel bar from basket (uncut) and DBI approach (Eau Claire STH 53 Joint#1).

The following activities were performed as part of the quality check prior to and during the analysis stage:

- The raw data files were analyzed using the DBI option in version 6. For each joint that was successfully analyzed, the software output includes the positions and the depths of the bars, the rotational misalignments (horizontal, vertical, and total), and the longitudinal translations (side shifts).
- Prior to analysis, the research team reviewed field notes to verify the dowel diameter for each section.
- Bars with extraneous signals from random tie bars or dowel bars, overhead power lines, or external metallic objects were excluded from analysis.
- MagnoProof version 6 did not report results for shallow or deep dowel bars. The comment "very shallow" is triggered when the calculated depth is less than 3.5 inches and the comment "very deep" is triggered at depths greater than 12 inches. When these limits are exceeded, the value is not shown since they are beyond the measuring limits of the sensors.
- If the data for a particular joint was considered unreliable, data from that joint was excluded from further analysis. Unreliable data based on information provided by MIT includes:
    - potential presence of external metal objects,
    - missing signal due to external influence or basket movement,
    - longitudinal translation greater than 3.2 inches,
    - horizontal skew greater than 1.6 inches,
    - vertical tilt greater than 1.6 inches, and
    - bar depth less than 4.2 inches or greater than 7.1 inches.

Sample contour plots generated by the software for three different joints are shown in Figure 10. Figure 10 (a) shows two dowel bars around 4.0-5.0 and 6.0-7.0 tilted with the right sides of the dowel bars closer to the surface than the left sides of these bars, as indicated by the red zones over the right sides of the dowel bars. Figure 10 (b) shows the contour plots for very shallow bars, which are only shown visually as uniformly intense red. In this case, the depth values are not computed by MagnoProof. Figure 10 (c) shows large side shifts and horizontal skews. This is indicated by the fact that the contour plots for the individual dowel bars are not centered with respect to the vertical centerline of the image and are also not parallel to the horizontal reference lines shown in the image.



(a) Presence of external metal object	(b) Very shallow bars	(c) Bars with large side shift and horizontal skew

Figure 10. Examples of 2d contour plots generated by MagnoProof version 6.

Dowel Bar Misalignment

Figure 11 through Figure 14 show the distribution of different types of misalignments (i.e., horizontal skew, vertical tilt, longitudinal translation, and vertical translation) of the dowel bars for all the counties. The analyses were limited to 1.25- and 1.5-inch dowel bars since these were the only two sizes of dowel bars encountered in this study. Figure 11 shows that approximately 83 percent of 1.25-inch and 91 percent of 1.5-inch dowel bars had horizontal skew within WisDOT specifications of between 0 and ± 0.5 inches. Approximately 95 percent of 1.25-inch dowel bars and 99 percent of 1.5-inch dowel bars had horizontal skew values between 0 and ± 1.0 inches. Figure 12 shows that approximately 70 percent and 72 percent of 1.25-inch and 1.5-inch diameter dowel bars, respectively, had vertical tilt values within WisDOT specifications of between 0 and ± 0.5 inches. Approximately 95 percent of 1.25-inch dowel bars and 98 percent of 1.5-inch dowel bars had vertical tilt values between 0 and ± 1.0 inches. Figure 13 shows that approximately 76 percent of 1.25-inch and 91 percent of 1.5-inch dowel bars had longitudinal translation within WisDOT specifications of between 0 and ± 2.0 inches. Figure 14 shows that approximately 88 percent of 1.25-inch and 84 percent of 1.5-inch dowel bars had vertical translation within WisDOT specifications of between 0 and ± 1.0 inches.

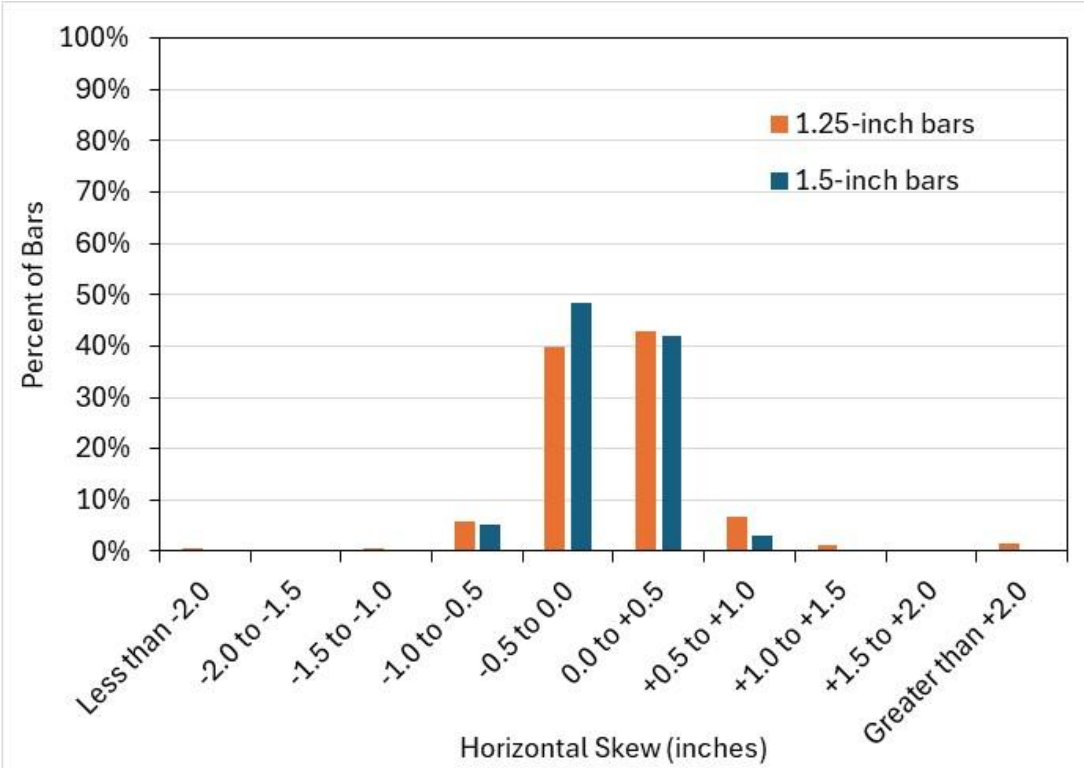


Figure 11. Distribution of horizontal skew for 1.25-inch and 1.5-inch dowel bars.

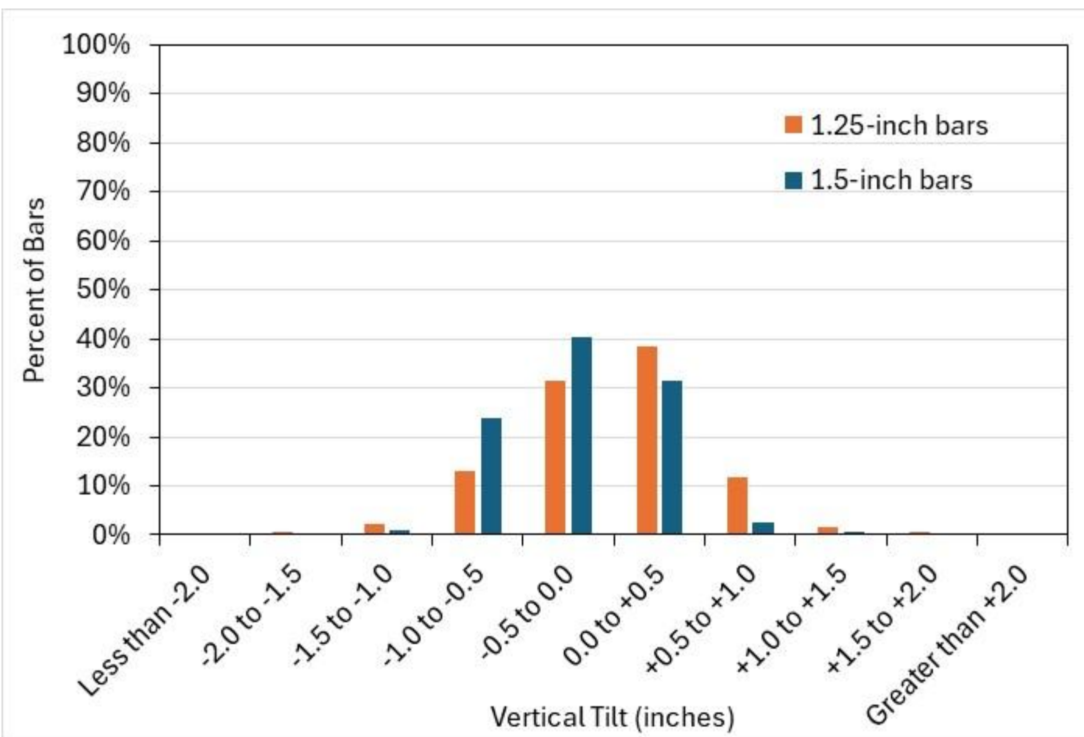


Figure 12. Distribution of vertical tilt for 1.25-inch and 1.5-inch dowel bars.

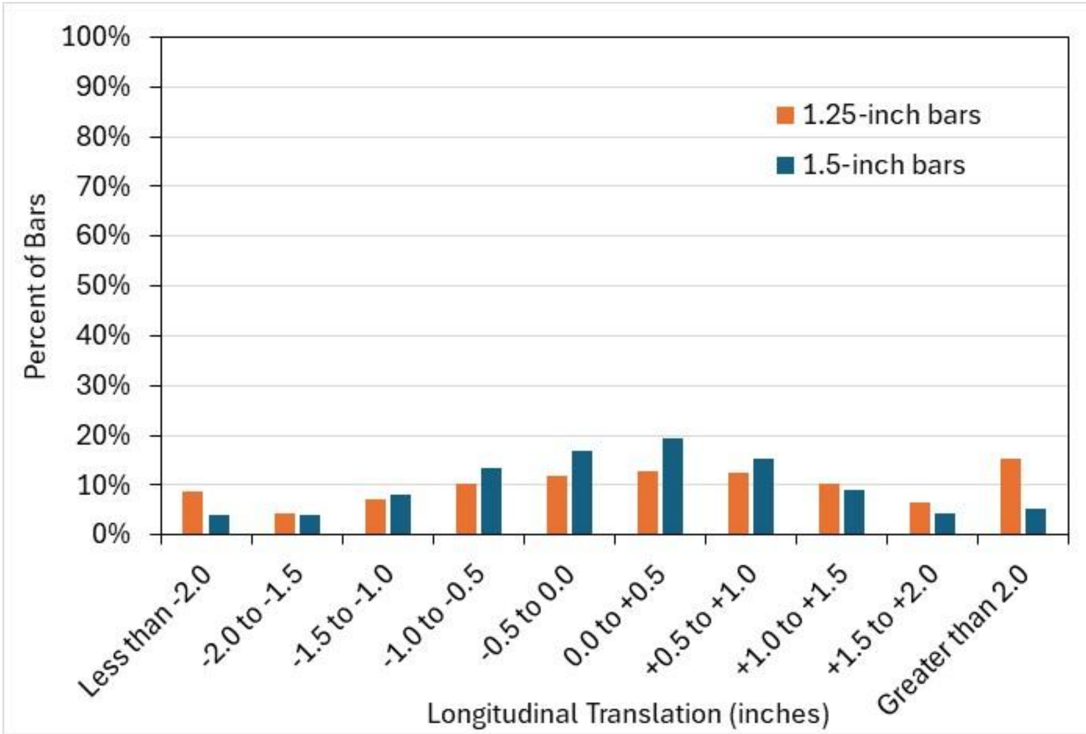


Figure 13. Distribution of longitudinal translation for 1.25-inch and 1.5-inch dowel bars.

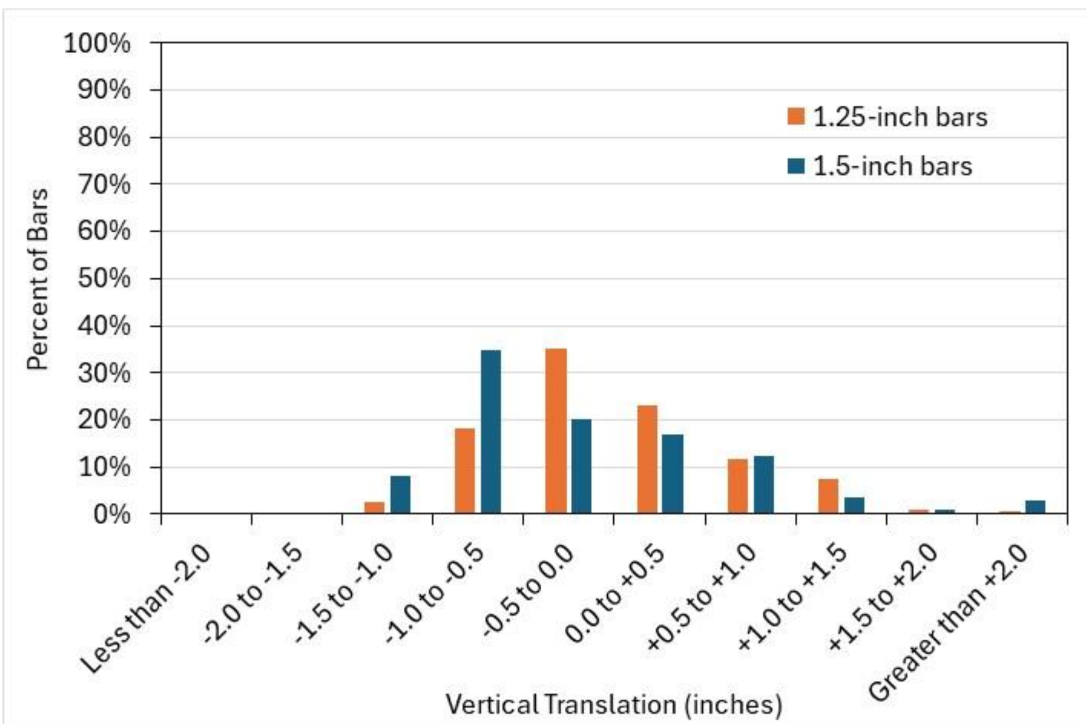


Figure 14. Distribution of vertical translation for 1.25-inch and 1.5-inch dowel bars.

Figure 15 through Figure 18 present the same results based on the installation method (i.e., DBI vs. basket) for all the counties considered for this study. While reviewing these comparisons, it is important to note that, as described above, the research team had to use version 6 (DBI analysis) for computing misalignments for both DBI-placed dowel bars and basket-placed dowel bars. Using version 6 (DBI analysis) is more accurate for DBI-placed dowel bars than basket-placed dowel bars. However, the results of the basket-placed dowel bars analyzed using version 6 (DBI analysis) are still valid on average for a large number of dowel bars, albeit less accurate on an individual dowel bar basis.

Figure 15 shows that approximately 80 percent of basket bars and 90 percent of DBI bars had horizontal skew within WisDOT specifications of between 0 and ± 0.5 inches. Approximately 94 percent of basket bars and 99 percent of DBI bars had horizontal skew values between 0 and ± 1.0 inches. Figure 16 shows that approximately 66 percent and 73 percent of basket and DBI dowel bars, respectively, had vertical tilt values within WisDOT specifications of between 0 and ± 0.5 inches. Approximately 94 percent of basket dowel bars and 98 percent of DBI dowel bars had vertical tilt values between 0 and ± 1.0 inches. Figure 17 shows that approximately 73 percent of basket bars and 88 percent of DBI bars had longitudinal translation within WisDOT specifications of between 0 and ± 2.0 inches. Figure 18 shows that approximately 86 percent of basket bars and 88 percent of DBI bars had vertical translation within WisDOT specifications of between 0 and ± 1.0 inches. Thus, the global analysis of alignment data of over 16,000 bars representing over 1,500 joints in Wisconsin shows that on average dowel bars installed using DBI had equal to or better alignment as compared to dowel bars installed using baskets. An interesting feature to note from Figure 18 is the distribution of the vertical translations. For dowels placed using baskets, the distribution is skewed to the bottom (positive) because the reference for the dowel placement is the base layer. Whereas, for dowels placed using DBI, the distribution is skewed to the top (negative), because the reference for the dowel placement is the concrete surface. This skewed distribution likely arises from the fact that the concrete layer is generally paved slightly thicker than specified (designed). Hence dowels placed in baskets are generally below measured mid depth, because the basket heights are selected at half of design thickness.

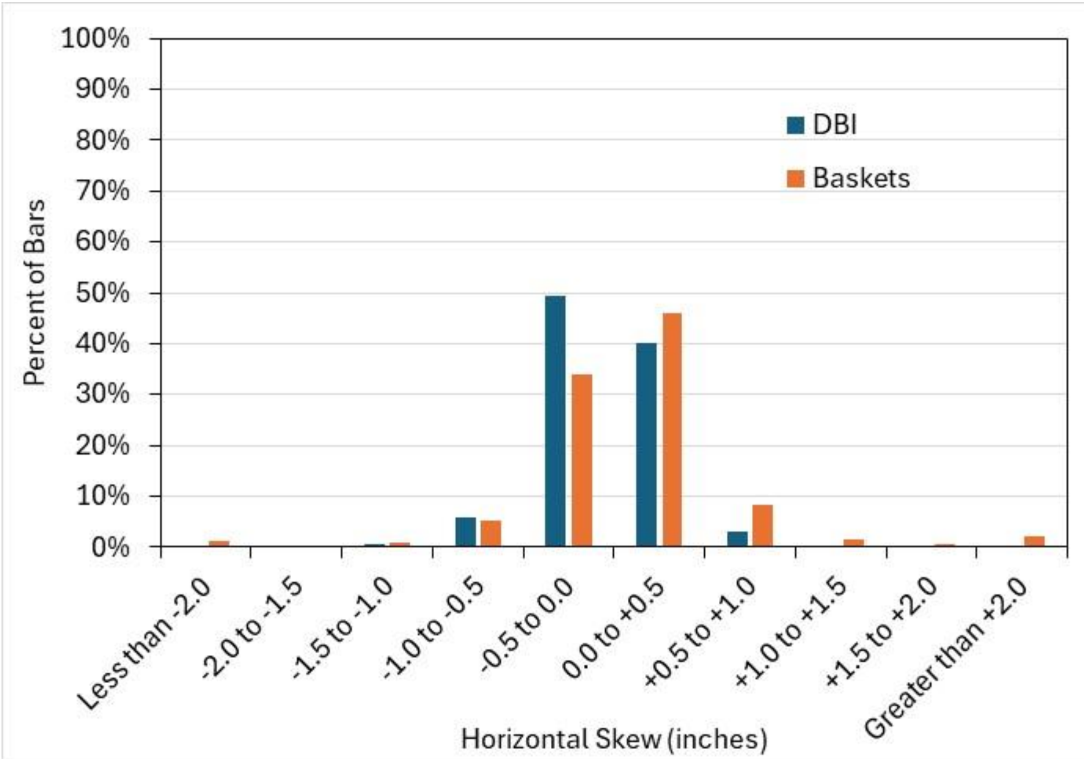


Figure 15. Distribution of horizontal skew based on the installation method.

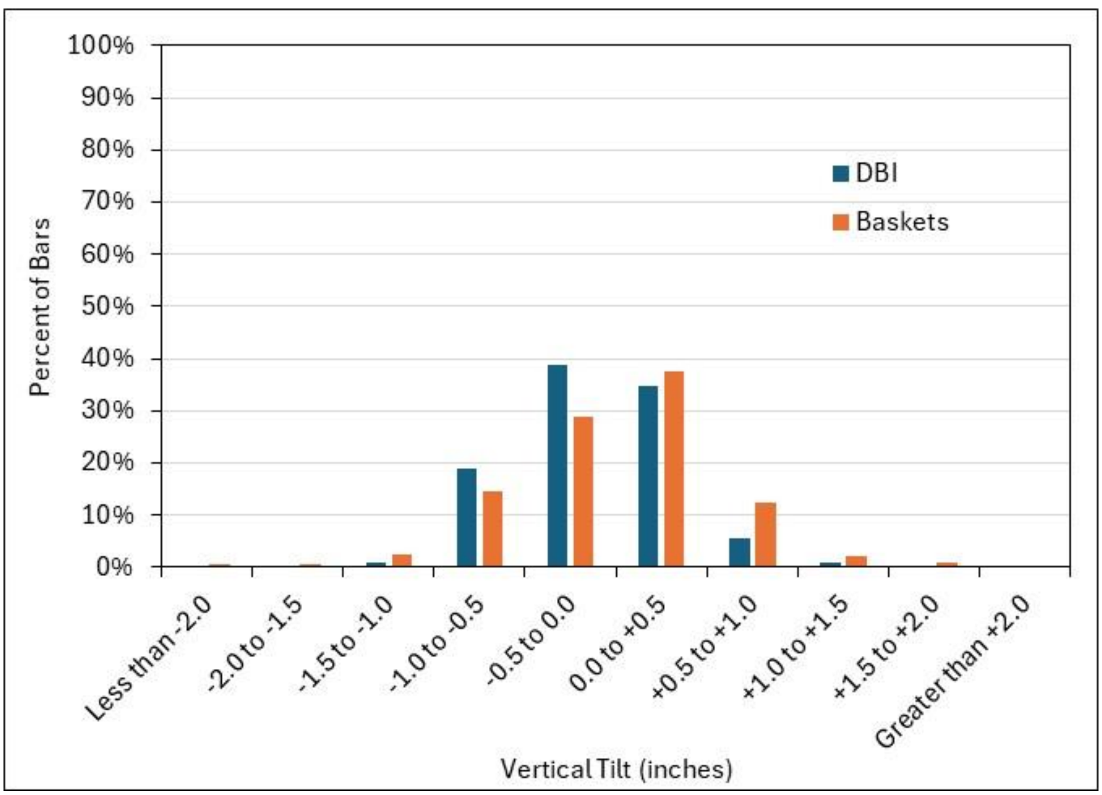


Figure 16. Distribution of vertical tilt based on the installation method.

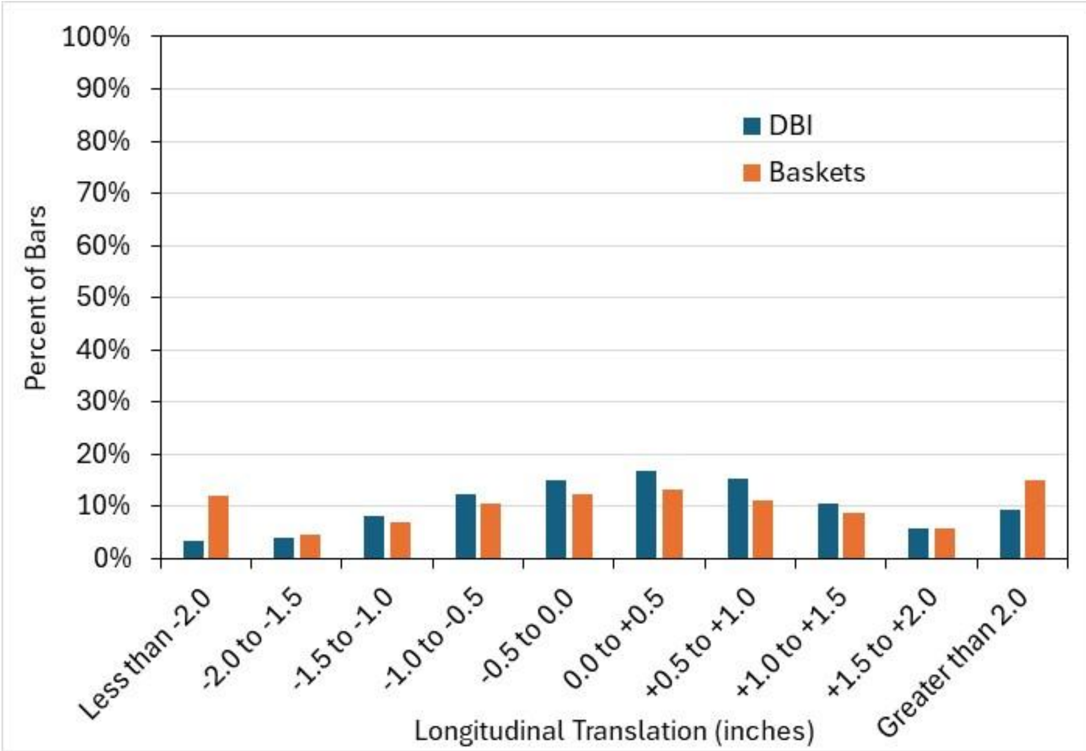


Figure 17. Distribution of longitudinal translation based on the installation method.

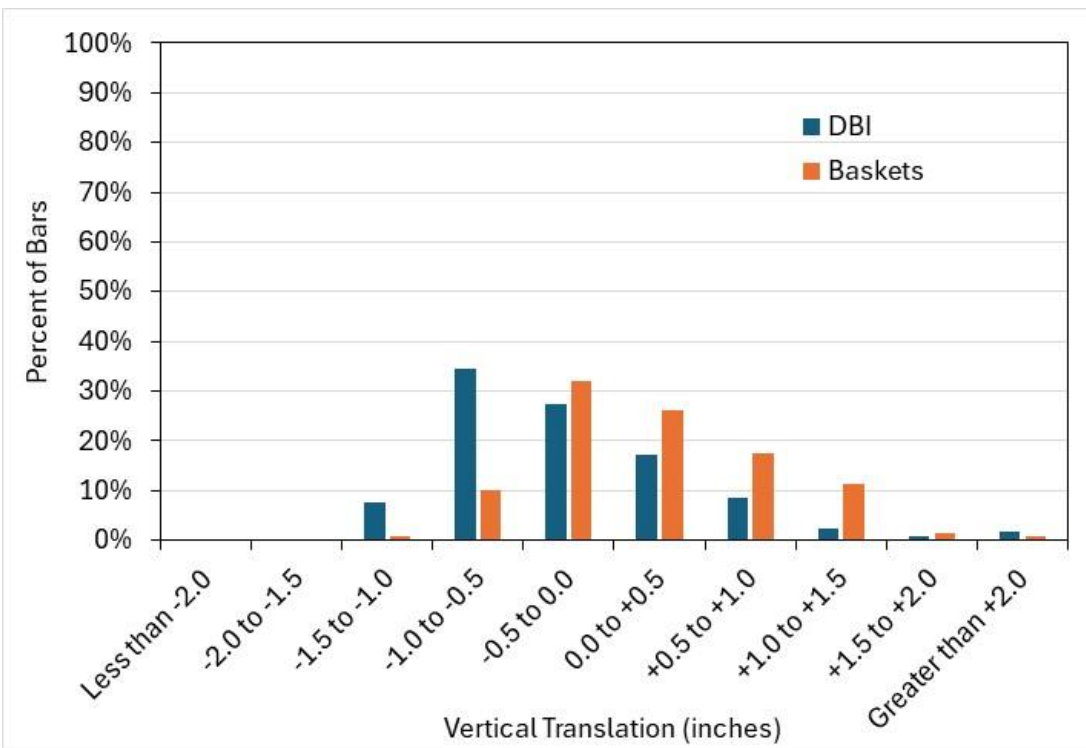


Figure 18. Distribution of vertical translation based on installation method.

Joint Score Analysis

Some transportation agencies have developed specifications for the acceptance or rejection of dowel bar placement based on the JS. JS represents the total misalignment of a single transverse joint. In this study the JS is calculated based on the ACPA guide specification published in 2018 (ACPA 2018). The process involves calculating the CM using Equation 1. Based on the CM, the weighting factor for each bar in the joint is determined using Table 8. Finally, the JS is calculated using Equation 2. Dowel bars influenced by external metal objects was excluded from the JS calculation.

$$\text{Composite Misalignment (CM)} = \sqrt{(\text{Horizontal Skew})^2 + (\text{Vertical Tilt})^2} \quad (1)$$

Table 8. Weighting factors used to determine Joint Score (ACPA 2018).

Range of Misalignment	Weight
0.0 inches < CM ≤ 0.6 inches	0
0.6 inches < CM ≤ 0.8 inches	2
0.8 inches < CM ≤ 1.0 inch	4
1.0 inch < CM ≤ 1.5 inches	5
CM > 1.5 inches	10

$$\text{Joint Score (JS)} = (1 + (\frac{x}{x-n}) \sum_{i=1}^{x} W_i) \quad (2)$$

where:

W_i= weighting factors for dowel i

x= number of dowels in a single joint

n= number of dowels excluded from the JS calculation

The distribution of the JS values for dowel bars of both 1.25-inch and 1.5-inch diameter is shown in Figure 19. Approximately 22 percent of the joints with 1.25-inch bars had JS values less than 5 and 21 percent of the joints had JS values more than 30. For 1.5-inch bars, almost 39 percent of the joints had JS values less than 5 and 11 percent of the joints had JS values greater than 30. The distribution of the JS values based on the installation method (i.e., basket versus DBI) is shown in Figure 20. Only 17 percent of the joints with bars installed in baskets had JS values less than 5. By comparison, approximately 37 percent of the bars installed with DBI had JS values less than 5. Approximately 28 percent of the bars with baskets had JS values more than 30 whereas only 9 percent of the bars installed with DBI had JS values more than 30. The JS analysis is consistent with the prior conclusion that on average dowel bars installed using DBI had equal to or better alignment as compared to dowel bars installed using baskets.

The summary of the JS values for all the sections along with the total number of tested joints considered in this study are presented in Table 9.

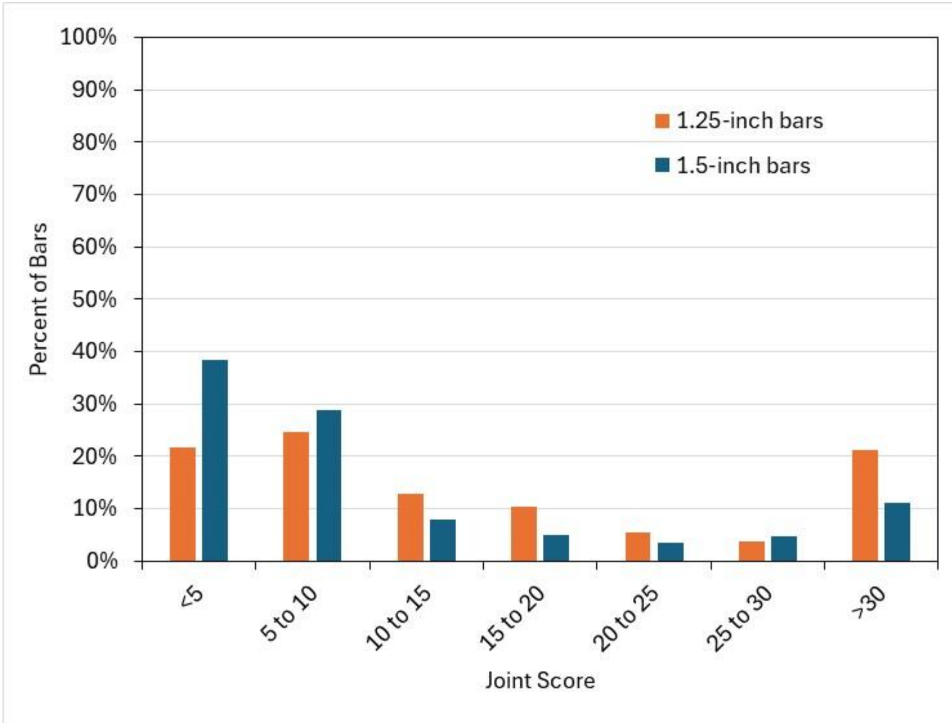


Figure 19. Distribution of joint score based on dowel bar diameter.

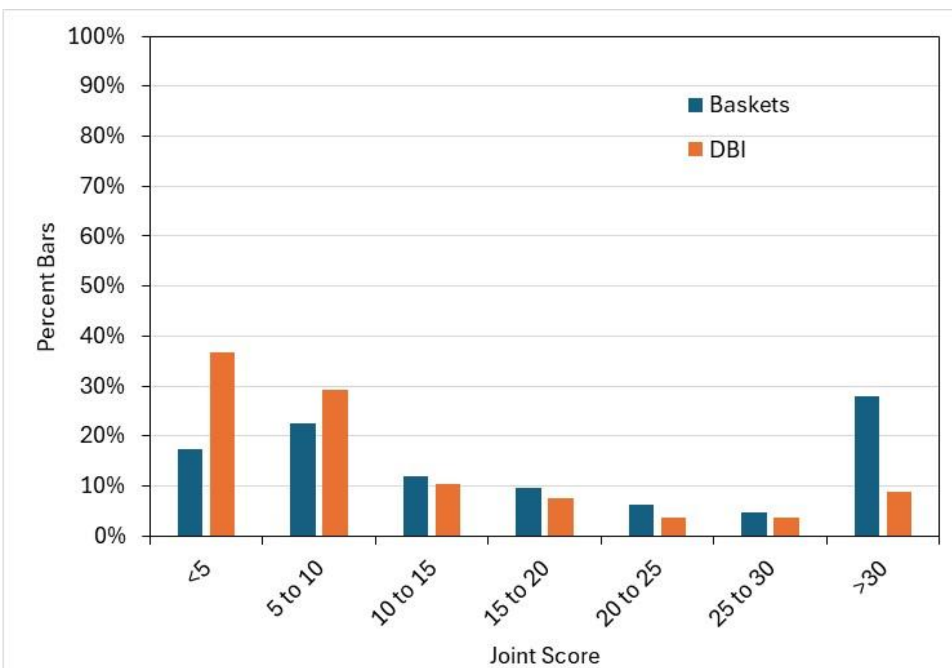


Figure 20. Distribution of joint score based on installation methods.

Table 9. Summary statistics of the Joint Score.

Section	Number of Joints Analyzed	Dowel Bar Diameter (inch)	Joint Score Average	Joint Score Standard Deviation
Chippewa STH 178 NB (Baskets)	120	1.25	40.04	57.76
Chippewa STH 178 SB (Baskets)	105	1.25	25.56	28.00
Eau Claire STH 53 (DBI)	110	1.25	9.08	14.43
Eau Claire STH 93 (Baskets)	120	1.25	12.66	11.24
Fond Du Lac US 151 EB (DBI)	110	1.5	7.32	14.11
Fond Du Lac US 151 WB (DBI)	98	1.5	10.81	23.37
Jefferson US12 WB (Baskets)	100	1.25	35.95	36.59
Jefferson US12 EB (Baskets)	90	1.25	15.92	18.21
Rock US 51 NB (Baskets)	115	1.25	13.97	16.91
Rock US 51 WB (Baskets)	105	1.25	17.29	14.87
Wood US 10 EB (DBI)	110	1.5	23.72	19.14
Wood US 10 WB (DBI)	110	1.5	10.60	7.78
STH 82 EB (DBI)*	50	1.25	30.96	20.25
STH 82 EB 5_25 (DBI)*	80	1.25	12.28	11.77
USH 12 SB Sec-1 Lane-1 (DBI)*	19	1.25	6.59	4.60
USH 12 SB Sec-1 Lane-2 (DBI)*	20	1.25	8.21	4.55
USH 12 SB Sec-2 Lane-1 (DBI)*	11	1.25	5.00	1.79
USH 12 SB Sec-2 Lane-2 (DBI)*	17	1.25	5.05	3.01
HW 151 SB Fond du Lac (DBI)*	22	1.5	5.45	10.88
HW 151 SB Fond du Lac 2 (DBI)*	34	1.5	3.00	2.71
I94 EB Dane County (DBI)*	24	1.5	4.07	3.73
STH 29 WB (DBI)*	28	1.5	6.37	21.04
US 53 NB (DBI)*	25	1.25	12.89	23.76
139 SB Columbia County (DBI)*	19	1.5	5.33	3.61
USH 12 SB (Baskets)*	6	1.5	53.67	46.52
CTG G to I-94 on Ramp (Baskets)*	31	1.25	19.78	22.39

* WisDOT provided

Critical Joint Score Analysis

According to the ACPA guide specification (ACPA 2018), $JS_{CRITICAL}$ represents a value of JS above which dowels at the joint have a higher probability of preventing the opening and closing of joint to an extent that affects the long-term performance of pavement. $JS_{CRITICAL}$ can be calculated based on Equation 3.

$$\text{Critical Joint Score } (JS_{CRITICAL}) = C * 15 * \frac{\text{Joint Width (foot)}}{12} \tag{3}$$

APCA recommends using C = 1.0 for typical panel (13 feet to 17 feet in length) constructed on unbound base with severe annual temperature, defined as (highest average monthly high temperature – lowest average monthly low temperature) greater than 70 °F. Hence, the value of C was assumed as 1.0 for this study. The APCA guide specifications also recommend the Maximum Effective Panel Length (MEPL) to be less than 60 feet and not contain more than three consecutive joints with JS greater than $JS_{CRITICAL}$. The number of joints with JS higher than $JS_{CRITICAL}$ and the number of instances where three consecutive joints were higher than $JS_{CRITICAL}$ for the sections in this study is presented in Table 10. Table 10 shows that about 30 percent (501 of 1,679 joints) analyzed had JS greater than $JS_{CRITICAL}$ and there were 69 instances of three or more consecutive joints having JS greater than $JS_{CRITICAL}$.

Table 10. Summary of Critical Joint Score analysis for all sections.

Section	Number of Joints Scanned	Dowel Diameter (inch)	JS > $JS_{CRITICAL}$		Number of Three Consecutive JS>$JS_{CRITICAL}$
			Instances	Percentage	
Chippewa STH 178 NB (Baskets)	120	1.25	68	56.7%	15
Chippewa STH 178 SB (Baskets)	105	1.25	50	47.6%	7
Eau Claire STH 53 (DBI)	110	1.25	10	9.1%	1
Eau Claire STH 93 (Baskets)	120	1.25	29	24.2%	1
Fond Du Lac US 151 EB (DBI)	110	1.5	7	6.4%	0
Fond Du Lac US 151 WB (DBI)	98	1.5	10	10.2%	1
Jefferson US12 WB (Baskets)	100	1.25	36	36.0%	3
Jefferson US12 EB (Baskets)	90	1.25	33	36.7%	2
Rock US 51 NB (Baskets)	115	1.25	33	28.7%	2
Rock US 51 WB (Baskets)	105	1.25	51	48.6%	8
Wood US 10 EB (DBI)	110	1.5	60	54.5%	13
Wood US 10 WB (DBI)	110	1.5	23	20.9%	2
STH 82 EB (DBI)*	50	1.25	36	72.0%	8
STH 82 EB 5_25 (DBI)*	80	1.25	27	33.8%	3
USH 12 SB Sec-1 Lane-1 (DBI)*	19	1.25	1	5.3%	0
USH 12 SB Sec-1 Lane-2 (DBI)*	20	1.25	2	10.0%	0
USH 12 SB Sec-2 Lane-1 (DBI)*	11	1.25	0	0.0%	0
USH 12 SB Sec-2 Lane-2 (DBI)*	17	1.25	0	0.0%	0
HW 151 SB Fond du Lac (DBI)*	22	1.5	1	4.5%	0
HW 151 SB Fond du Lac 2 (DBI)*	34	1.5	0	0.0%	0
I94 EB Dane County (DBI)*	24	1.5	0	0.0%	0
STH 29 WB (DBI)*	28	1.5	1	3.6%	0
US 53 NB (DBI)*	25	1.25	4	16.0%	0
139 SB Columbia County (DBI)*	19	1.5	0	0.0%	0
USH 12-SB (Baskets)*	6	1.5	1	16.7%	0
CTG G to I-94 on Ramp (Baskets)*	31	1.25	18	58.1%	3

* WisDOT provided

Joint Score Trigger Analysis

According to the 2013 ACPA guide specification (ACPA 2013), a JS higher than joint score trigger ($JS_{TRIGGER}$) indicates higher potential for locking of joints. $JS_{TRIGGER}$ was calculated using Equation 4 and scales the JS values to account for the actual number of dowels at a joint rather than the fixed value of 10. The number of times the JS was greater than $JS_{TRIGGER}$ for each section is shown in

Table 11.

Table 11 shows that about 45 percent (752 of 1,679 joints) analyzed had JS greater than $JS_{TRIGGER}$ and there were 134 instances of three or more consecutive joints having JS greater than $JS_{TRIGGER}$.

$$\text{Joint score trigger } (JS_{TRIGGER}) = 10 * \frac{\text{\# of dowel bars in single joint}}{12} \tag{4}$$

Table 11. Summary of joint score trigger for all the sections.

Section	Number of Joints Scanned	Dowel Diameter (inch)	JS > JSTRIGGER		Number of Three Consecutive JS>JSTRIGGER
			Instances	Percentage	
Chippewa STH 178 NB (Baskets)	120	1.25	90	75.00%	23
Chippewa STH 178 SB (Baskets)	105	1.25	72	68.57%	17
Eau Claire STH 53 (DBI)	110	1.25	31	28.18%	4
Eau Claire STH 93 (Baskets)	120	1.25	54	25.71%	5
Fond Du Lac US 151 EB (DBI)	110	1.5	21	19.09%	1
Fond Du Lac US 151 WB (DBI)	98	1.5	15	15.31%	1
Jefferson US12 WB (Baskets)	100	1.25	52	52.00%	9
Jefferson US12 EB (Baskets)	90	1.25	39	43.33%	4
Rock US 51 NB (Baskets)	115	1.25	52	45.22%	7
Rock US 51 WB (Baskets)	105	1.25	62	59.05%	13
Wood US 10 EB (DBI)	110	1.5	86	78.18%	22
Wood US 10 WB (DBI)	110	1.5	41	37.27%	7
STH 82 EB (DBI)*	50	1.25	41	82.00%	11
STH 82 EB 5_25 (DBI)*	80	1.25	37	46.25%	7
USH 12 SB Sec-1 Lane-1 (DBI)*	19	1.25	5	26.32%	0
USH 12 SB Sec-1 Lane-2 (DBI)*	20	1.25	6	30.00%	0
USH 12 SB Sec-2 Lane-1 (DBI)*	11	1.25	0	0.00%	0
USH 12 SB Sec-2 Lane-2 (DBI)*	17	1.25	1	5.88%	0
HW 151 SB Fond du Lac (DBI)*	22	1.5	1	4.55%	0
HW 151 SB Fond du Lac 2 (DBI)*	34	1.5	1	2.94%	0
I94 EB Dane County (DBI)*	24	1.5	4	16.67%	0
STH 29 WB (DBI)*	28	1.5	1	3.57%	0
US 53 NB (DBI)*	25	1.25	8	32.00%	0
139 SB Columbia County (DBI)*	20	1.5	1	5.00%	0
USH 12-SB (Baskets)*	5	1.5	3	60.00%	0
CTG G to I-94 on Ramp (Baskets)*	31	1.25	28	90.32%	3

* WisDOT provided

Equivalent Dowel Diameter Analysis

The EDD was calculated based on the procedure outlined in the NCHRP Report 637 (Khazanovich et al. 2009). The study showed that the primary impact of dowel misalignment is a loss in load transfer across the joint. As such, the EDD approach assumes that a joint with misaligned dowel bars is equivalent to a joint with perfectly aligned dowel bar of smaller diameter. The EDD can be then used in PMED to estimate the long-term performance of the pavement section. The summary statistics of the EDD for different sections along with the average reduction in dowel diameter as compared to the actual dowel diameter are shown in Table 12, which also shows the average JS for the same sections for comparison. For computation of EDD, the research team used the as-designed pavement thickness, because the as-constructed thickness was not available. The pavement thickness is a factor in computing vertical translation and the associated adjustment factor in the computation of EDD. When available, the as-constructed pavement thickness should be used to properly compute vertical translation adjustment factor.

Table 12. Summary statistics of equivalent dowel bar diameter.

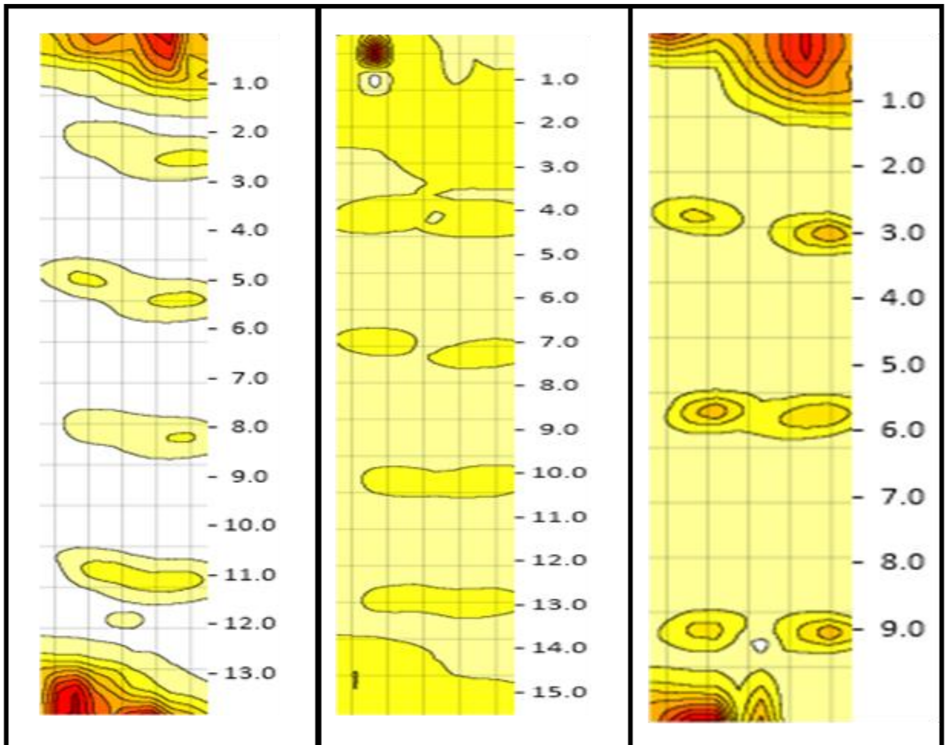
Section	Number of Joints Scanned	Dowel Diameter (inch)	Average EDD (inch)	Std Dev EDD (inch)	EDD Reduction (percent)	Joint Score
Chippewa STH 178 NB (Baskets)	120	1.25	1.042	0.296	16.64%	40.04
Chippewa STH 178 SB (Baskets)	105	1.25	1.092	0.306	12.64%	25.56
Eau Claire STH 53 (DBI)	110	1.25	1.205	0.081	3.60%	9.08
Eau Claire STH 93 (Baskets)	120	1.25	1.103	0.146	11.76%	12.66
Fond Du Lac US 151 EB (DBI)	110	1.5	1.467	0.035	2.20%	7.32
Fond Du Lac US 151 WB (DBI)	98	1.5	1.447	0.105	3.53%	10.81
Jefferson US12 WB (Baskets)	100	1.25	1.206	0.041	3.52%	35.95
Jefferson US12 EB (DBI)	90	1.25	1.172	0.083	6.24%	15.92
Rock US 51 NB (Baskets)	115	1.25	1.197	0.13	4.24%	13.97
Rock US 51 WB (Baskets)	105	1.25	1.196	0.092	4.32%	17.29
Wood US 10 EB (DBI)	110	1.5	1.418	0.072	5.47%	23.72
Wood US 10 WB (DBI)	110	1.5	1.396	0.039	6.93%	10.60
STH 82 EB (DBI)*	50	1.25	1.221	0.031	2.32%	30.96
STH 82 EB 5_25 (DBI)*	80	1.25	1.224	0.044	2.08%	12.28
USH 12 SB Sec-1 Lane-1 (DBI)*	19	1.25	1.210	0.018	3.20%	6.59
USH 12 SB Sec-1 Lane-2 (DBI)*	20	1.25	1.226	0.012	1.95%	8.21
USH 12 SB Sec-2 Lane-1 (DBI)*	11	1.25	1.226	0.011	1.92%	5.00
USH 12 SB Sec-2 Lane-2 (DBI)*	17	1.25	1.223	0.012	2.16%	5.05
HW 151 SB Fond du Lac (DBI)*	22	1.5	1.476	0.018	1.60%	5.45
HW 151 SB Fond du Lac 2 (DBI)*	34	1.5	1.329	0.224	11.40%	3.00
I94 EB Dane County (DBI)*	24	1.5	1.349	0.113	10.07%	4.07
STH 29 WB (DBI)*	28	1.5	1.350	0.31	10.00%	6.37
US 53 NB (DBI)*	25	1.25	1.192	0.084	4.64%	12.89
139 SB Columbia County (DBI)*	19	1.5	1.394	0.037	7.07%	5.33
USH 12-SB (Baskets)*	6	1.25	1.125	0.05	10.00%	53.67
CTG G to I-94 on Ramp (Baskets)*	31	1.25	0.994	0.31	20.48%	19.78

* WisDOT provided

Table 12 shows that average EDD reductions range from less than 2 percent to greater than 20 percent. While some locations, such as Chippewa STH 178 NB and SB, have both high JS and high EDD reduction, and other locations, such as Fond du Lac US 151 EB and WB have low JS and low EDD reduction, the correlation between JS and EDD is not always true. This is because JS only accounts for horizontal skew and vertical tilt, while EDD accounts for horizontal skew, vertical tilt, vertical translation, and horizontal translation.

Tie Bar Misalignment

The research team performed MIT-DOWEL-SCAN testing on the lane-shoulder joint to evaluate the position and the alignment of tie bars on STH 178 SB in Chippewa County. Data analysis was performed using MagnoProof version 6. Due to the presence of external metal objects, shallow tie bars, or large longitudinal translation, version 6 did not compute the misalignment values for the tie bars. The 2d signal maps generated by the software for tie bar analysis are shown in Figure 21 to demonstrate examples of the hindrance mentioned above. The contour images show some bars with two peaks (darker yellow to red) within a contour for the individual tie bars instead of one single peak. This could potentially be due to the tie bars being bent at the longitudinal joint during phased construction installation. This may have been done to accommodate the construction sequence by allowing the tie bars to be straightened once the adjacent concrete lane was poured.



(a) Presence of large side shift	(b) Very shallow bars	(c) Presence of external metal object

Figure 21. Sample contour maps from tie bar analysis.

Performance Modeling Using Equivalent Dowel Diameter

To evaluate the effect of the EDD on the long-term performance of Wisconsin sections, the research team compared predicted performance using PMED for both the actual (design) dowel diameter and the computed EDD. Wisconsin-specific calibration coefficients (appendix A) and available material information, and section-specific traffic data was used to develop the PMED files. The subgrade information for all sections were estimated from information developed by the National Cooperative Soil Survey. The results of the PMED runs for all sections over their 20-year design life at 90 percent reliability are presented in Table 13 and

Table 14 and detailed in appendix B.

As expected, the results indicate an increase in IRI and faulting when EDD is used instead of actual diameter, because the EDD is always less than or equal to the actual dowel diameter. In instances where the EDD was significantly different from the actual dowel diameter due to higher levels of misalignment, the increase in faulting and IRI were pronounced. For example, the EDD for Chippewa STH 178 NB is estimated to be 1.042 inches which is almost 17 percent less than the actual dowel diameter. For that section, when EDD was used, IRI increased from 149.18 inches per mile to 152.53 inches per mile and faulting increased from 0.02 inches to 0.05 inches. While these increases are relatively small and still within WisDOT performance criteria limits, they still point to increased faulting and roughness over time and potential earlier maintenance and rehabilitation treatments such as diamond grinding or overlays. Similarly, for CTG G to I-94 SB on Ramp section, the EDD was estimated to be 0.994 inches which is over 20 percent less than the actual dowel diameter. For that section, when EDD was used, IRI increased from 120.15 inches per mile to 131.75 inches per mile and faulting increased from 0.05 inches to 0.09 inches. The results support the fact that the reduction in EDD impacts transverse joint LTE, which in turn induce adverse effects in terms of long-term pavement performance.

The results of this analysis are consistent with the observations noted in the FHWA study conducted by Rao and Premkumar (2020). In that study, the researchers also compared the predicted distresses with the actual distress using both EDD and actual diameter. The results of PMED runs using the actual diameter and EDD show that using the EDD instead of actual dowel diameter produces a reduced bias of the in-service LTE. However, the results were reversed when evaluating faulting, where using EDD instead of actual dowel diameter produces a greater bias of faulting as modeled using PMED. Rao and Premkumar suggested that although contradictory, the results may make sense when considering PMED was calibrated using LTPP test sections, and that some level of 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.

Table 13. **Pavement ME Design results for the sections tested by the research team.**

Section	Dowel Diameter (inch)	Terminal IRI (inch/mile)	Faulting (inch)
Chippewa STH 178 NB (Baskets)	1.042 (effective)	152.53	0.05
	1.25 (actual)	149.18	0.02
Chippewa STH 178 SB (Baskets)	1.092 (effective)	152.22	0.05
	1.25 (actual)	148.91	0.03
Eau-Claire STH-53_NB (DBI)	1.205 (effective)	101.99	0.03
	1.25 (actual)	101.39	0.03
Eau-Claire STH-93_NB (Baskets)	1.103 (effective)	104.45	0.04
	1.25 (actual)	102.39	0.03
Fond Du Lac US 151 EB (DBI)	1.467 (effective)	136.02	0.01
	1.5 (actual)	135.98	0.00
Fond Du Lac US 151 WB (DBI)	1.447 (effective)	136.16	0.01
	1.5 (actual)	136.16	0.01
Jefferson US12 EB (Baskets)	1.172 (effective)	125.2	0.04
	1.25 (actual)	124.46	0.03
Jefferson US12 WB (DBI)	1.206 (effective)	124.93	0.04
	1.25 (actual)	124.6	0.03
Rock US 51 NB (Baskets)	1.197 (effective)	120.32	0.04
	1.25 (actual)	119.82	0.04
Rock US 51 WB (Baskets)	1.196 (effective)	120.44	0.04
	1.25 (actual)	119.94	0.04
Wood US 10 EB (DBI)	1.418 (effective)	144.14	0.02
	1.5 (actual)	144.1	0.02
Wood US 10 WB (DBI)	1.396 (effective)	144.55	0.02
	1.5 (actual)	144.51	0.02

Table 14. Pavement ME Design results the sections received from WisDOT.

Section	Dowel Diameter (inch)	Terminal IRI (in/mile)	Faulting (inch)
USH 12-SB_Section-1_Lane 1 (DBI)	1.210 (effective)	134.58	0.04
	1.25 (actual)	134.01	0.04
USH 12-SB_Section-1_Lane 2 (DBI)	1.226 (effective)	134.25	0.04
	1.25 (actual)	134.01	0.04
USH 12-SB_Section-2_Lane 1 (DBI)	1.226 (effective)	134.25	0.04
	1.25 (actual)	134.01	0.04
USH 12-SB_Section-2_Lane 2 (DBI)	1.223 (effective)	134.42	0.04
	1.25 (actual)	134.01	0.04
HW 151 SB Fond du Lac (DBI)	1.476 (effective)	137.15	0.03
	1.5 (actual)	137.07	0.03
HW 151 SB Fond du Lac County 2 (DBI)	1.329 (effective)	137.56	0.03
	1.5 (actual)	137.07	0.03
STH 29 WB (DBI)	1.350 (effective)	154.06	0.06
	1.5 (actual)	152.68	0.05
US 53 NB (DBI)	1.192 (effective)	153.05	0.04
	1.25 (actual)	151.96	0.03
139 SB Columbia County (DBI)	1.394 (effective)	96.83	0.03
	1.5 (actual)	96.58	0.03
CTG G to I-94 SB on Ramp (Baskets)	0.994 (effective)	131.75	0.09
	1.25 (actual)	120.15	0.05

Distress Evaluation

Chi-squared test for independence was conducted to investigate the relationship between JS and cracking, spalling, and longitudinal translation. Chi-squared test of independence is a statistical test used for analysis of two categorical variables, in this case severity of JS, and presence of cracking, spalling, or longitudinal translation. The severity of JS was categorized based on Table 15.

Table 15. Joint Score category.

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

The chi-squared statistical analysis was set up based on the following hypothesis:

- Null hypothesis: H_O: JS and cracking, spalling, longitudinal translation are independent.
- Alternative hypothesis: H_A: JS and cracking, spalling, longitudinal translation are dependent.

The hypothesis was tested at 95 percent confidence level, i.e., the null hypothesis is rejected if the p-value is found less than 0.05. In other words, the correlation between JS and spalling, cracking, or longitudinal translation is statistically significant if p-value is less than 0.05. A 95 percent confidence interval is considered a standard practice in statistics because it provides a widely accepted level of confidence that the true population parameter lies within the calculated range, with a balance between being too narrow (less confident) and too wide (less precise); most statistical analyses typically use a 95 percent confidence interval as default unless there is a specific reason to choose otherwise.

The chi-squared analysis was done for each site independently to neutralize the effect of age and thickness of the pavement, traffic, climate, subgrade condition, and sample size on the relationship between JS and spalling, cracking, or longitudinal translation. Results of chi-squared analysis for all sites is presented in

Table 16.

The p-values from

Table 16 indicate no statistically significant relationship between JS and spalling or cracking corresponding to the typical levels of misalignment in Wisconsin pavements. It is quite possible that much higher levels of misalignment (e.g., JS > 40) may contribute to some or even significant amount of spalling or cracking. This outcome is consistent with the results from FHWA study conducted by Rao and Premkumar (2020) which included analysis of over 3,700 joints from over 120 Specific Pavement Studies-2 (SPS-2) pavement sections representing 11 states. The results suggests that other factors may have a stronger effect on transverse cracking and spalling compared to JS for pavement with typical levels of dowel misalignment.

As shown in

Table 16, the statistical analysis does indicate a relationship between longitudinal translation and JS for Chippewa and Rock counties. While JS (which only accounts for horizontal skew and vertical tilt) and longitudinal translation are independent measures, the relationship between the two in these two counties suggest the contractor may have experienced challenges with dowel bar placement during paving.

Table 16. Summary of the results from chi-squared independence test.

Section	Number of Joint Analyzed	Dowel Diameter (inch)	p-Value, Spalling	p-Value, Cracking	p-Value, Longitudinal Translation
Chippewa STH 178 NB (Baskets)	120	1.25	0.085	0.599	***<0.001***
Chippewa STH 178 SB (Baskets)	105	1.25	0.314	0.663	***<0.001***
Eau Claire STH-53 (DBI)	110	1.25	0.6	0.356	0.197
Eau Claire STH-93 (Baskets)	120	1.25	0.34	0.436	0.128
Fond Du Lac US 151 EB (DBI)	110	1.5	N/A	0.803	0.436
Fond Du Lac US 151 WB (DBI)	98	1.5	0.776	0.229	0.685
Jefferson US12 WB (Baskets)	100	1.25	0.087	0.869	0.306
Jefferson US12 EB (Baskets)	90	1.25	0.635	0.543	0.192
Rock US 51 NB (Baskets)	115	1.25	0.335	0.546	0.077
Rock US 51 WB (Baskets)	105	1.25	0.587	0.433	***0.005***
Wood US 10 EB (DBI)	110	1.5	N/A	N/A	0.224
Wood US 10 WB (DBI)	110	1.5	N/A	0.514	0.075

The chi-squared analysis was only performed on the data collected as part of this research effort because individual joint distress information was unavailable for the WisDOT-provided data sections. To evaluate the effect of critical variables, such as pavement age, pavement thickness, spalling, and cracking, logistic regression analysis was conducted on the entire dataset, which included the additional data provided by WisDOT.

Logistic regression is a form of regression analysis used to predict categorical outcome variable. In this case, the logistic regression model was fit to the dataset to predict presence of spalling and presence of cracking based on predictor variables: age, thickness, and JS. With the inclusion of JS as predictor variable, the relationship between pavement age and pavement thickness and the outcome variable (cracking or spalling) can be obtained, while also accounting for any potential influence of JS. The logistic regression function is expressed as follows:

$$logit[p(y)] = \ln\left[\frac{p(y)}{1-p(y)}\right] = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \ldots + b_nx_n \quad (5)$$

where:

$p(y)$ = probability of the outcome variable. In this case, probability of presence of spalling or cracking.

$b_1, b_2, b_3 \ldots b_n$ = coefficient of each predictor variable, and

$x_1, x_2, x_3 \ldots x_n$= predictor variable.

As mentioned earlier, the outcome variables are presence of spall or crack, and the predicting variables are age of the pavement, thickness of the pavement, and JS. Therefore, Equation 5 can be expressed on the following condensed form:

$$l \ln\left[\frac{p(spall/crack)}{1 - p(spall/crack)}\right] = b_0 + b_1 * Age + b_2 * Thickness + b_3 * JS \quad (6)$$

The results of the logistic regression models for spalling and cracking are shown in Table 17. According to Table 17, only age is statistically significant at the 95 percent confidence level in predicting the presence of spalling. The coefficient corresponding to spalling indicates a positive correlation between age and spalling likelihood, i.e., older pavements are more likely to exhibit spalling. A similar positive relationship exists between cracking and pavement age, although the effect is less pronounced as indicated by the smaller coefficient as compared with spalling. Nonetheless, the relationship is statistically significant at a confidence level of 95 percent. For both the spalling and cracking regression models, the relationship between the outcome variables and thickness of the pavement and between the outcome variables and JS, were not statistically significant. This result is consistent with that of the chi-squared analysis.

Table 17. Results of logistic regression analysis.

Outcome Variable	**Predictor variable**	**Coefficient**	**Std. Error**	**P-Value**
Spalling	Intercept	-4.2736	2.061	0.038*
	Age	0.2524	0.039	<0.001*
	Thickness	0.0004	0.003	0.870
	JS	-0.2322	0.175	0.185
Cracking	Intercept	-5.818	2.311	0.012*
	Age	0.0669	0.034	0.048*
	Thickness	0.0046	0.003	0.103
	JS	0.2312	0.21	0.270

Conclusions

Guidelines for allowable dowel misalignment vary from agency to agency. Despite more than 30 years of research, no consensus exists on dowel bar tolerances. To help the Wisconsin Department of Transportation (WisDOT) develop tolerance limits and proper thresholds for dowel and tie bar alignments to achieve long-term satisfactory joint performance and practical installation of bars, the research team collected dowel and tie bar data from various counties in Wisconsin using the MIT-DOWEL-SCAN and MIT-SCAN-T2 devices.

The data were analyzed using the latest version of the MagnoProof (version 6) to calculate the various dowel alignment parameters including horizontal skew, vertical tilt, longitudinal translation, and vertical translation. For each joint, the Joint Score (JS) and equivalent dowel diameter (EDD) were also calculated. Results from comparisons between MagnoProof version 5 and MagnoProof version 6 (DBI analysis) were comparable except for a few dowel bars. Thus, all sections with dowels placed using DBIs were analyzed using version 6 (DBI analysis). The research team also compared MagnoProof version 6 (DBI analysis) with MagnoProof version 6 (basket uncut analysis) and ascertained that MagnoProof version 6 (basket uncut analysis) does not provide horizontal skew and vertical tilt values for individual dowel bars but reports these values as an average for all dowel bars within a basket. Also, MagnoProof version 6 (basket cut analysis) option did not function with the data files for this project. Thus, the use of version 6 (basket uncut analysis and basket cut analysis) was deemed unacceptable by the research team for analysis conducted under this project since computing JS and EDD requires alignment values for individual dowel bars within a joint and not averaged for all dowel bars within the joint. Therefore, analysis for all sections were conducted using version 6 (DBI analysis). This results in reduced accuracy of the alignment values for bars placed using baskets for individual dowel bars, but the results are still valid on average for the large number of bars and joints evaluated under this research.

In total, 1,293 joints were evaluated by the research team across twelve sites in six counties which included 12,862 dowel bars after the data was passed through the initial filtering process. In addition, MIT-DOWEL-SCAN testing was performed on 20 joints in Chippewa County STH 178 SB to evaluate the alignment of tie bars. The data set also included additional MIT-DOWEL-SCAN data provided by WisDOT, which included of 386 joint consisting of 3,954 dowel bars. The results of the analysis are summarized below:

- 83 percent of 1.25-inch and 91 percent of 1.5-inch dowel bars had horizontal skew values within WisDOT specifications of between 0 and ± 0.5 inches. 95 percent of 1.25-inch dowel bars and 99 percent of 1.5-inch dowel bars had horizontal skew values between 0 and ± 1.0 inches.

- 70 percent and 72 percent of 1.25-inch and 1.5-inch diameter dowel bars, respectively, had vertical tilt values within WisDOT specifications of between 0 and ± 0.5 inches. 95 percent of 1.25-inch dowel bars and 98 percent of 1.5-inch dowel bars had vertical tilt values between 0 and ± 1.0 inches.
- 76 percent of 1.25-inch and 91 percent of 1.5-inch dowel bars had longitudinal translation within WisDOT specifications of between 0 and ± 2.0 inches. Over 95 percent of all dowel bars had longitudinal translation between 0 and ± 3.0 inches.
- 88 percent of 1.25-inch and 84 percent of 1.5-inch dowel bars had vertical translation within WisDOT specifications of between 0 and ± 1.0 inches. Over 95 percent of all dowel bars had vertical translation between 0 and ± 1.5 inches.
- 80 percent of basket bars and 90 percent of dowel bar inserter (DBI) bars had horizontal skew values within WisDOT specifications of between 0 and ± 0.5 inches. 94 percent of basket bars and 99 percent of DBI bars had horizontal skew values between 0 and ± 1.0 inches.
- 66 percent and 73 percent of basket and DBI dowel bars, respectively, had vertical tilt values within WisDOT specifications of between 0 and ± 0.5 inches. 94 percent of basket dowel bars and 98 percent of DBI dowel bars had vertical tilt values between 0 and ± 1.0 inches.
- 73 percent of basket bars and 88 percent of DBI bars had longitudinal translation within WisDOT specifications of between 0 and ± 2.0 inches.
- 86 percent of basket bars and 88 percent of DBI bars had vertical translation within WisDOT specifications of between 0 and ± 1.0 inches.
- Thus, the global analysis of alignment data of over 16,000 bars representing over 1,500 joints, and over 20 sites from 12 counties in Wisconsin show that on average dowel bars installed using DBI had equal to or better alignment as compared to dowel bars installed using baskets.
- 22 percent and 47 percent of the joints with 1.25-inch bars had JS values less than 5 and 10, respectively. 21 percent of the joints with 1.25-inch bars had JS values more than 30.
- 39 percent and 68 percent of the joints with 1.5-inch bars had JS values less than 5 and 10, respectively. 11 percent of the joints with 1.5-inch bars had JS values more than 30.
- Only 17 percent and 39 percent of the bars installed with baskets had JS values less than 5 and 10, respectively. By comparison, approximately 37 percent and 66 percent of the bars installed with DBI had JS values less than 5 and 10, respectively.
- 28 percent of the bars with baskets had JS values more than 30, whereas only 9 percent of the bars installed with DBI had JS values more than 30.

- 30 percent (501 of 1,679 joints) analyzed had JS greater than $JS_{CRITICAL}$ and there were 69 occurrences where three or more consecutive joints had JS greater than $JS_{CRITICAL}$.
- 45 percent (752 of 1,679 joints) analyzed had JS greater than $JS_{TRIGGER}$ and there were 134 occurrences where three or more consecutive joints had JS greater than $JS_{TRIGGER}$.
- Average EDD reductions range from less than 2 percent to greater than 20 percent. Some sections tested had EDD as low as 0.994 inches for a 1.25-inch dowel bar and as low as 1.329 inches for a 1.5-inch dowel bar.
- AASHTOWare® Pavement ME Design (PMED) analysis indicates an increase in International Roughness Index (IRI) and faulting when EDD is used instead of actual diameter. In instances where the EDD was significantly different from the actual dowel diameter due to higher levels of misalignment, the increase in faulting and IRI was pronounced and could impact the service life of the pavement. However, slab cracking was not affected by the change in dowel diameter to any significant extent.
- Chi-squared tests were performed to determine any relationship between JS and spalling, slab cracking, and longitudinal translation. Results did not indicate any relationship between JS and spalling or cracking for any of the sections, at the levels of misalignment typically found in Wisconsin. The results of logistic regression analysis indicated that only age of the pavement was statistically significant in predicting presence of both spalling and cracking. Other variables, such as thickness of the pavement and JS were not found to be statistically significant.
- In two counties, results showed a relationship between JS and longitudinal translation. Although JS and longitudinal translation are independent metrics, the relationship between the two in these two counties suggest the contractor experienced challenges with dowel bar placement during paving.
- These results indicate that other project specific factors may have a stronger impact on spalling and transverse cracking than JS. However, given that almost all the joints tested had JS values less than 40, the research team cannot rule out potential impact of cracking and spalling when the JS is much higher (e.g., JS > 40).

The data collected by the research team and WisDOT and analyzed by the research team provides a baseline of typical levels of dowel alignment in Wisconsin for basket and DBI sections. The analysis performed also offers a window into the impacts of typical dowel alignment in Wisconsin on potential pavement performance.

The recommendations provided in the following section are suggested to achieve satisfactory long-term joint performance balanced with practical installation in Wisconsin. The JS proposed by the American

Concrete Pavement Association (ACPA) guide specifications are not recommended to be used in Wisconsin because of (1) need to compute JS, a fictitious unsubstantiated parameter rather than using actual measured data, (2) the poor relationship between JS and pavement performance, (3) the JS does not take into account vertical translation and longitudinal translation, and (4) the large percentage of joints in Wisconsin that exceed $JS_{CRITICAL}$ and $JS_{TRIGGER}$. EDD combined with PMED runs are also not recommended because of the added complexities of computing EDD and modeling pavement performance using EDD.

Recommendations

Based on field data from typical construction quality and performance in Wisconsin, review of literature including American Concrete Pavement Association (ACPA) guide specifications, and other agency specifications, the research team's experience with dowel and tie bar alignment and pavement performance data throughout the U.S., and to provide a balance between what is achievable practically vis-à-vis the impact of dowel misalignment on pavement performance in Wisconsin, the research team proposes the following changes to Wisconsin specifications and protocols. While reviewing these recommendations, it is important to note that joints in concrete pavements fail due to a number of reasons including incompressible materials in the joints, corrosion of dowel bars, weak or unconsolidated concrete around dowel bars, very high levels of dowel misalignment (much higher than seen on typical Wisconsin pavements), high levels of early age curling/warping and restraint from dowel bars (including properly aligned dowel bars), durability distresses such as ASR, D-cracking, etc.

Recommended additions are shown in bold italic font. Recommended deletions are show in strikethrough font.

415.2.2 Reinforcement

Recommendation: No change

505 Steel Reinforcement

Recommendation: No change

415.3.5 Reinforcement

Recommendation: No change

415.3.7 Jointing

415.3.7.1 General

Recommendation: No change

415.3.7.2 Longitudinal Joints

(1) If the plans do not show a specific location, construct parallel to the centerline along lane edges. On two-lane pavements, construct along the pavement centerline. On multilane pavements, construct along traffic and taper lane edges. Make joints perpendicular to the pavement surface. Do not deviate more than 1/2 inch in 10 feet from the required line.

(2) Install tie bars parallel to the substrate surface and perpendicular to longitudinal joint.

415.3.7.3 Transverse Joints

(1) Extend transverse joints across the entire width of paving and through curb or median placed integrally with pavement. When the pavement abuts existing pavement, curb and gutter, or median, construct transverse joints in locations matching existing joints or cracks.

(2) Install dowel bars parallel to the substrate surface and parallel to the centerline of the pavement. Before placing the concrete, mark the location on both sides of each transverse joint. Ensure the proposed saw cut is centered on the dowel bars and that the dowels remain parallel to the centerline. Transfer the markings to the top surface of the fresh concrete immediately after completing the final finishing operations.

~~*(3)* Install dowel bars as follows:~~

~~- Within one inch of the planned transverse location and depth.~~

~~- Within 2 inches of the planned longitudinal location.~~

~~- Parallel to the pavement surface and centerline within a tolerance of 1/2 inch in 18 inches.~~

(3) Hold dowel bars in the correct position and alignment using an engineer-approved device during construction. Do not allow bonded longitudinal bars or reinforcement to extend across transverse expansion or contraction joints. The contractor need not cut dowel basket tie wires. ***Fasten the baskets to the substrate surface so that they do not move vertically or horizontally more than 1/4 inches.***

(4) At least 7 Calendar Days before the beginning of concrete paving, provide a Quality Control Plan in writing to the engineer for acceptance that provides a method for keeping the dowel basket assemblies anchored. The Quality Control Plan shall include the following at a minimum:

- Proposed type, location, number and length of fasteners

- Proposed installation equipment

- Dowel basket assembly anchoring plan (i.e., anchor all basket assemblies before concrete placement, one lane at a time, anchor all basket assemblies during the concrete placement operation, etc.)

- Action plan if misaligned baskets are identified during concrete pavement placement

Before the beginning of concrete pavement placement and each day before beginning paving, demonstrate the fastening method to the engineer for approval. The engineer will suspend paving operations if the Contractor fails to comply with their Quality Control Plan.

(5) If using a mechanical device to install dowel bars, conform to the following:

- Place and consolidate the pavement to full depth before inserting the dowel bars.

- Insert the dowel bars into the plastic concrete in front of the finishing beam or screed.
- ***Initially and on each production day, demonstrate to the engineer that the inserted dowel bars in the completed concrete pavement are parallel to the surface and centerline slab and are located at mid-depth of the slab thickness.***

~~Effective with the November 2023 Letting 149 2024 Standard Specifications~~

- Ensure that the installing device consolidates the concrete with no voids around the dowel bars.
- Do not interrupt the forward movement of the finishing beam or screed while inserting the dowel bars.
- ~~Provide a positive method of marking the locations of the transverse joints.~~

(6) Remove concrete directly above expansion joint filler, if necessary, by sawing the full width of the filler to remove concrete bridging the joint.

(7) Form a construction joint at the end of each day's run or when an interruption long enough for the concrete to develop its initial set occurs by doing one of the following:

- Set a header board to support dowel bars. Use production quality concrete, hand vibrated behind the header board, and protect protruding steel from anything that might damage the bars or weaken the bond.
- Saw back the concrete full depth to expose solid concrete then drill and epoxy in dowel bars.

415.3.7.4 Tolerance in Dowel Bar and Tie Bar Placement (OPTION 1)

(1) Install dowel bars as follows:

- ***Within one inch of the planned transverse location and depth.***
- ***Within ~~2~~3 inches of the planned longitudinal location.***
- ***Parallel to the pavement surface and centerline within a tolerance of 1/2 inch in 18 inches.***

(2) Install tie bars as follows:

- ***Within 5 inches of the planned transverse location.***
- ***Within one inch of the planned depth.***
- ***Parallel to the pavement surface and centerline within a vertical tilt tolerance of 2 inches end to end for pavements less than 8-inches design thickness, 2 1/2 inches end to end for pavements between 8- and 10-inches design thickness, 3 inches end to end for pavements greater than 10-inches design thickness.***

(3) Dowel bar and tie bar placement will be tested at the discretion of the engineer. If tested, 85 percent of all bars properly tested are to be within the above-specified limits.

415.3.7.4 Tolerance in Dowel Bar and Tie Bar Placement (OPTION 2)

(1) Install dowel bars as follows:

- ***Within one inch of the planned transverse location and depth.***
- ***Within ~~2~~3 inches of the planned longitudinal location.***
- ***Parallel to the pavement surface and centerline within a tolerance of 1/2 inch in 18 inches.***

(2) Install tie bars as follows:

- ***Within 5 inches of the planned transverse location.***
- ***Within one inch of the planned depth.***
- ***Parallel to the pavement surface and centerline within a vertical tilt tolerance of 2 inches end to end for pavements less than 8-inches design thickness, 2 1/2 inches end to end for pavements between 8- and 10-inches design thickness, 3 inches end to end for pavements greater than 10-inches design thickness.***

(3) Dowel bar and tie bar placement will be tested at the discretion of the engineer. If tested, 85 percent of all bars properly tested are to be within the above-specified limits.

415.3.7.4.1 Dowel Bar and Tie Bar Placement Testing Using Magnetic Pulse Induction (OPTION 2)

(1) For concrete paving projects greater than 3,500 cubic yards, the engineer will test for dowel bars and tie bars using magnetic pulse induction. The device shall have the ability to locate dowel bars and tie bars, and measure concrete pavement thickness in a single device. The engineer's observations do not relieve the contractor of the requirement to properly place the tie bars and dowel bars.

(2) The engineer will identify the magnetic pulse induction random testing locations. The engineer will locate the dowel bar and tie bar steel in the plastic concrete, utilizing a walk bridge that spans the width of the pavement and perform the following:

- ***Verify the adequacy of the dowel bar basket anchoring by locating both the upstream and downstream edges of the dowel bar baskets.***
- ***Verify the presence and alignment of tie bar steel by locating both ends of the tie bar.***
- ***Verify the presence and alignment of dowel bar steel by locating both ends of the dowel bar.***

(3) If the engineer determines from the scan that bars are potentially misaligned beyond the acceptable limits or are missing, the engineer will scan both upstream and downstream from the random testing location until at least 3 joints comply.

(4) If at any time the engineer determines the dowel bar anchoring or tie bar placement processes are unacceptable due to alignment tolerance issues, the engineer may request the contractor amend the

placement process for the operation in question to achieve satisfactory placement of the dowel bars and tie bars.

415.3.7.4 Tolerance in Dowel Bar and Tie Bar Placement (OPTION 3)

(1) Install dowel bars as follows:

- ***Within one inch of the planned transverse location and depth.***
- ***Within ~~2~~3 inches of the planned longitudinal location.***
- ***Parallel to the pavement surface and centerline within a tolerance of 1/2 inch in 18 inches.***

(2) Install tie bars as follows:

- ***Within 5 inches of the planned transverse location.***
- ***Within one inch of the planned depth.***
- ***Parallel to the pavement surface and centerline within a vertical tilt tolerance of 2 inches end to end for pavements less than 8-inches design thickness, 2 1/2 inches end to end for pavements between 8- and 10-inches design thickness, 3 inches end to end for pavements greater than 10-inches design thickness.***

415.3.7.4.1 Dowel Bar and Tie Bar Placement Testing Using Magnetic Pulse Induction (OPTION 3)

(1) For concrete paving projects greater than 3,500 cubic yards, the engineer will test for dowel bars and tie bars using magnetic pulse induction on hardened concrete. The device shall have the ability to measure and report the positions and alignments of dowel bars and tie bars in a single device.

(2) All testing shall be carried out by the department. Test results shall be forwarded to the contractor as they become available.

(3) The contractor shall notify the department when the pavement is ready for testing. Provisions shall be made for access to the site for acceptance testing of position and alignment of dowel bars. The area to be measured shall be free of loose stone, debris, and obstructions.

(4) When weather conditions are unsuitable for testing according to the equipment manufacturer's recommendations, testing shall be suspended and shall resume only when conditions are acceptable for testing.

(5) The total quantity of concrete pavement shall be divided into lots, with each lot containing all the transverse joints with dowel bars placed by the same method. Every 10 transverse joints shall represent a sublot.

(6) One joint for every sublot or a minimum of 10 joints shall be randomly selected by the department and dowel position and alignment shall be measured for that joint according to ASTM E3013.

(7) The dowel bar closest to the longitudinal joint shall be removed from the analysis due to possible interference of the tie bar.

(8) A lot that does not have at least 90 percent of joints meeting two or more of the four tolerances (horizontal skew [parallel to the centerline], vertical tilt [parallel to the surface], vertical location [translation], and longitudinal location [translation] is rejectable.

(9) Any joint not meeting at least one of the four tolerances (horizontal skew [parallel to the centerline], vertical tilt [parallel to the surface], vertical location [translation], and longitudinal location [translation] is rejectable, and shall be removed and replaced.

(10) Any joint that has an individual dowel bar exceeding any of the rejection criteria, is rejectable, and shall be removed and replaced. The rejection criteria are:

- ***Within 2 inches of the planned depth.***
- ***Within 6 inches of the planned longitudinal location.***
- ***Parallel to the pavement surface and centerline within a tolerance of 2 inches in 18 inches.***

(11) The department shall scan joints on either side of the unacceptable joint, until five consecutive joints on each side are found with no rejectable joints or bars. Any rejectable joint shall be removed and replaced.

415.3.7.4 Dowel Bar and Tie Bar Placement Testing Using Magnetic Pulse Induction (OPTION 4)

Include both OPTION 2 and OPTION 3.

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Appendix A

JPCP Transverse Fatigue (Mid-Slab) Cracking WisDOT Calibration Coefficients.

Model Types	PMED Model Coefficients	Global Coefficients (v3.0)	WisDOT Values (v3.14)
PCC Material Fatigue Strength Model Coefficients	C1	2.0	2.00
	C2	1.22	1.22
JPCP Mid-Slab Cracking Transfer Function Coefficients	C4	0.431	2.00
	C5	-2.303	-2.125

JPCP Transverse Joint Faulting WisDOT Calibration Coefficients.

Model Types	PMED Model Coefficients	Global Coefficients (v3.0)	WisDOT Values (v3.14)
JPCP Transverse Joint Faulting Transfer Function	C1	0.2	0.1
	C2	1.636	1.636
	C3	0.005	0.005
	C4	0.00444	0.00444
	C5	250	250
	C6	0.2	0.2
	C7	20	20
	C8	400	400

JPCP IRI Calibration Coefficients.

Model Types	PMED Model Coefficients	Global Coefficients (3.0)	WisDOT Values (v3.14)
JPCP IRI Regression Equation	J1 (for Cracking)	0.446	0.446
	J2 (for Spalling)	0.373	0.373
	J3 (for Faulting)	0.993	0.993
	J4 (for Site Factor)	46.422	46.422

Appendix B

Chippewa NB

Table 1. Details of test sections in Chippewa NB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Chippewa NB	8.85	1.25	10/16/2023	14

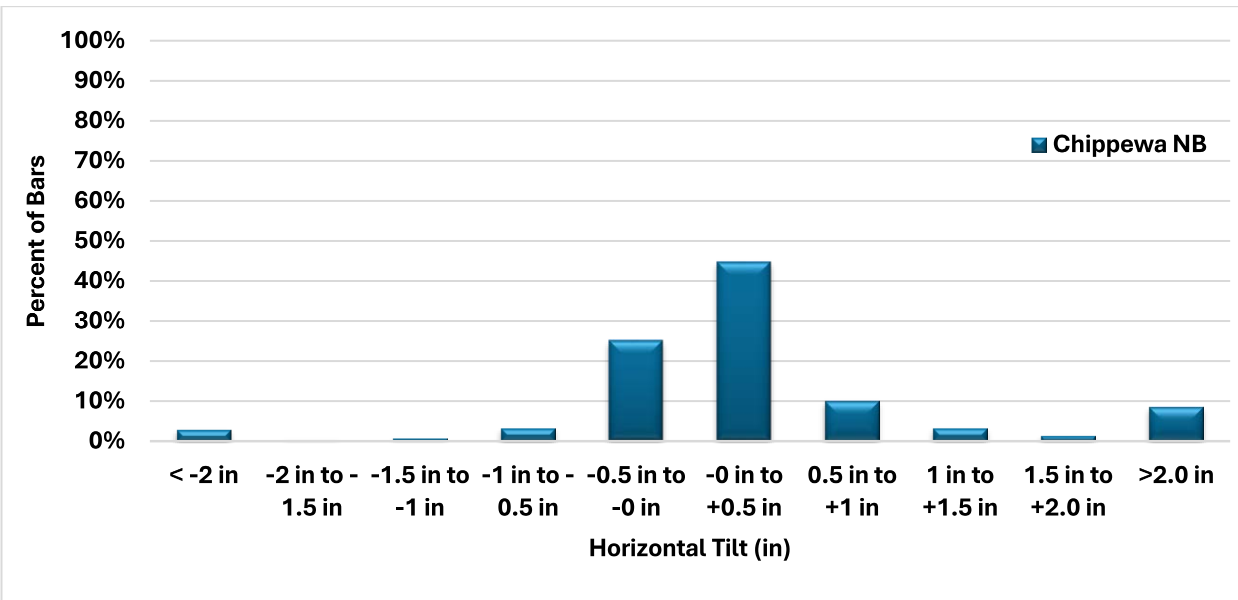

Figure 1. Horizontal Skew distribution for Chippewa NB.

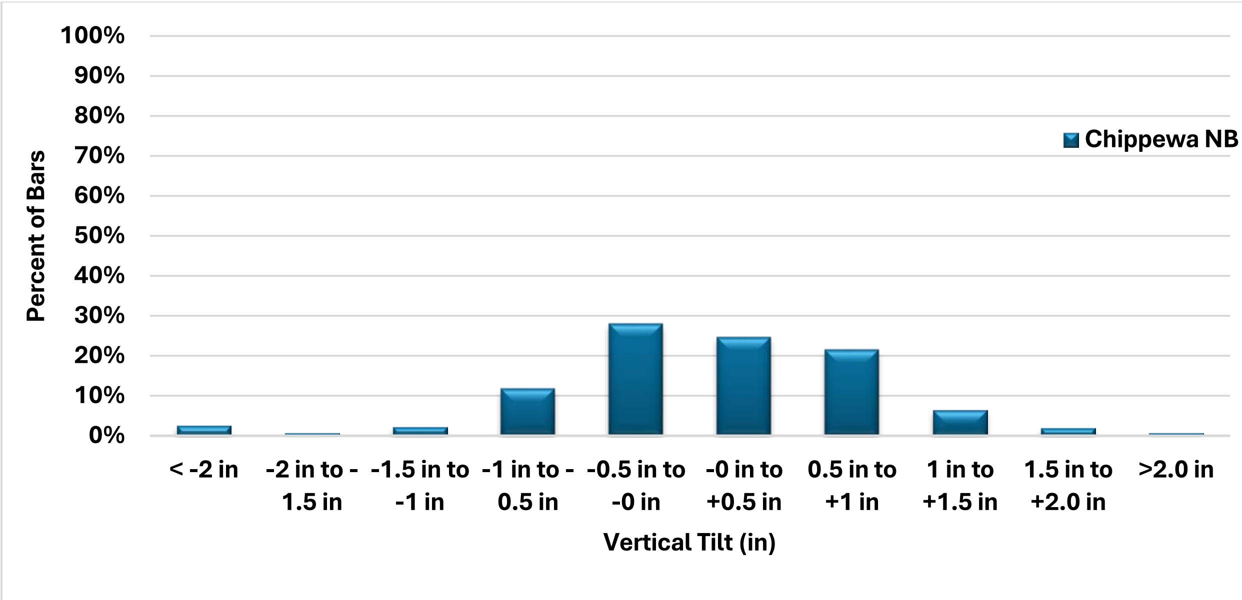

Figure 22. Vertical Tilt distribution for Chippewa NB.

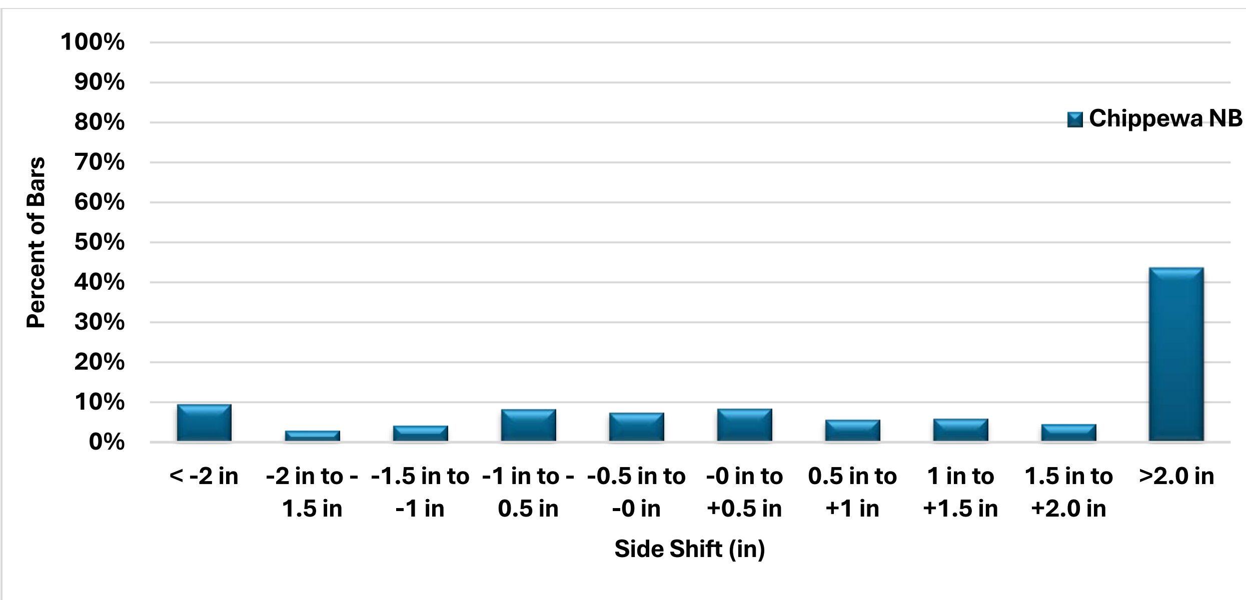

Figure 3. Longitudinal Translation distribution for Chippewa NB.

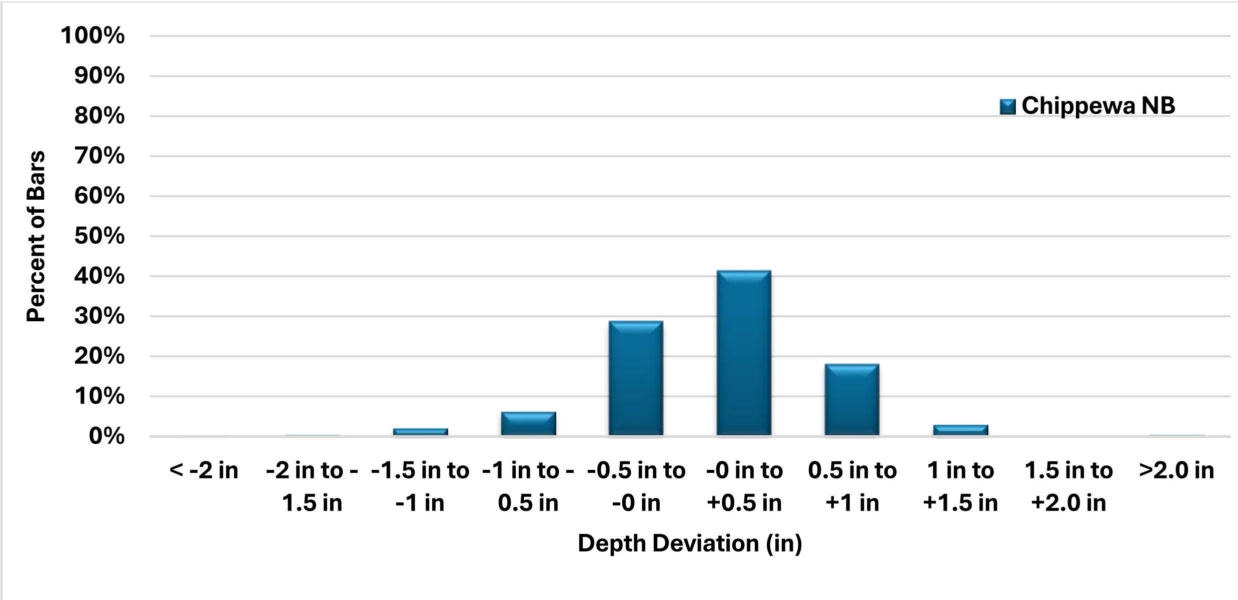

Figure 4. Vertical Translation distribution for Chippewa NB.

Table 2. Dowel misalignment summary for Chippewa NB.

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Chippewa NB	0.42	2.04	-0.05	1.86	1.74	2.40	0.14	0.74

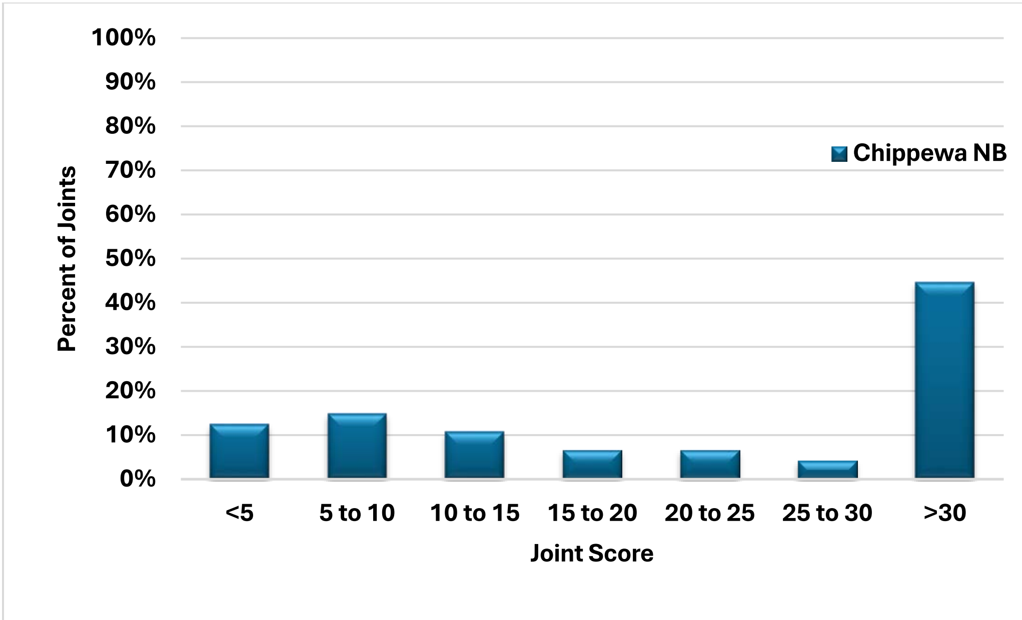

Figure 5. Joint score distribution for Chippewa NB

Table 3. Joint score and effective dowel diameter for Chippewa NB.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Chippewa NB	40.0	57.8	8.85	1.25	1.042	0.296	16.64

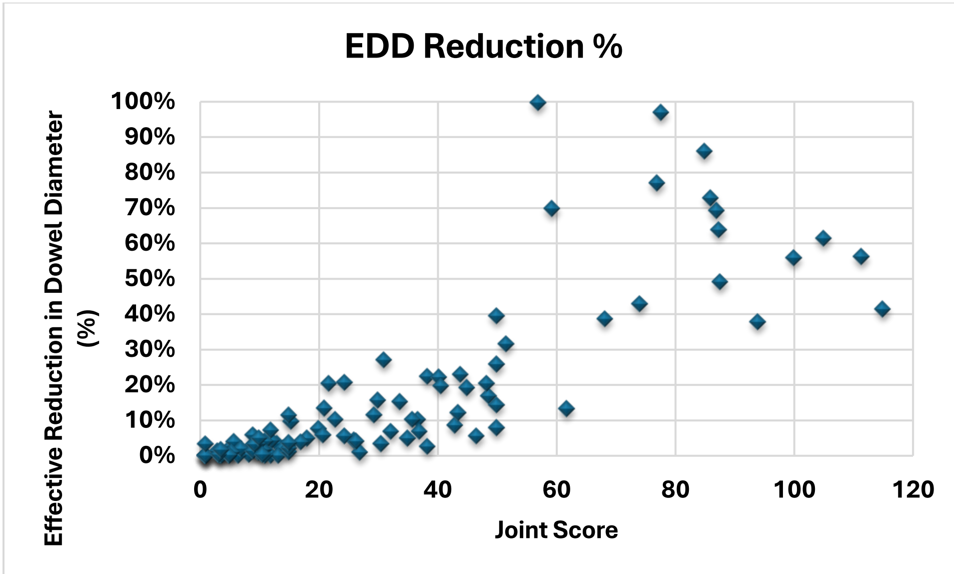

Figure 6. Joint score versus effective reduction in dowel diameter for Chippewa NB.

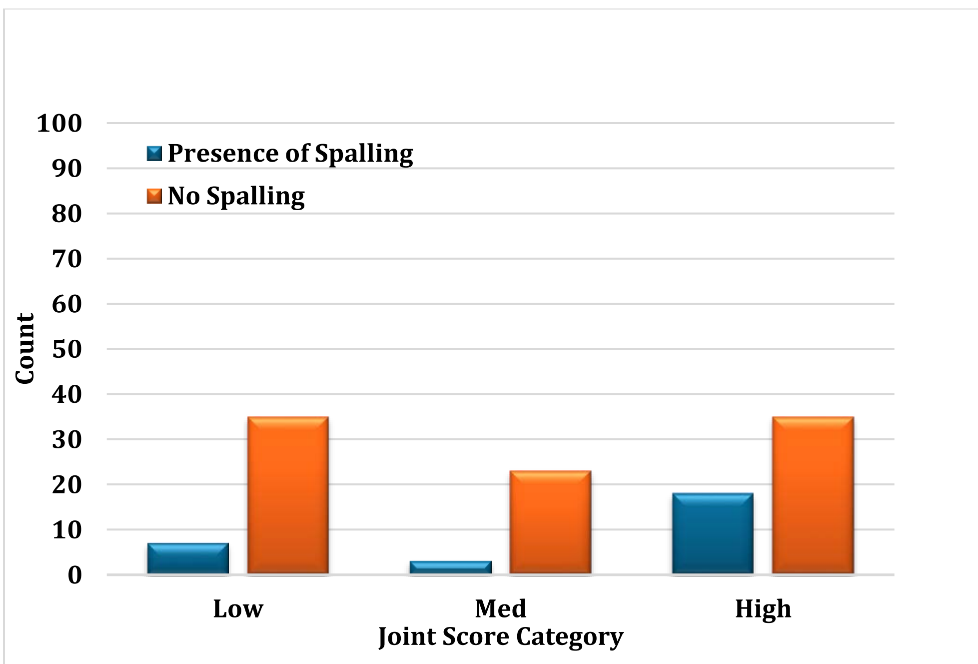

Figure 723. Joint score and presence of spalling for Chippewa NB.

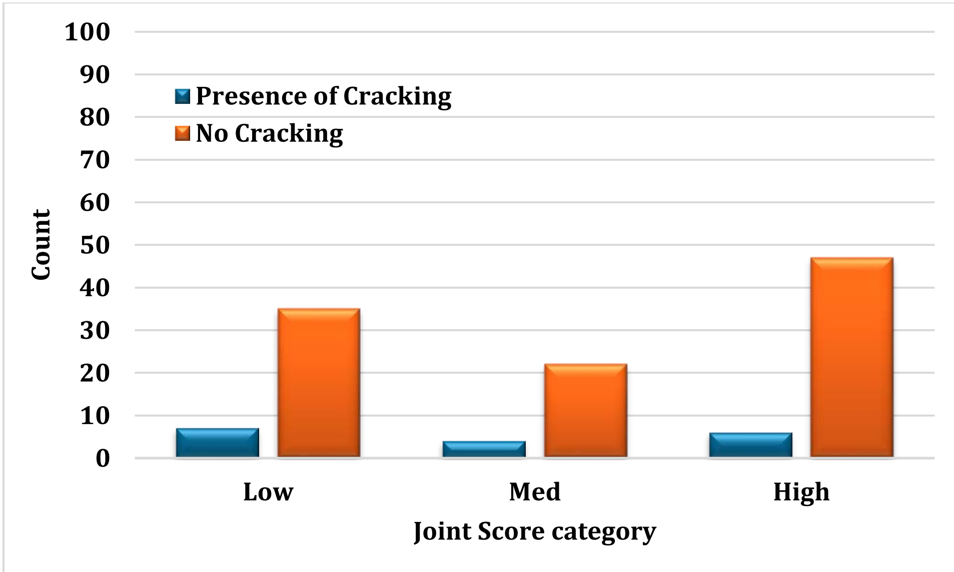

Figure 824. Joint score and presence of cracking for Chippewa NB.

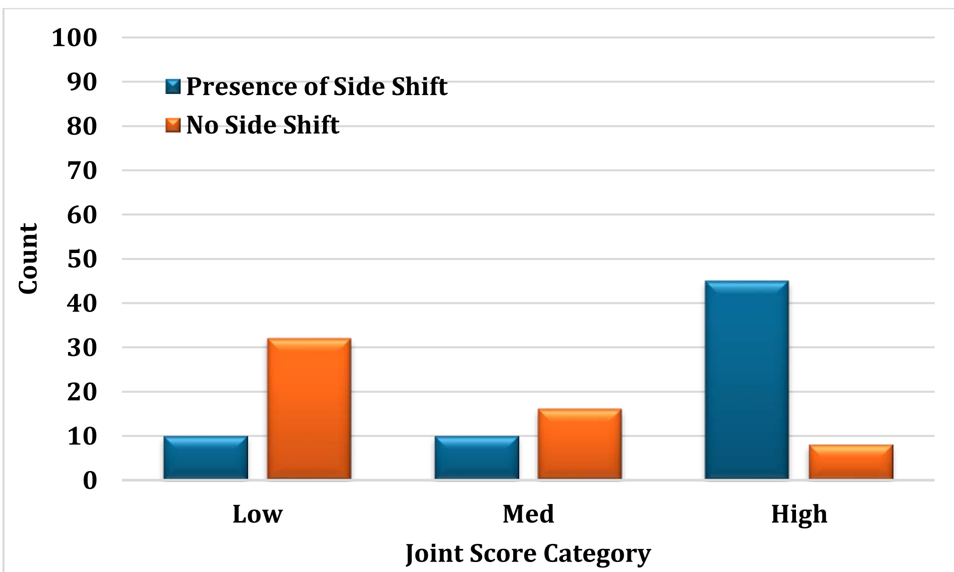

Figure 925. Joint score and presence of side shift for Chippewa NB.

Chippewa SB

Table 4. Details of test sections in Chippewa NB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Chippewa SB	8.85	1.25	10/16/2023	14

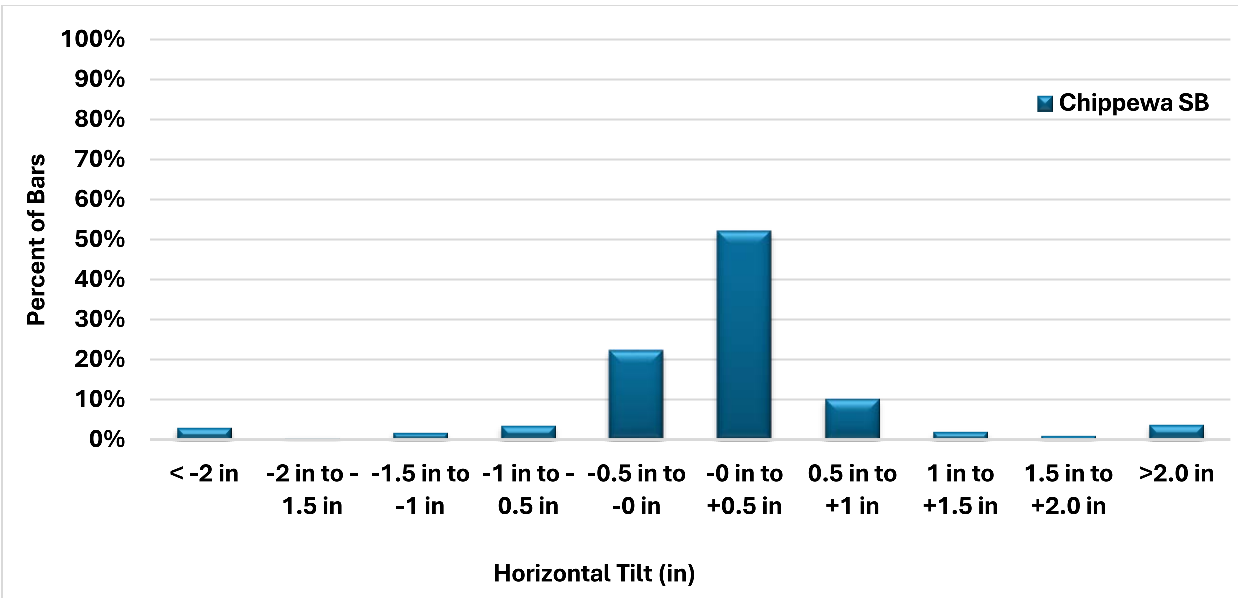

Figure 10. Horizontal Skew distribution for Chippewa SB.

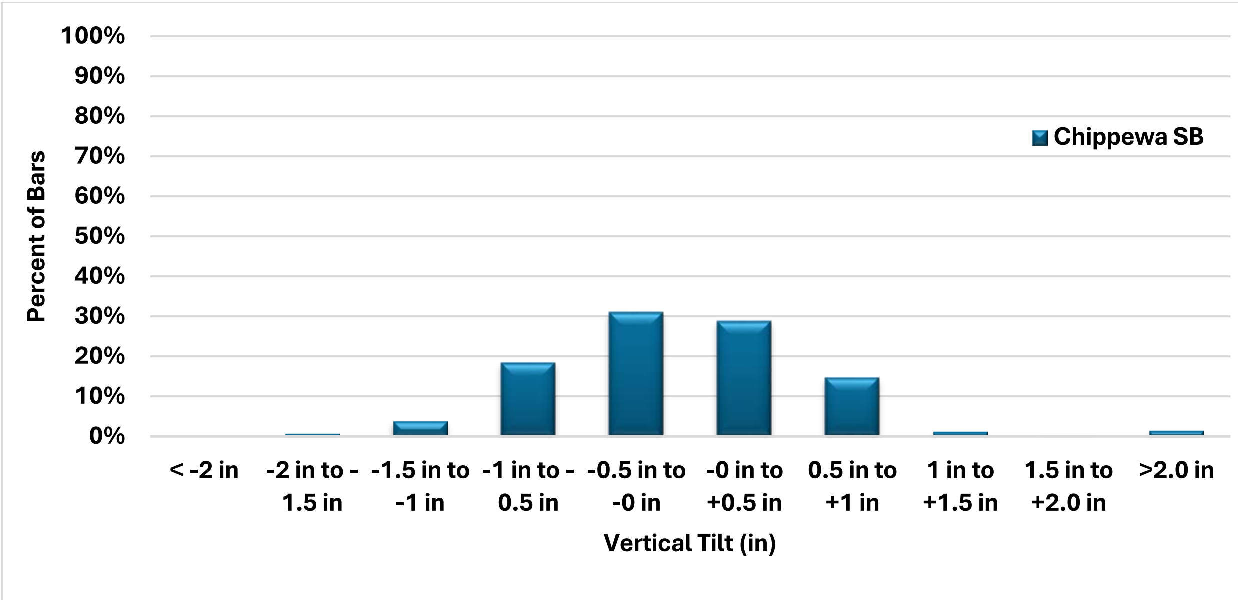

Figure 11. Vertical Tilt distribution for Chippewa SB.

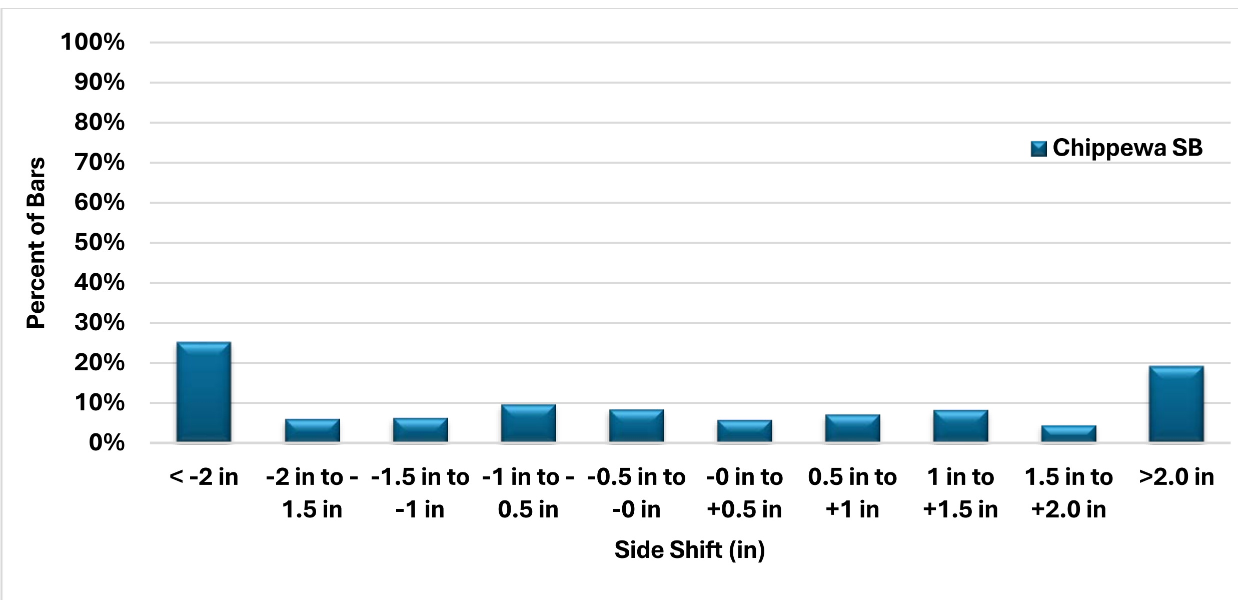

Figure 12. Longitudinal Translation distribution for Chippewa SB.

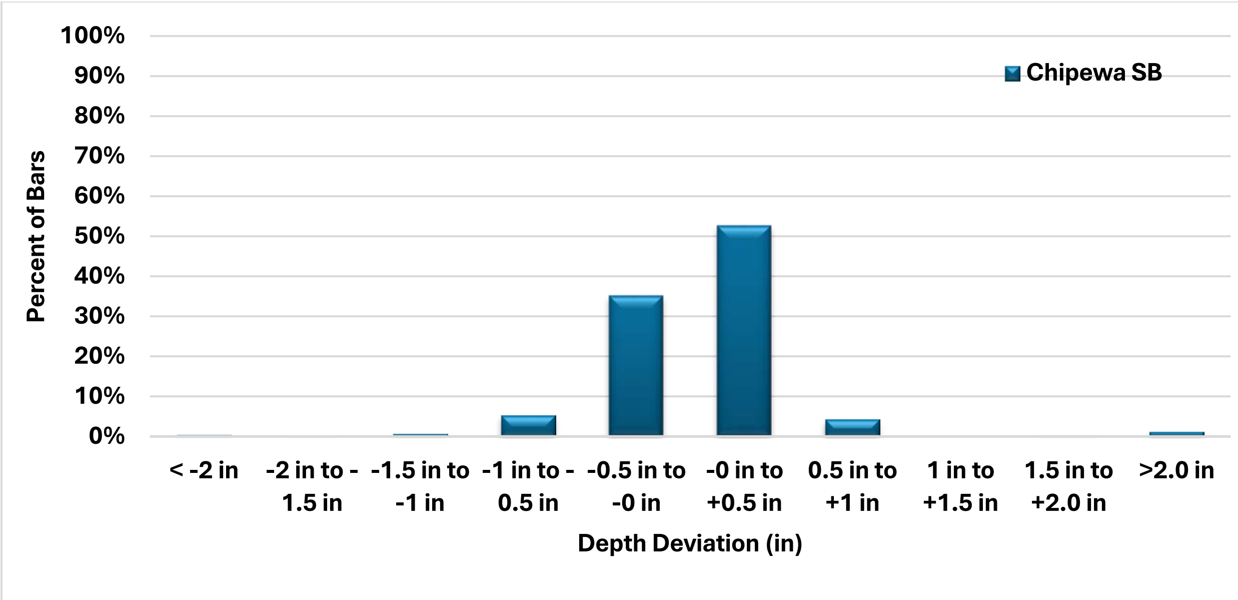

Figure 13. Vertical Translation distribution for Chippewa SB.

Table 5. Dowel misalignment summary for Chippewa SB.

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Chippewa SB	0.12	1.48	0.06	2.04	-0.43	2.62	0.08	1.46

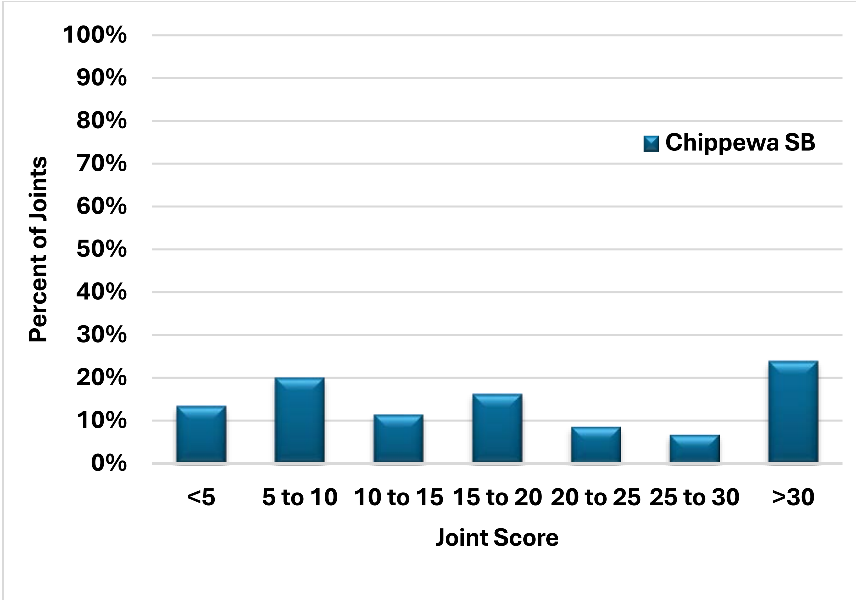

Figure 14. Joint score distribution for Chippewa SB

Table 6. Joint score and effective dowel diameter for Chippewa SB.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Chippewa SB	25.6	28.0	8.85	1.25	1.092	0.306	12.64

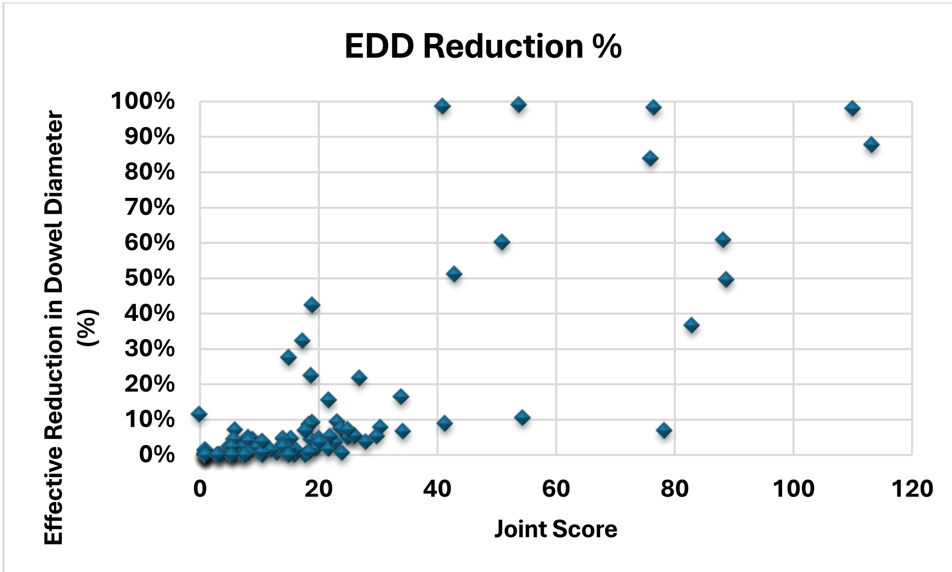

Figure 15. Joint score versus effective reduction in dowel diameter for Chippewa SB.

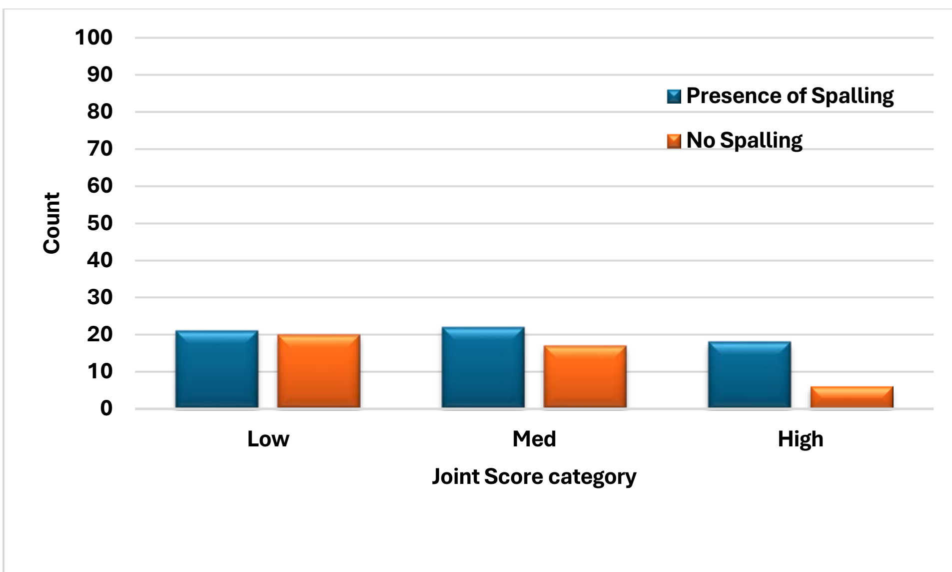

Figure 1626. Joint score and presence of spalling for Chippewa SB.

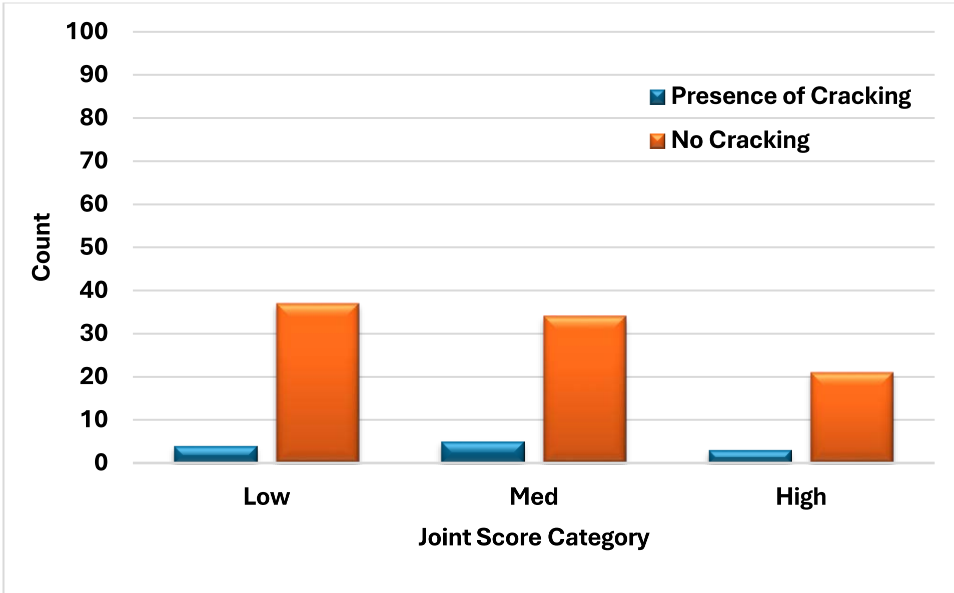

Figure 1727. Joint score and presence of cracking for Chippewa SB.

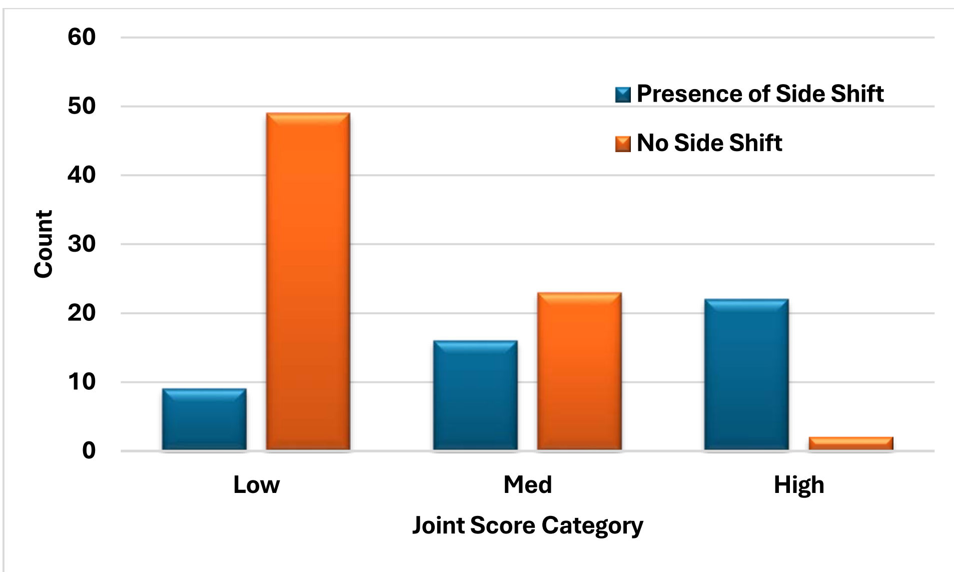

Figure 1828. Joint score and presence of side shift for Chippewa SB.

Eau Claire STH-93 NB

Table 7. Details of test sections in Eau claire STH-93 NB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Eau Claire STH-93 NB	8	1.25	10/17/2023	12

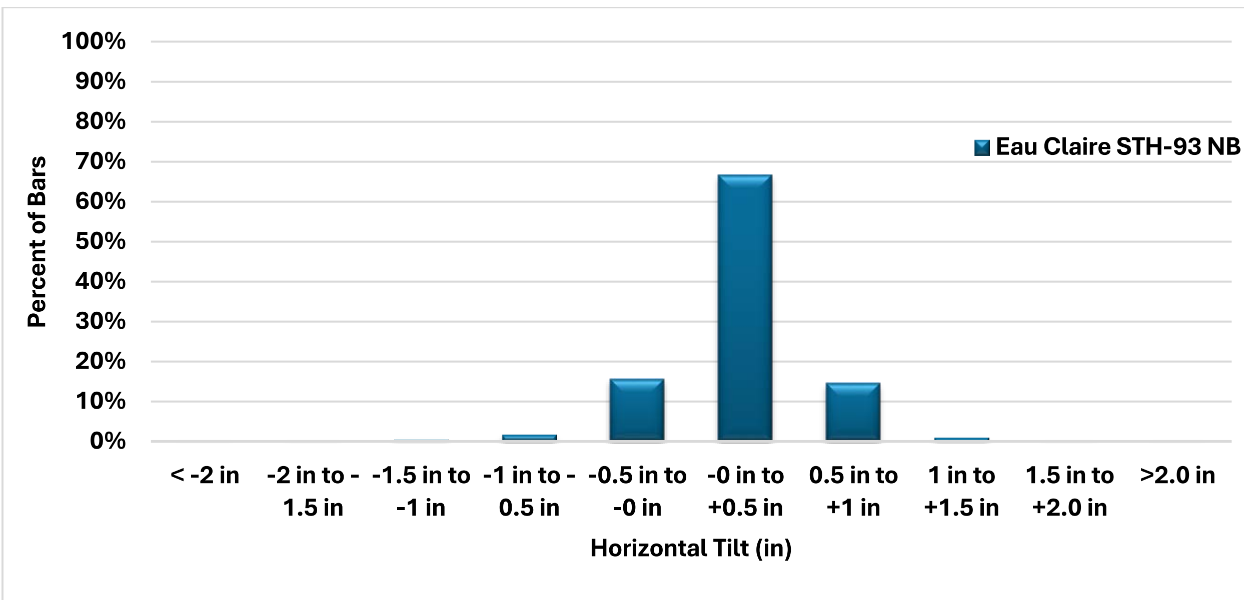

Figure 19. Horizontal Skew distribution for Eau Claire STH-93 NB

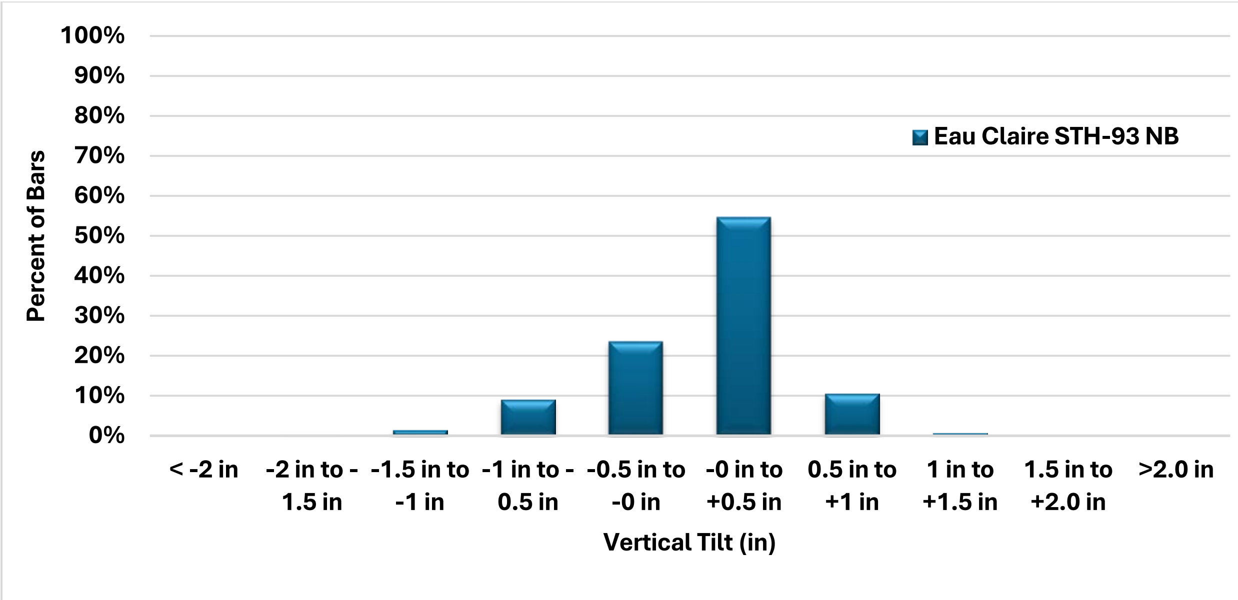

Figure 20. Vertical Tilt distribution for Eau Claire STH-93 NB.

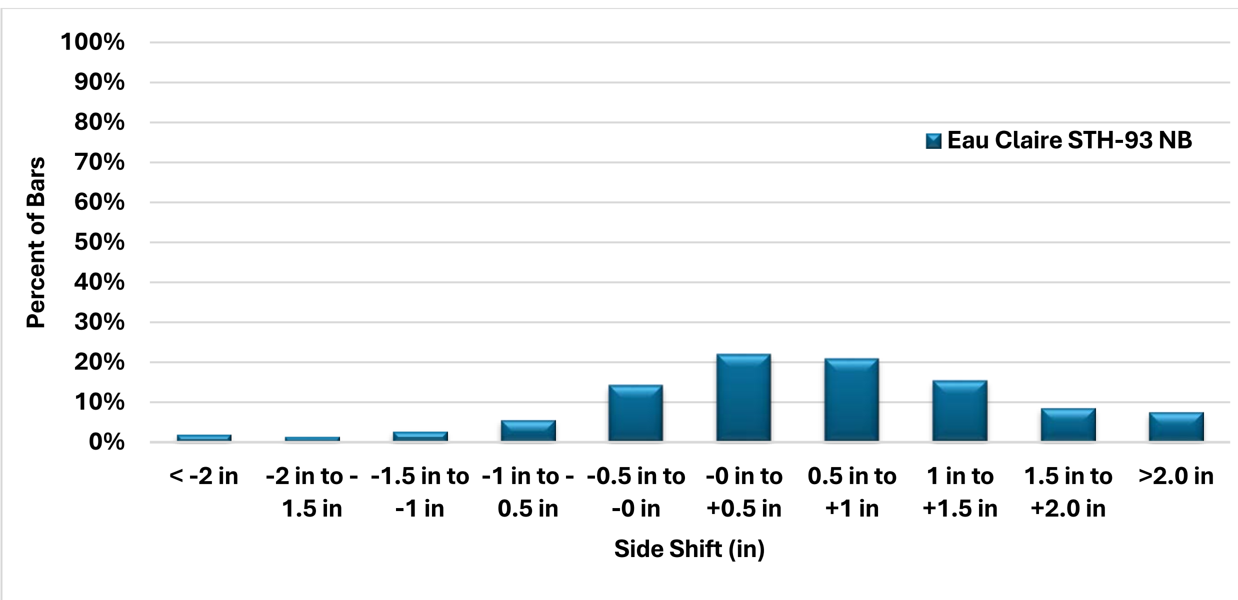

Figure 21. Longitudinal Translation distribution for Eau Claire STH-93 NB.

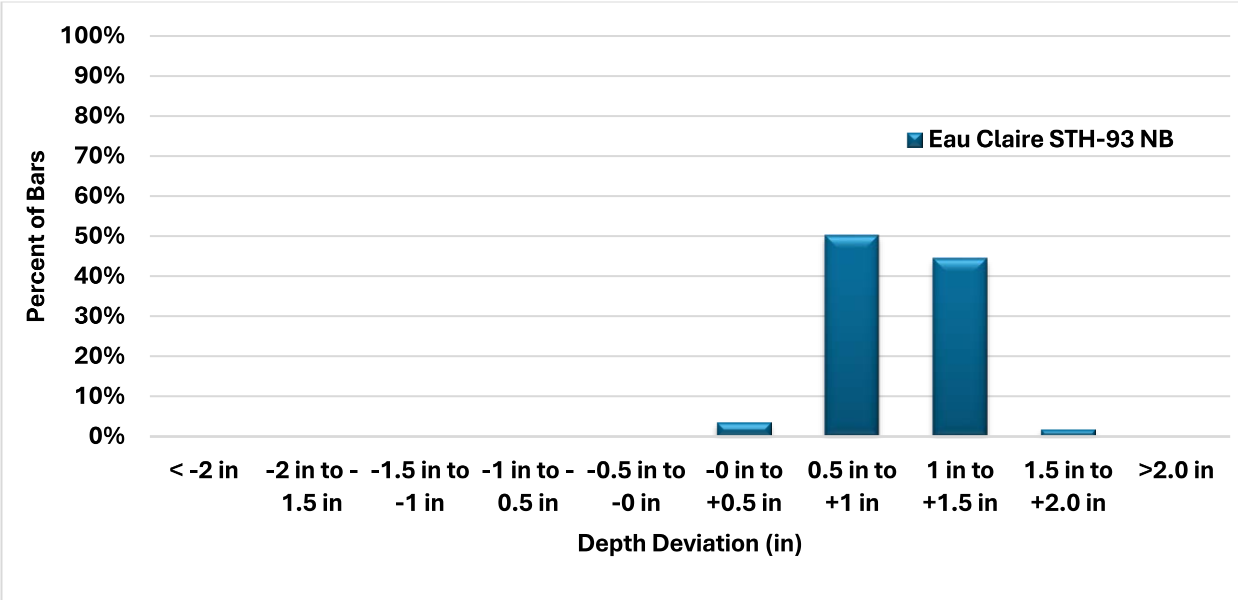

Figure 22. Vertical Translation distribution for Eau Claire STH-93.

Table 8. Dowel misalignment summary for Eau Claire STH-93.

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Eau Claire STH-93 NB	0.20	0.25	0.06	0.26	0.58	0.83	0.96	0.24

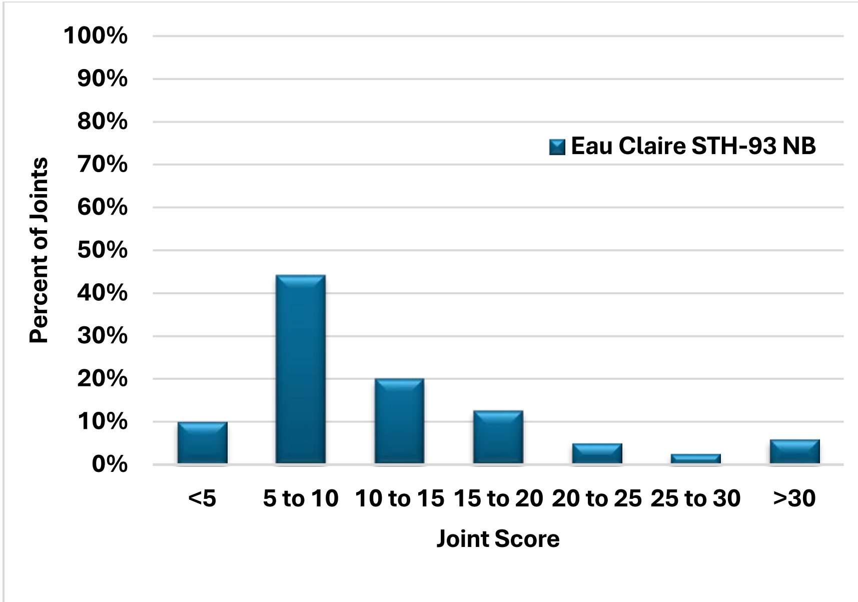

Figure 23. Joint score distribution for Eau Claire STH-93.

Table 9. Joint score and effective dowel diameter for Eau Claire STH-93.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Eau Claire STH-93 NB	12.7	11.2	8.85	1.25	1.103	0.146	11.76

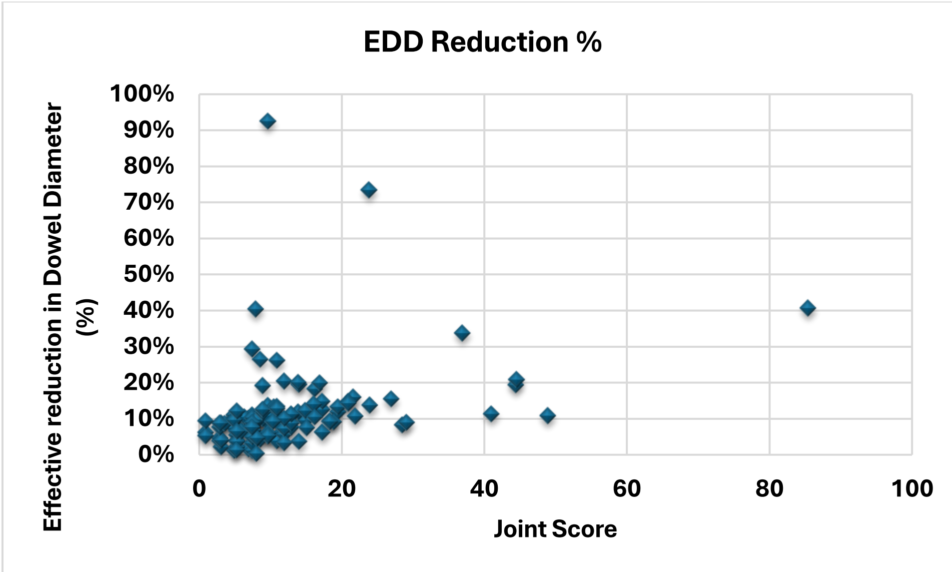

Figure 24. Joint score versus effective reduction in dowel diameter for Eau Claire STH-93.

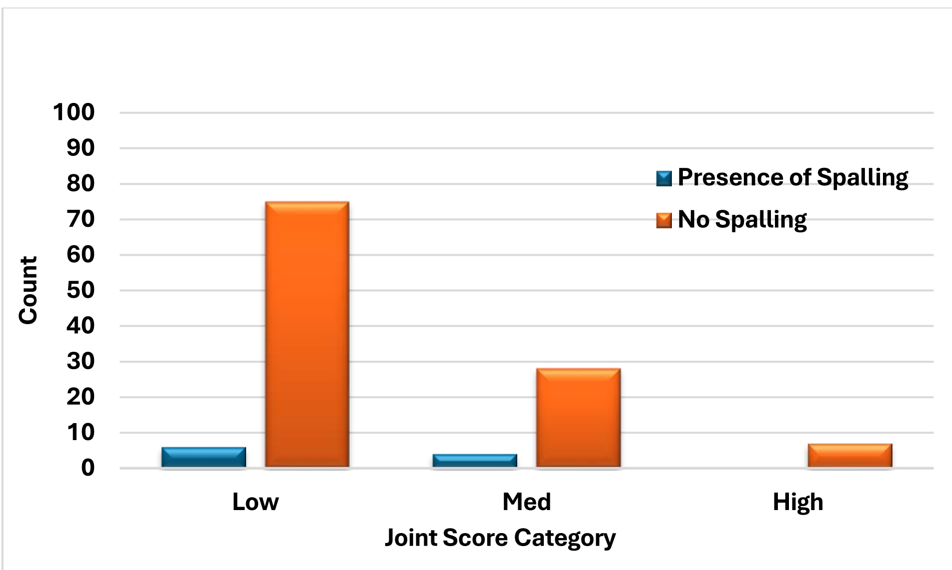

Figure 2529. Joint score and presence of spalling for Eau Claire STH-93.

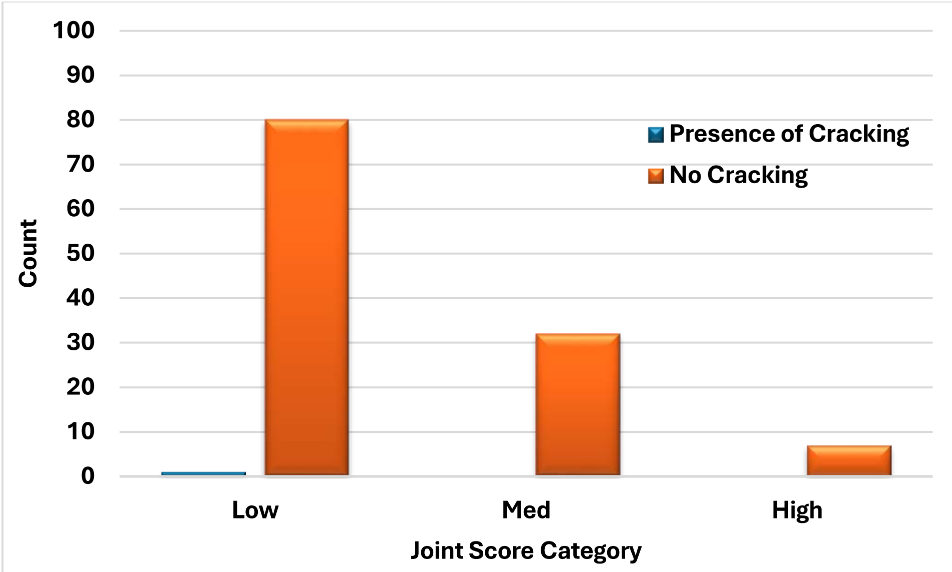

Figure 2630. Joint score and presence of cracking for Eau Claire STH-93.

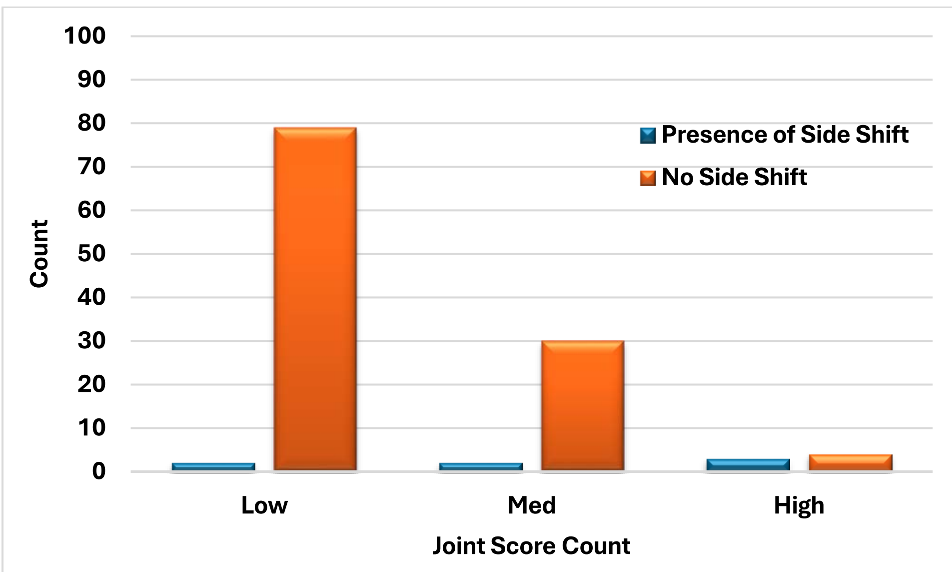

Figure 2731. Joint score and presence of side shift for Eau Claire STH-93.

Eau Claire STH-53 NB

Table 10. Details of test sections in Eau Claire STH-53 NB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Eau Claire STH-53 NB	9.5	1.25	10/17/2023	14

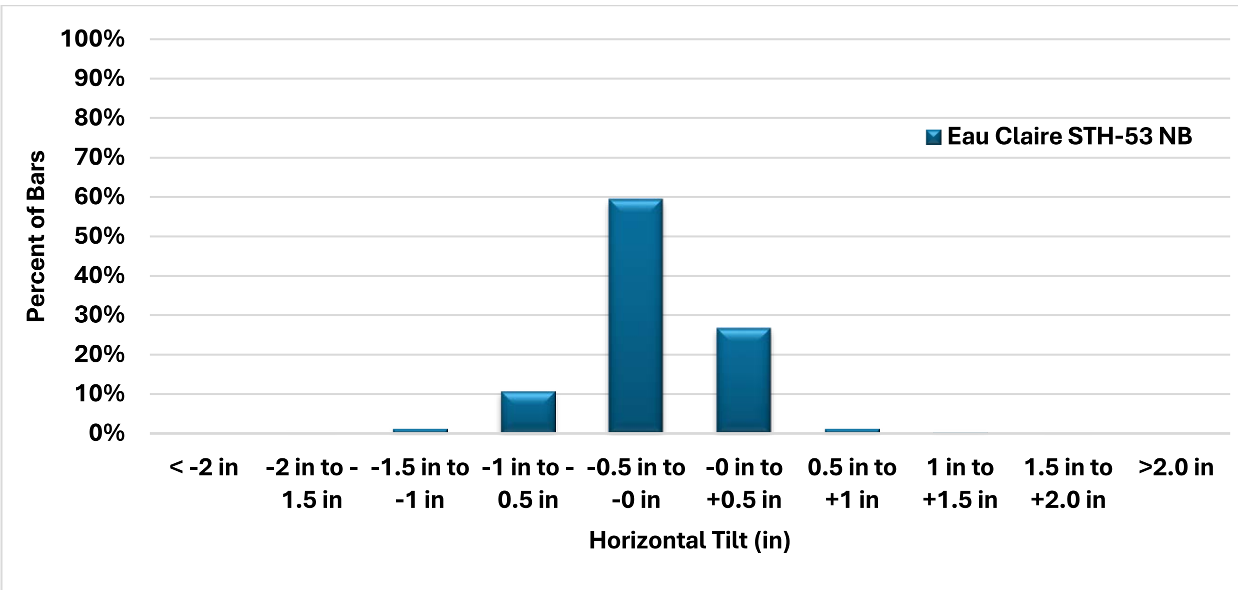

Figure 28. Horizontal Skew distribution for Eau Claire STH-53 NB

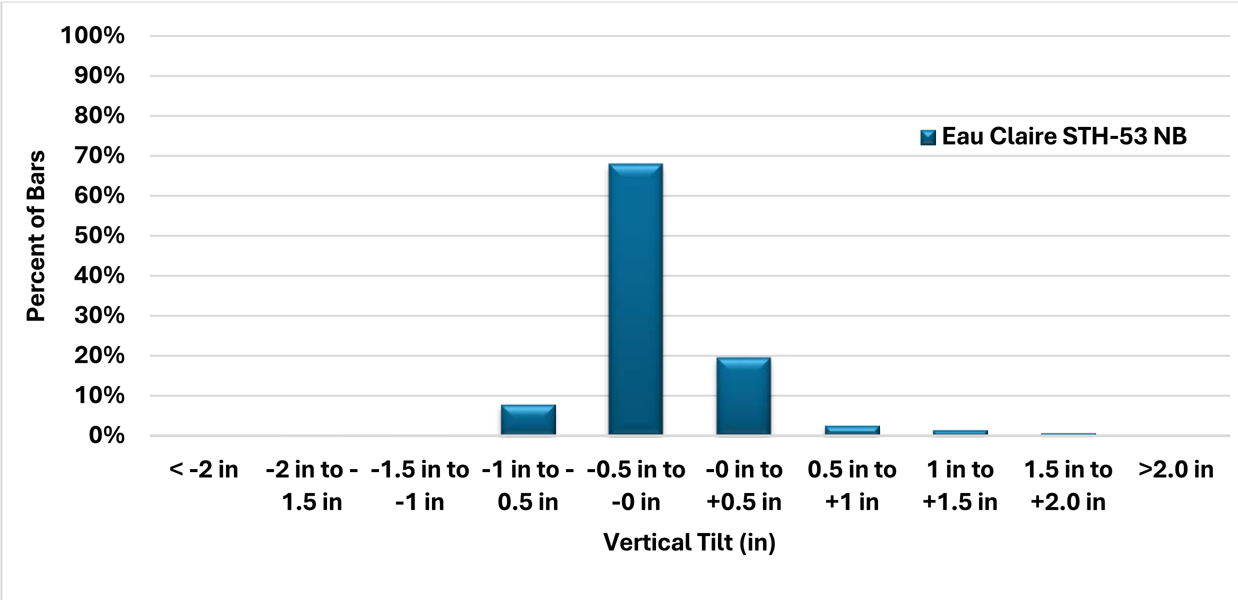

Figure 29. Vertical Tilt distribution for Eau Claire STH-53 NB.

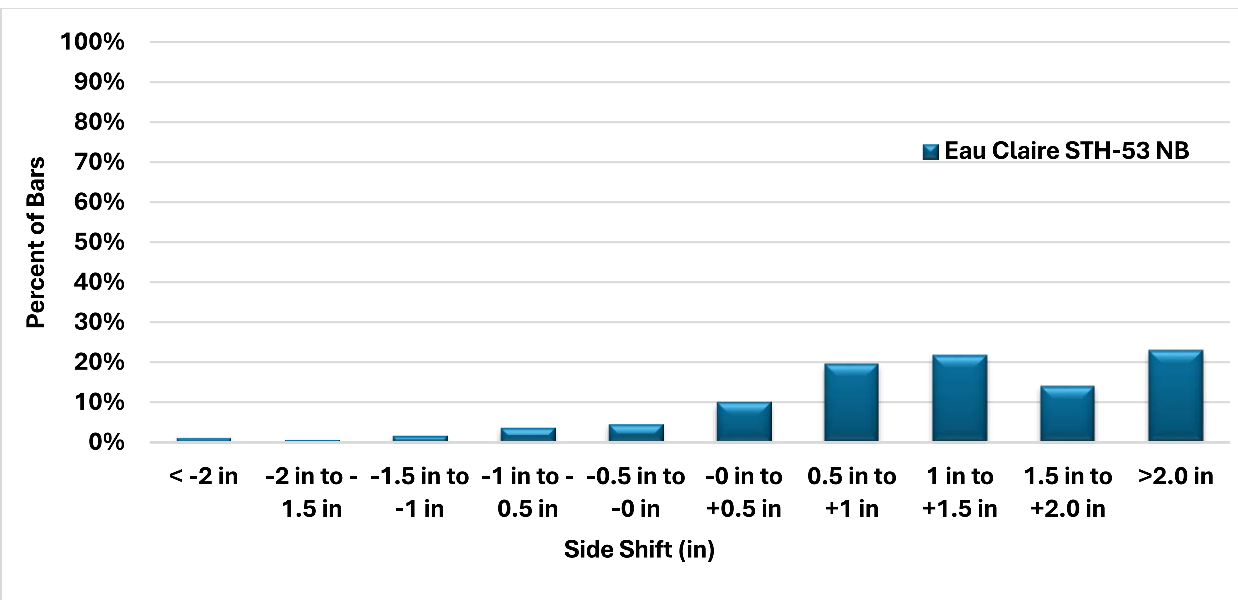

Figure 30. Longitudinal Translation distribution for Eau Claire STH-53 NB.

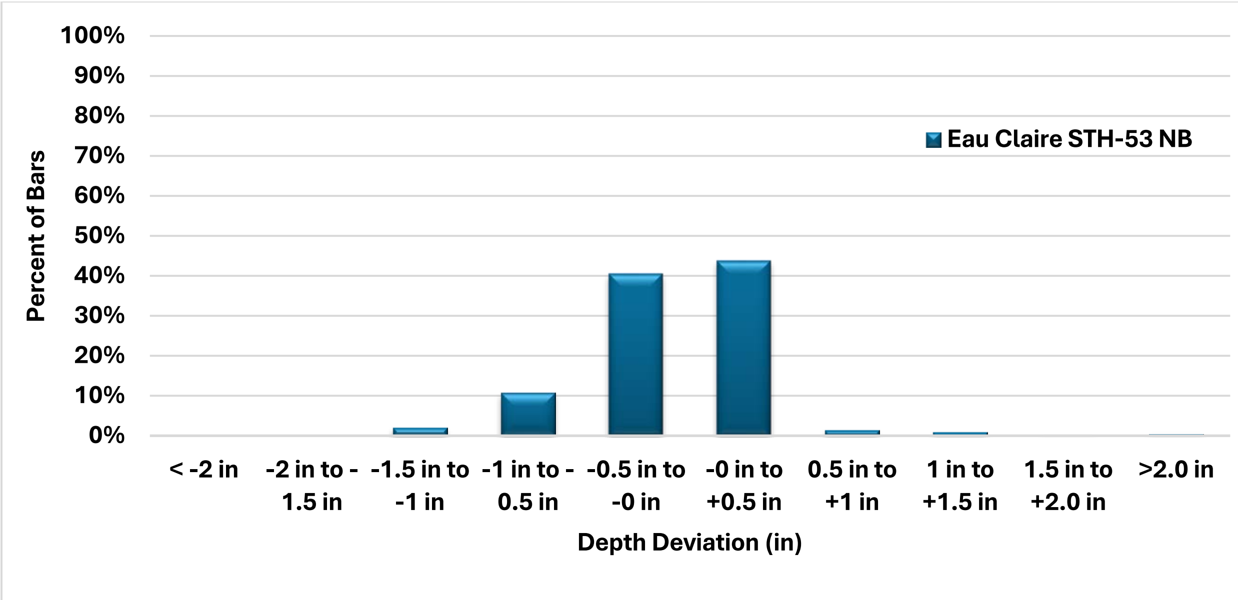

Figure 31. Vertical Translation distribution for Eau Claire STH-53 NB.

Table 11. Dowel misalignment summary for Eau Claire STH-53 NB.

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Eau Claire STH-53 NB	-0.17	0.25	-0.13	0.26	1.22	0.91	-0.06	0.44

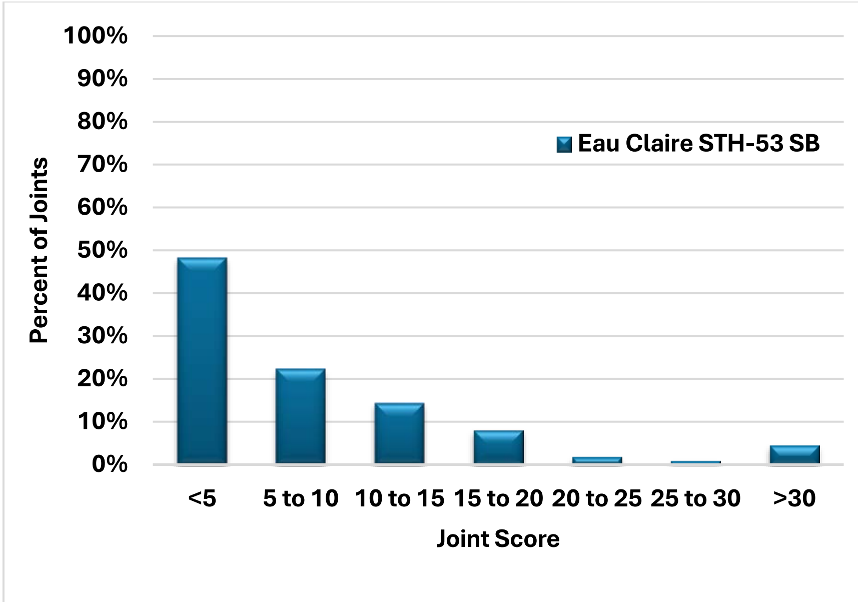

Figure 32. Joint score distribution for Eau Claire STH-53.

Table 12. Joint score and effective dowel diameter for Eau Claire STH-53.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Eau Claire STH-53 NB	9.1	14.4	9.5	1.25	1.205	0.081	3.60

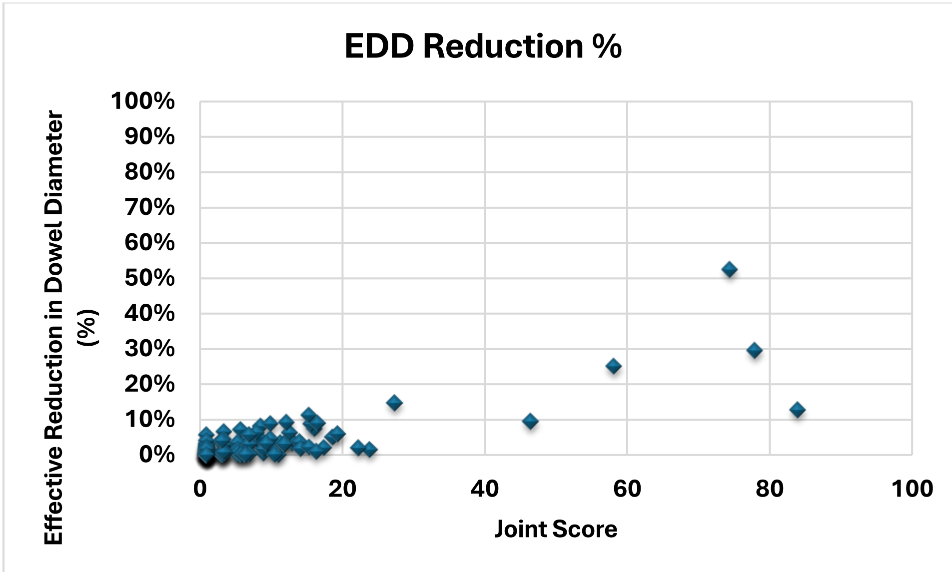

Figure 33. Joint score versus effective reduction in dowel diameter for Eau Claire STH-53.

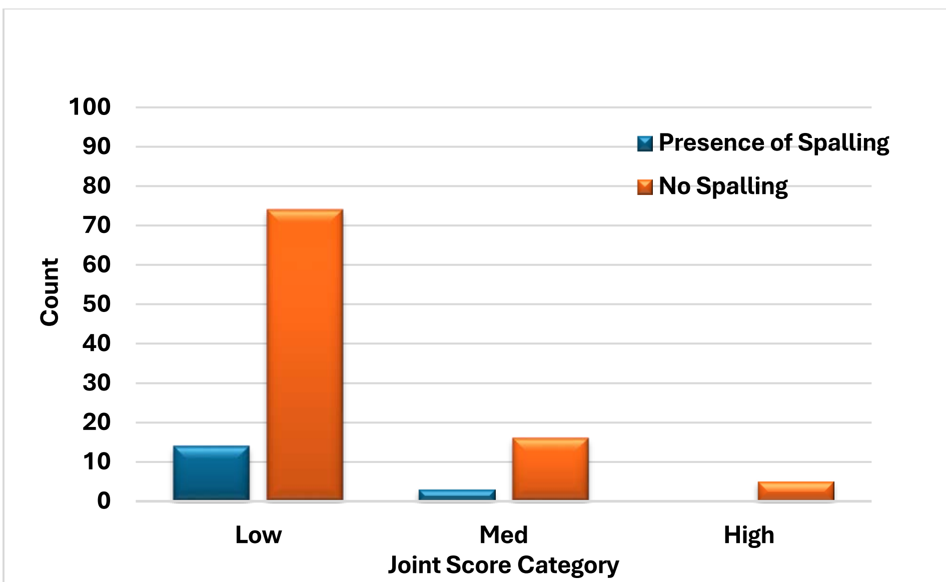

Figure 34. Joint score and presence of spalling for Eau Claire STH-53.

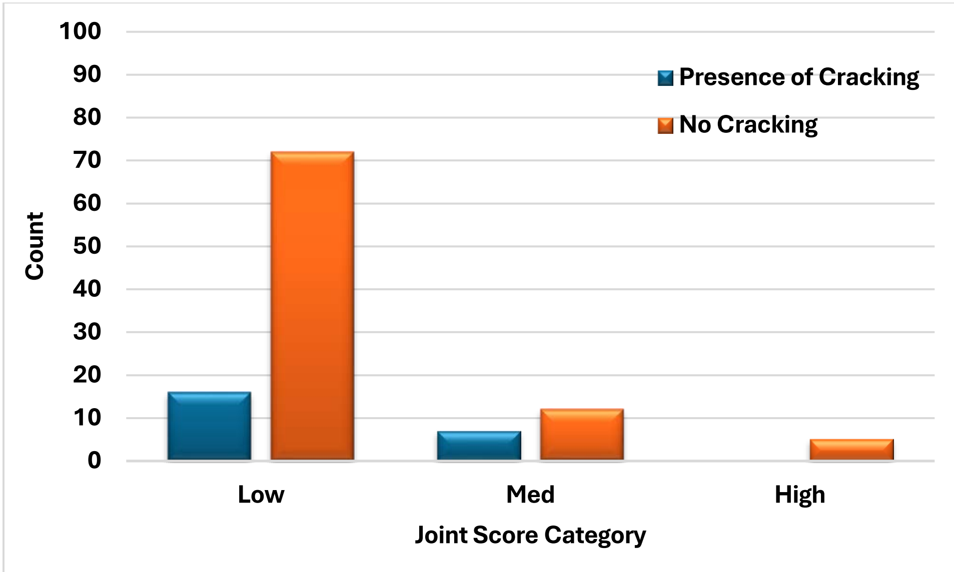

Figure 3532. Joint score and presence of cracking for Eau Claire STH-53.

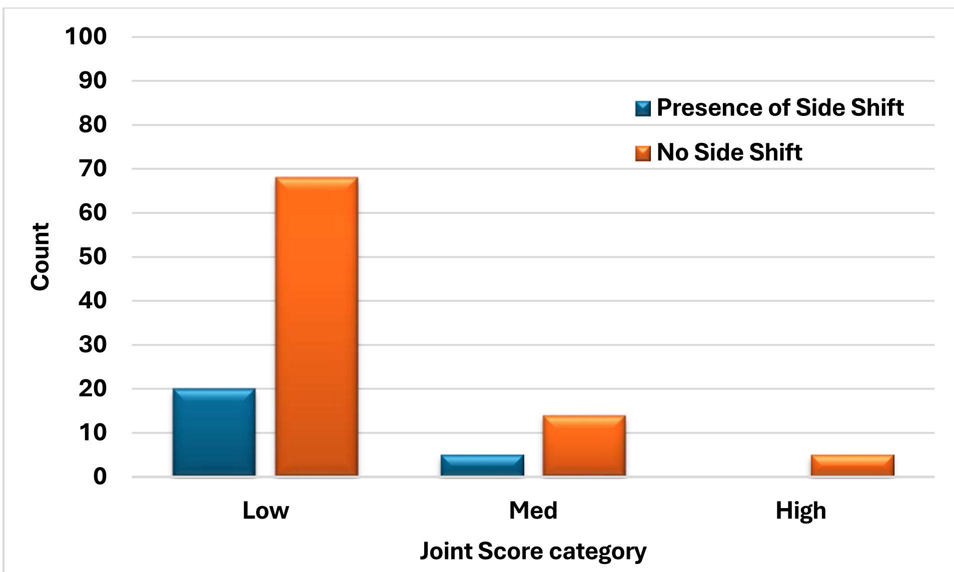

Figure 3633. Joint score and presence of side shift for Eau Claire STH-53.

Wood EB

Table 13. Details of test sections in Wood EB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Wood EB	10	1.5	10/18/2023	14.5

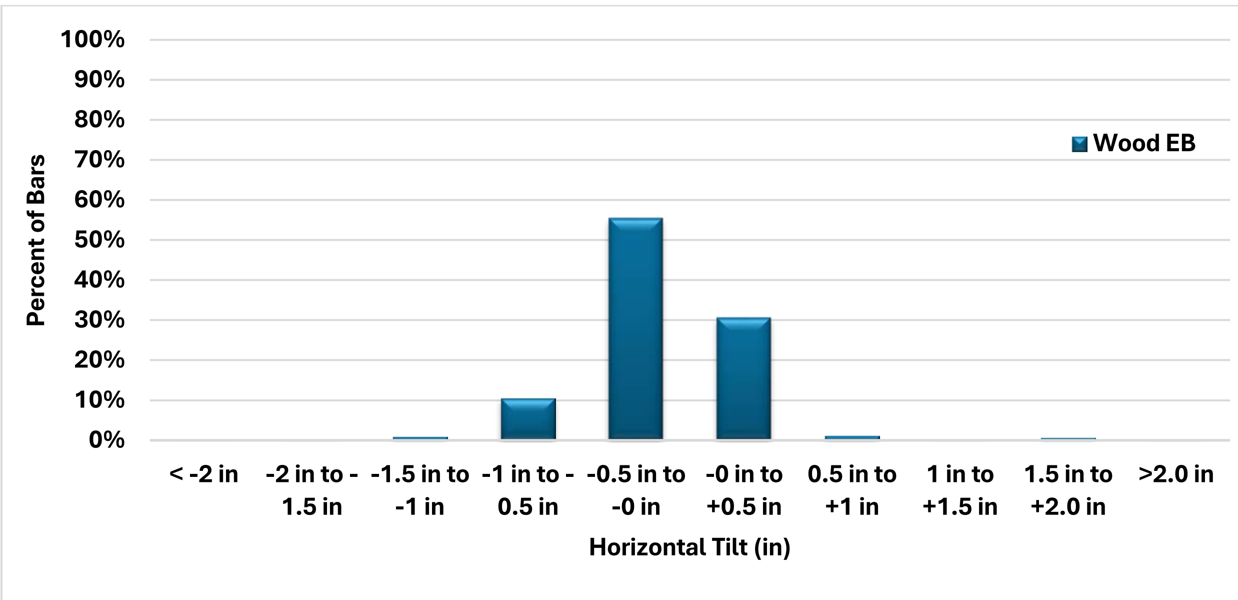

Figure 37. Horizontal Skew distribution for Wood EB.

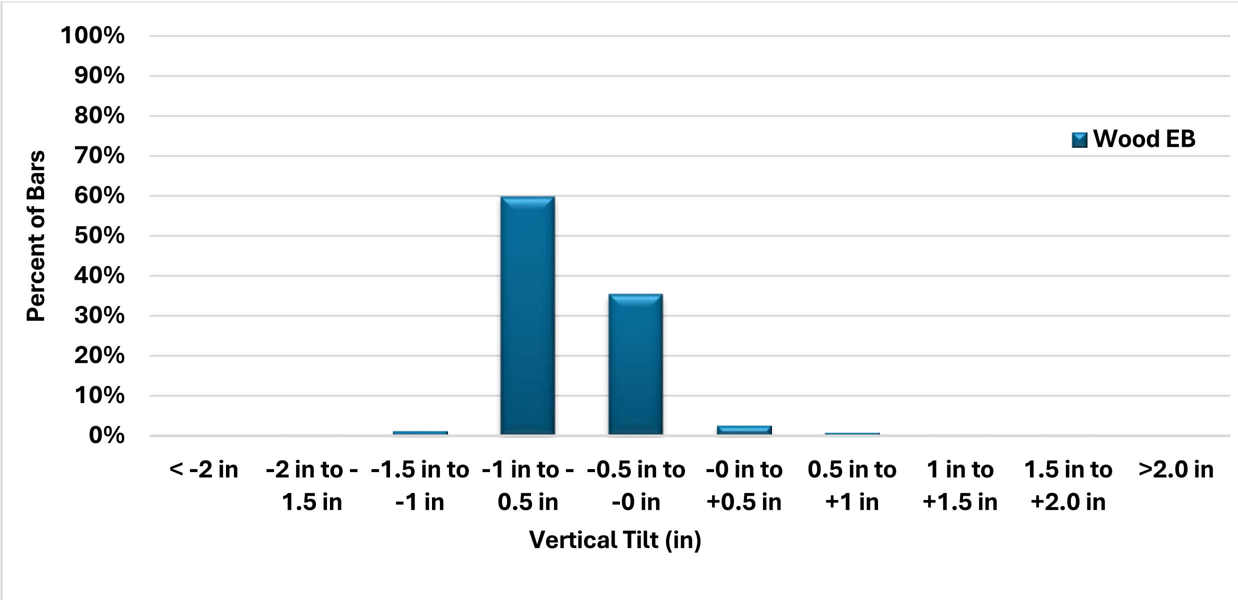

Figure 38. Vertical Tilt distribution for Wood EB.

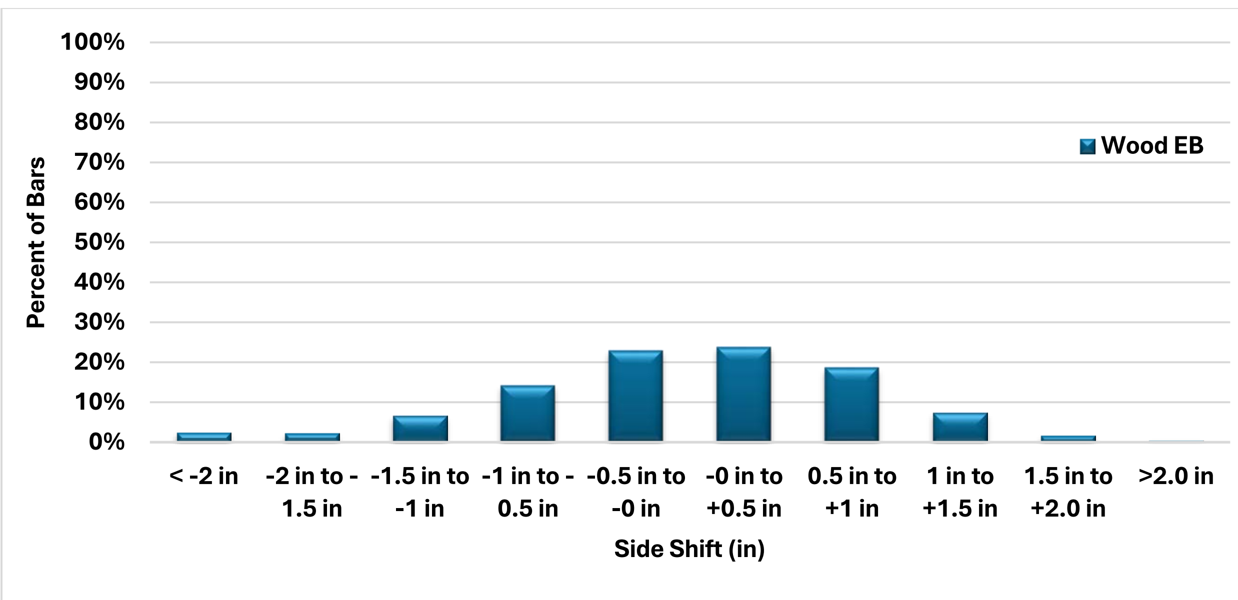

Figure 39. Longitudinal Translation distribution for Wood EB.

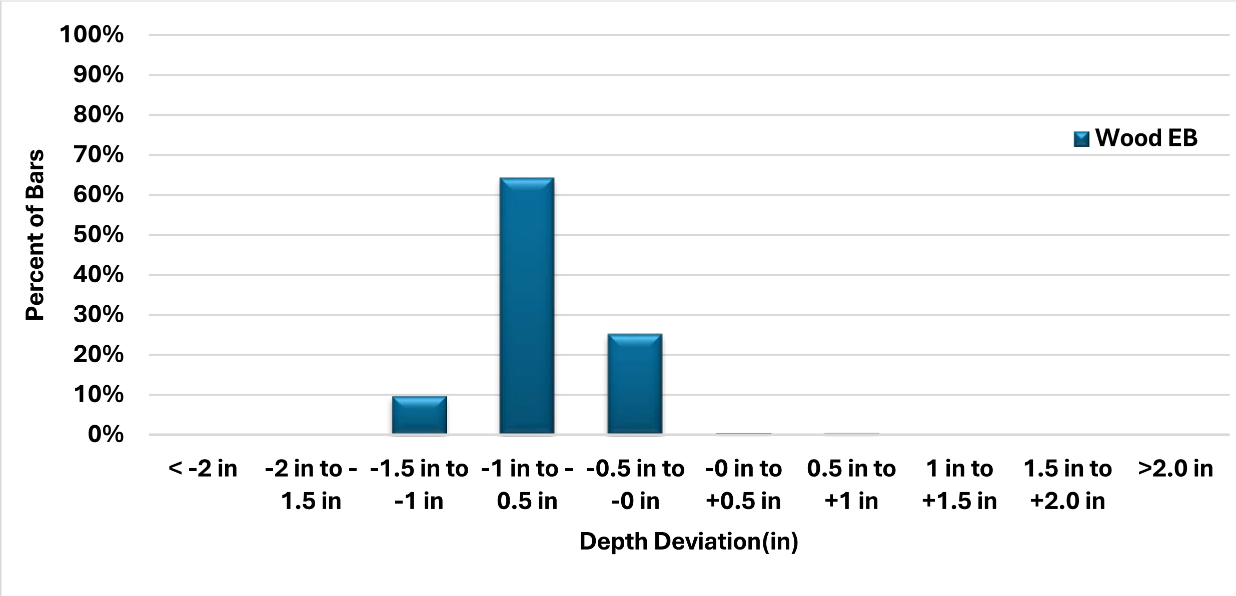

Figure 40. Vertical Translation distribution for Wood EB.

Table 14. Dowel misalignment summary for Wood EB.

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Wood EB	-0.16	0.30	-0.52	0.23	-0.06	0.62	-0.65	0.27

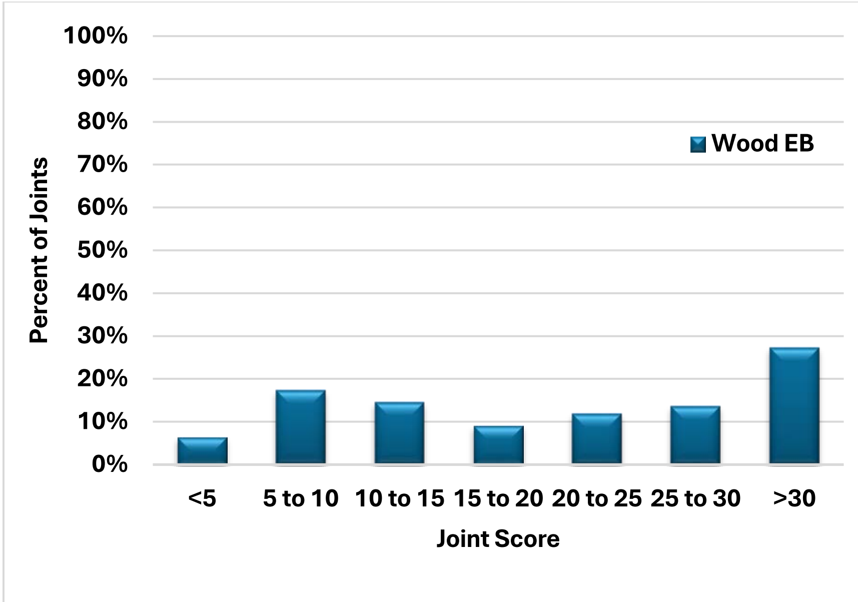

Figure 41. Joint score distribution for Wood EB.

Table 15. Joint score and effective dowel diameter for Wood EB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Wood EB	23.7	19.1	10	1.5	1.418	0.072	5.47

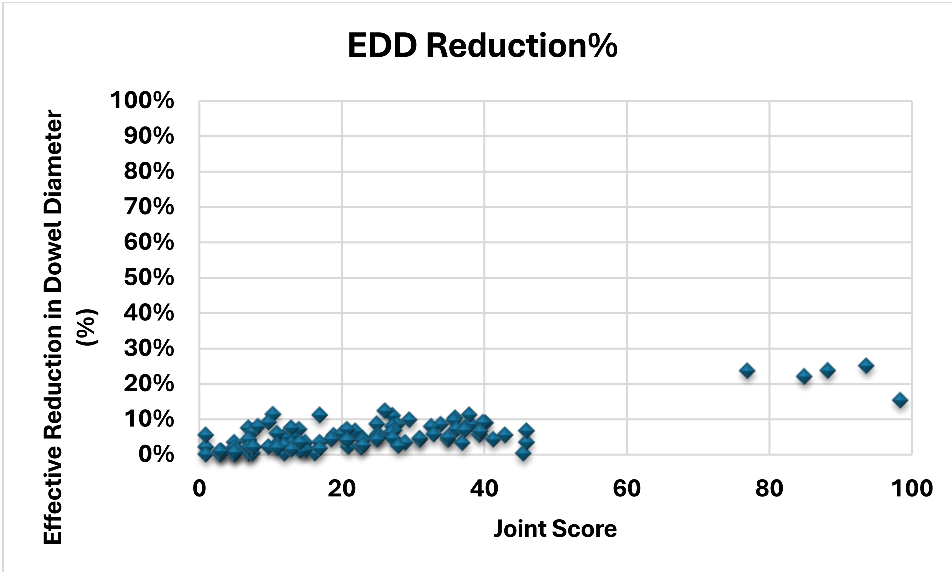

Figure 42. Joint score versus effective reduction in dowel diameter for Wood EB.

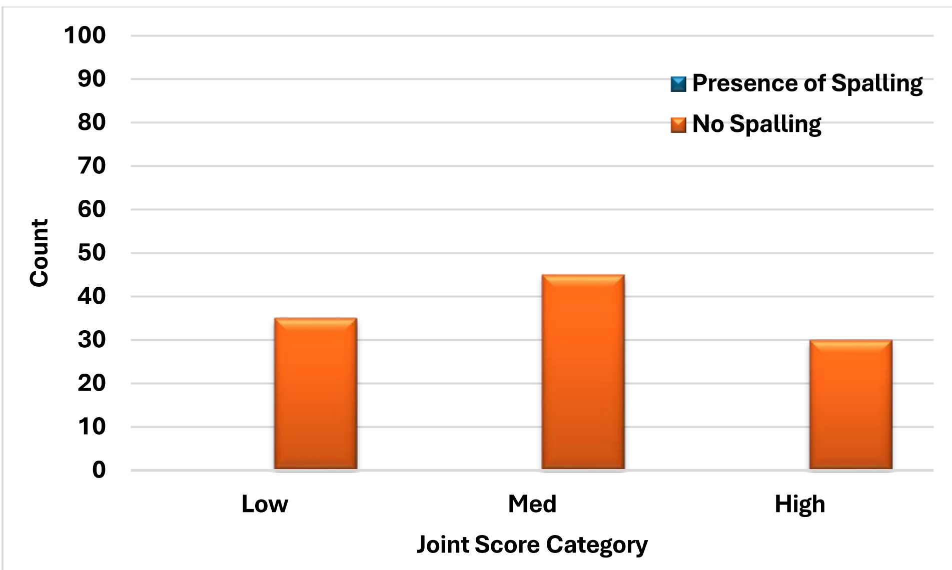

Figure 43. Joint score and presence of spalling for Wood EB.

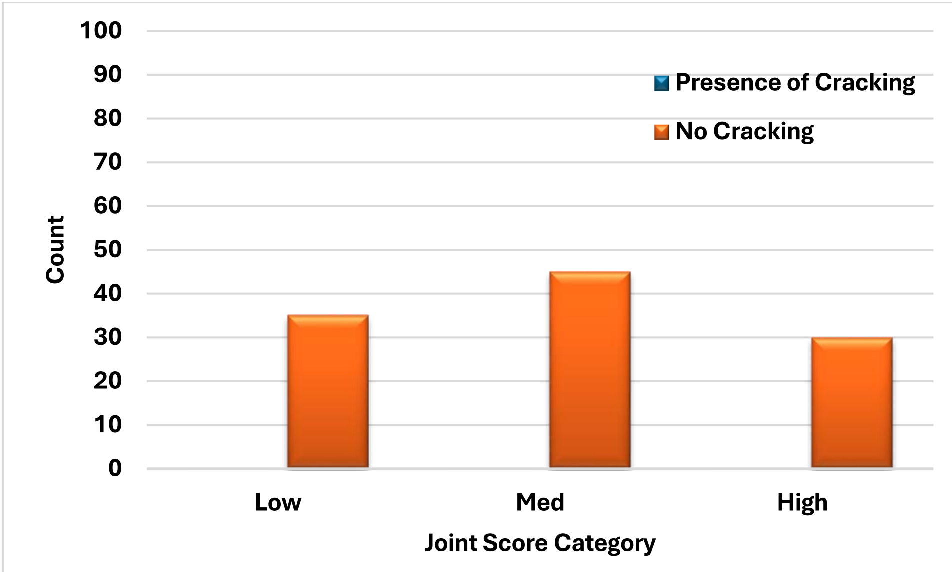

Figure 4434. Joint score and presence of cracking for Wood EB.

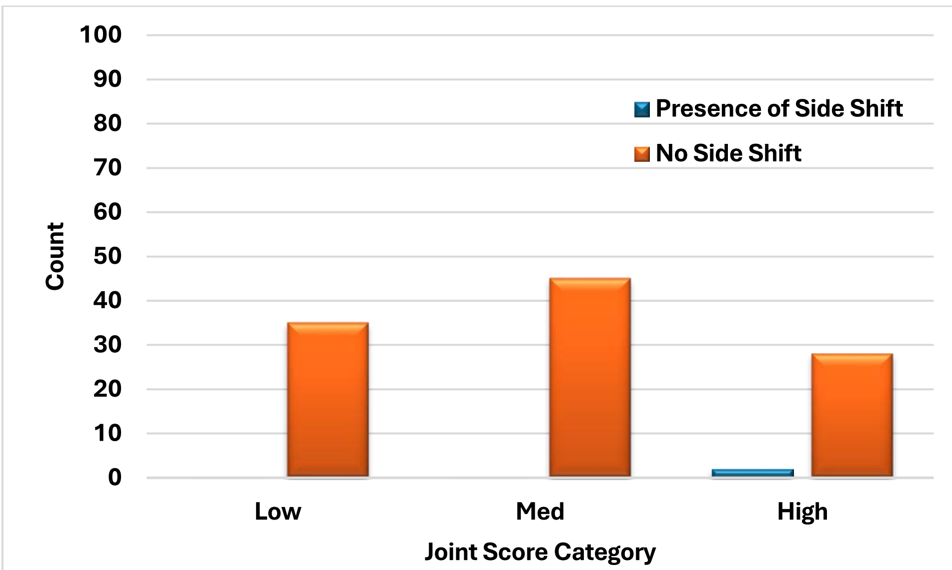

Figure 4535. Joint score and presence of side shift for Wood EB.

Wood WB

Table 16. Details of test sections in Wood WB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Wood WB	10	1.5	10/18/2023	14

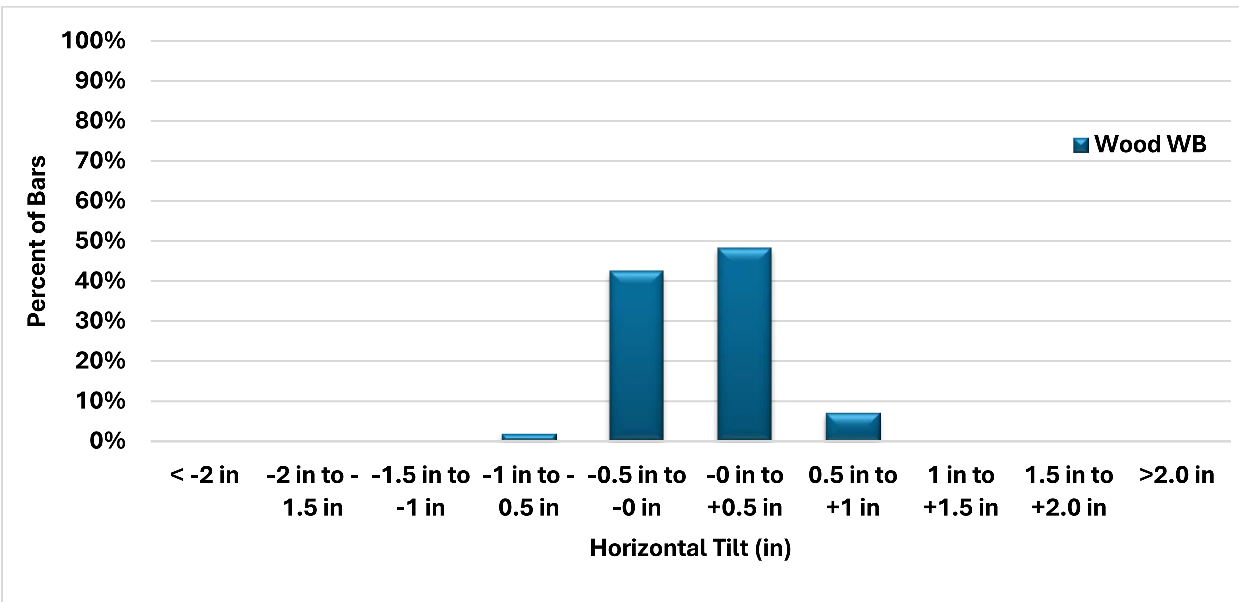

Figure 46. Horizontal Skew distribution for Wood WB.

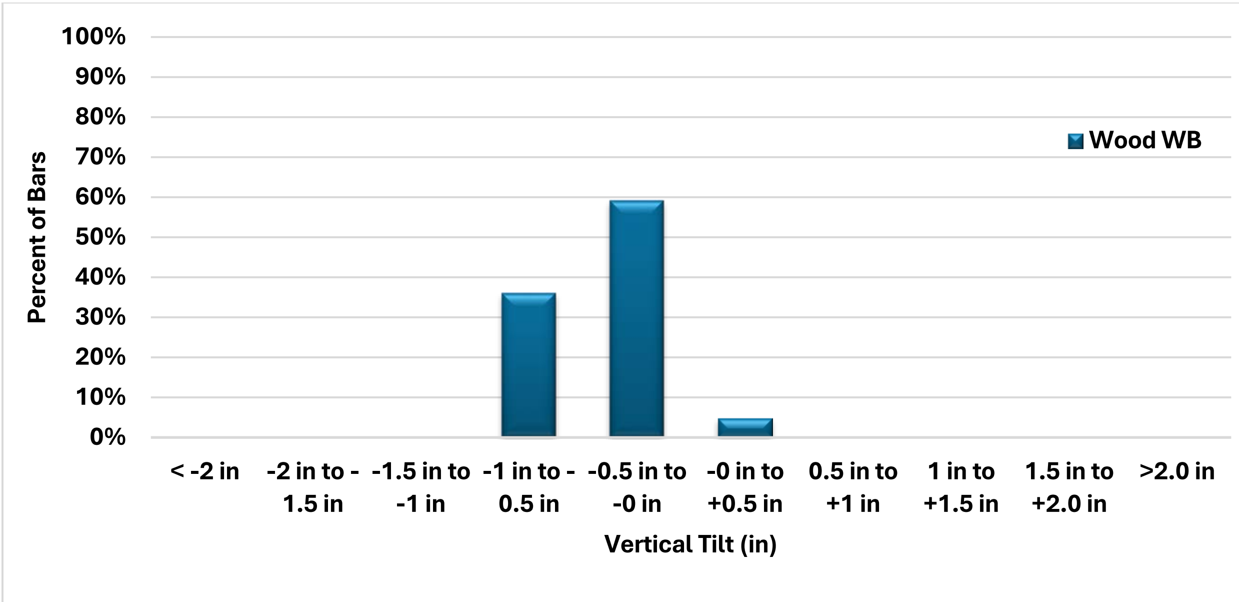

Figure 47. Vertical Tilt distribution for Wood WB.

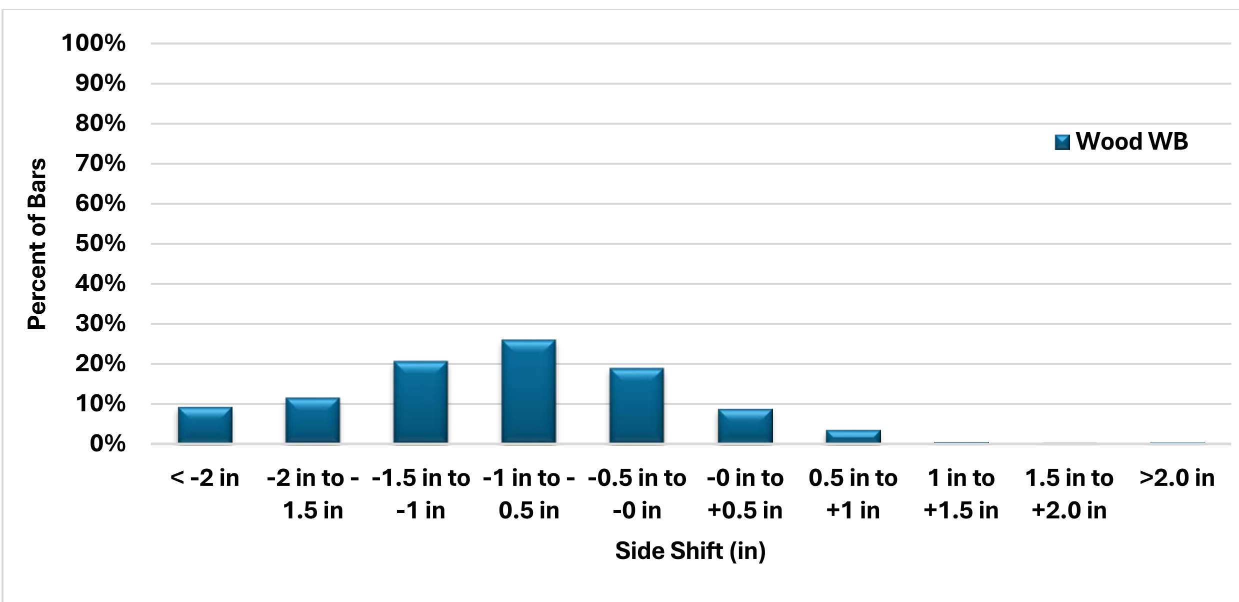

Figure 48. Longitudinal Translation distribution for Wood WB.

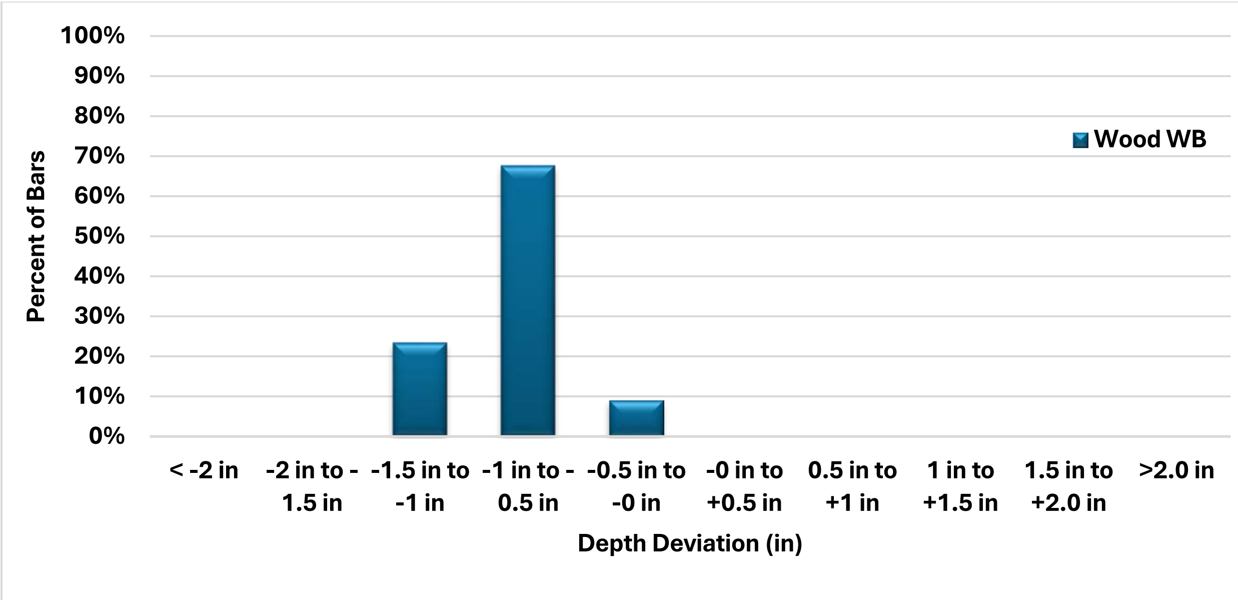

Figure 49. Vertical Translation distribution for Wood WB.

Table 17. Dowel misalignment summary for Wood WB.

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Wood WB	0.03	0.18	-0.40	0.21	-0.86	0.67	-0.82	0.26

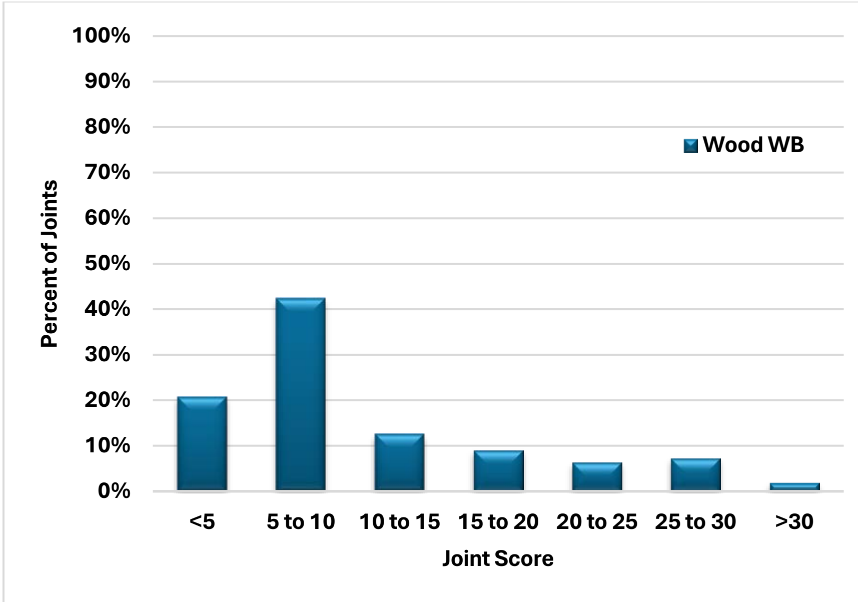

Figure 50. Joint score distribution for Wood WB.

Table 18. Joint score and effective dowel diameter for Wood WB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Wood WB	10.6	7.8	10	1.5	1.396	0.039	6.93

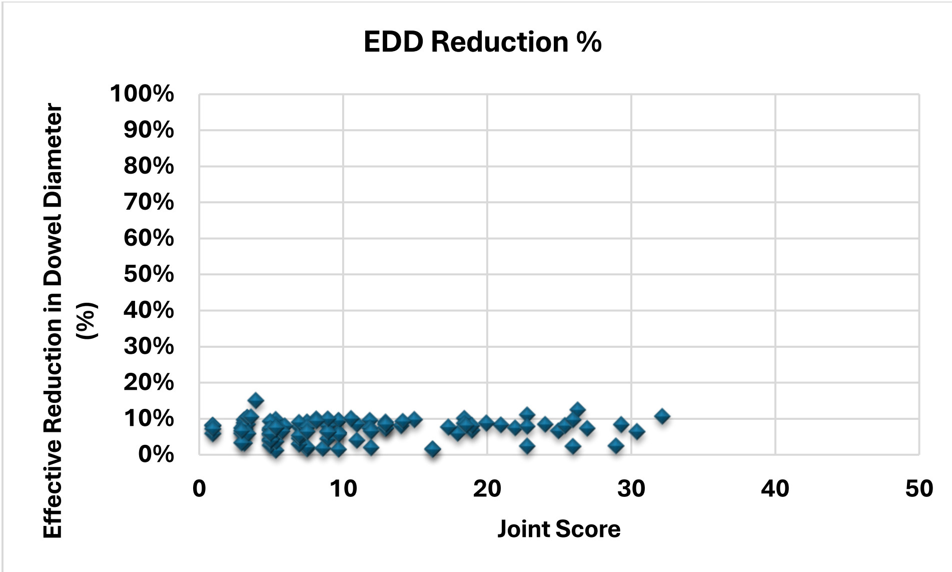

Figure 51. Joint score versus effective reduction in dowel diameter for Wood WB.

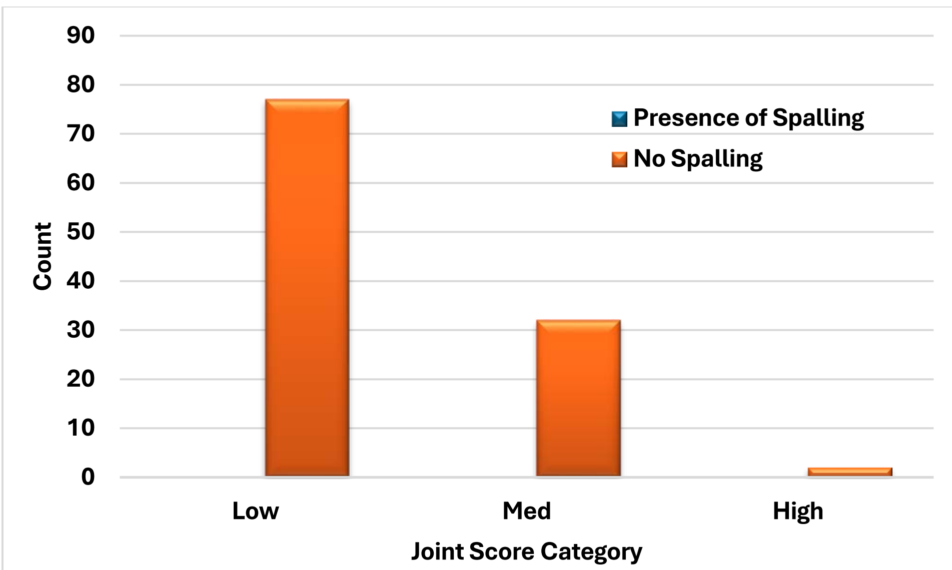

Figure 52. Joint score and presence of spalling for Wood WB.

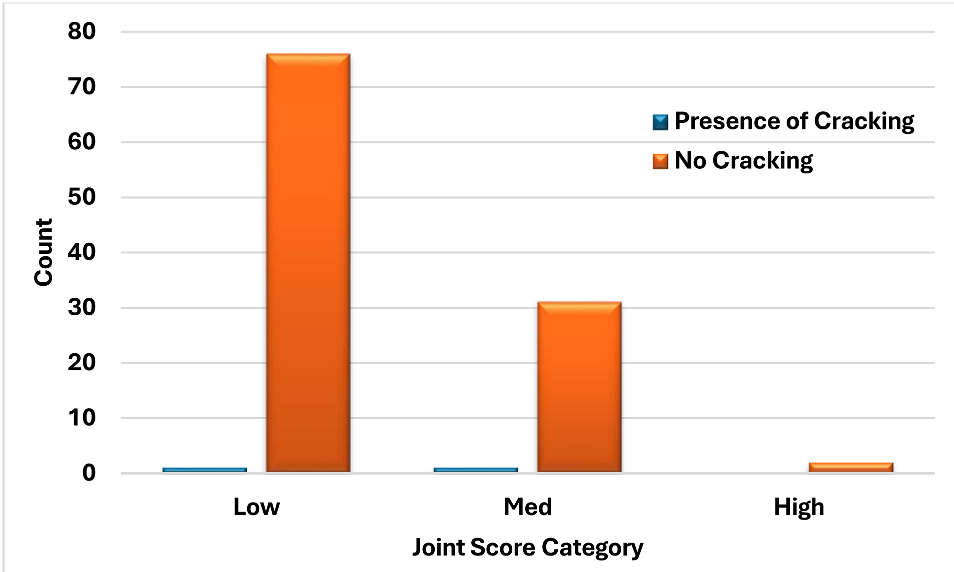

Figure 5336. Joint score and presence of cracking for Wood WB.

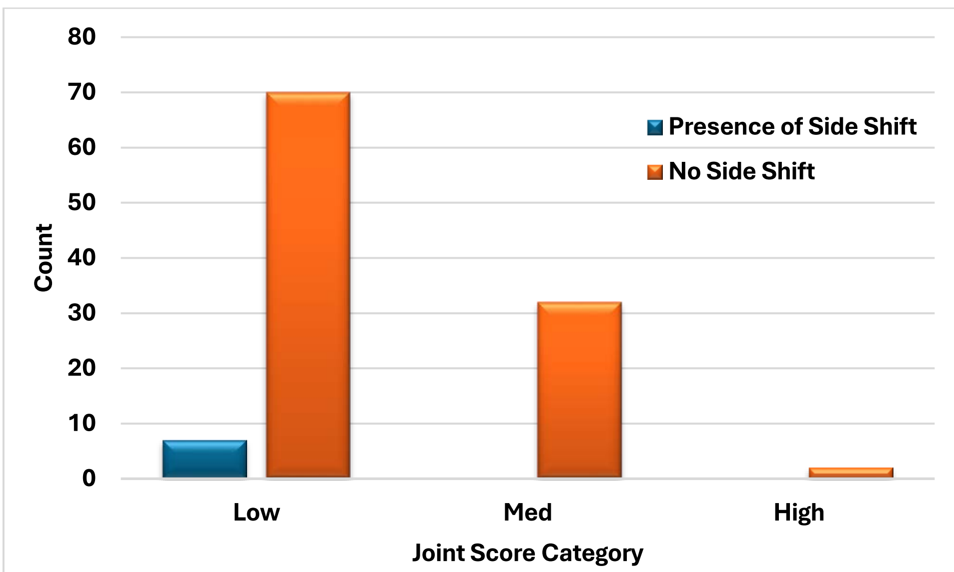

Figure 5437. Joint score and presence of side shift for Wood WB.

Fond du Lac EB

Table 19. Details of test sections in Fond du Lac EB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Fond du Lac EB	10	1.5	10/19/2023	14

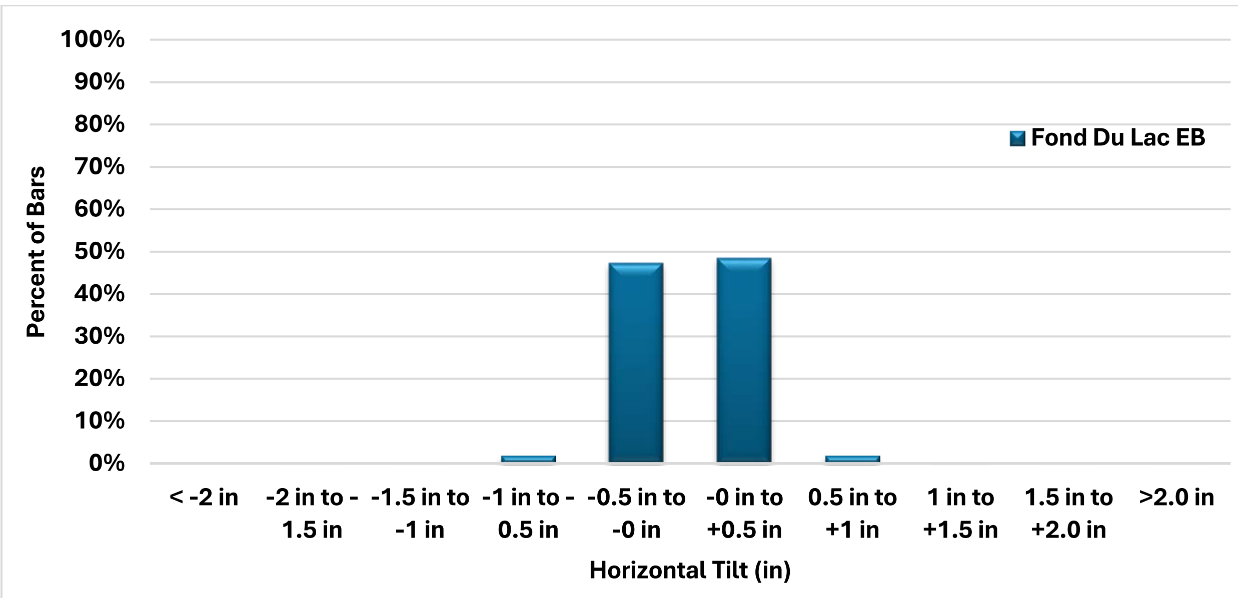

Figure 55. Horizontal Skew distribution for Fond du Lac EB

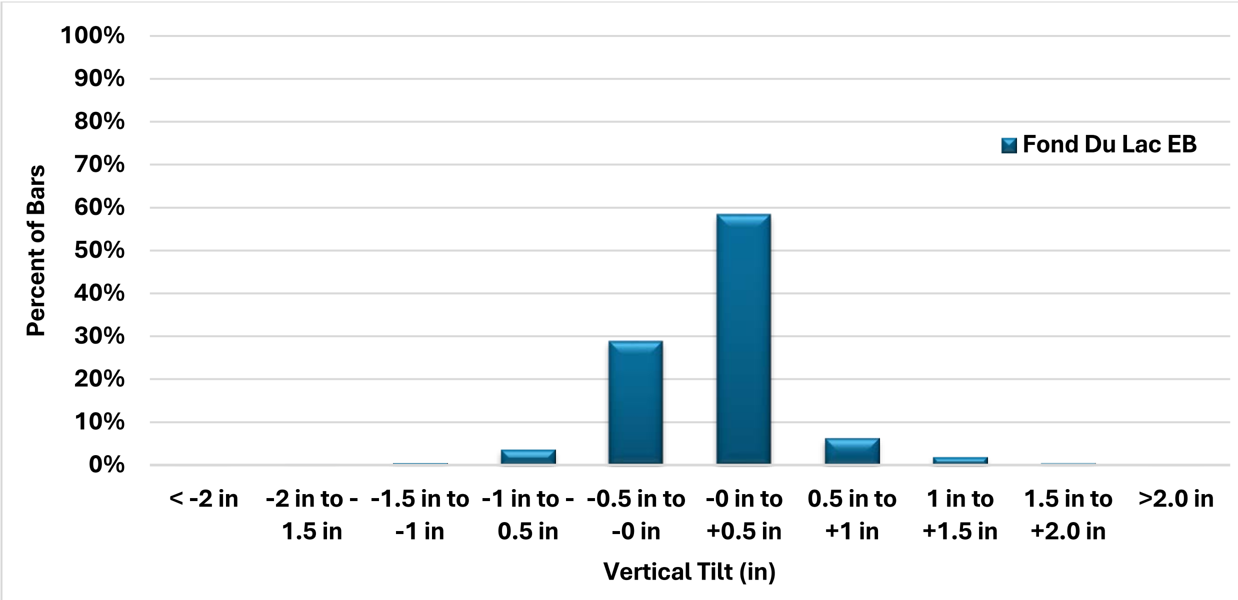

Figure 56. Vertical Tilt distribution for Fond du Lac EB.

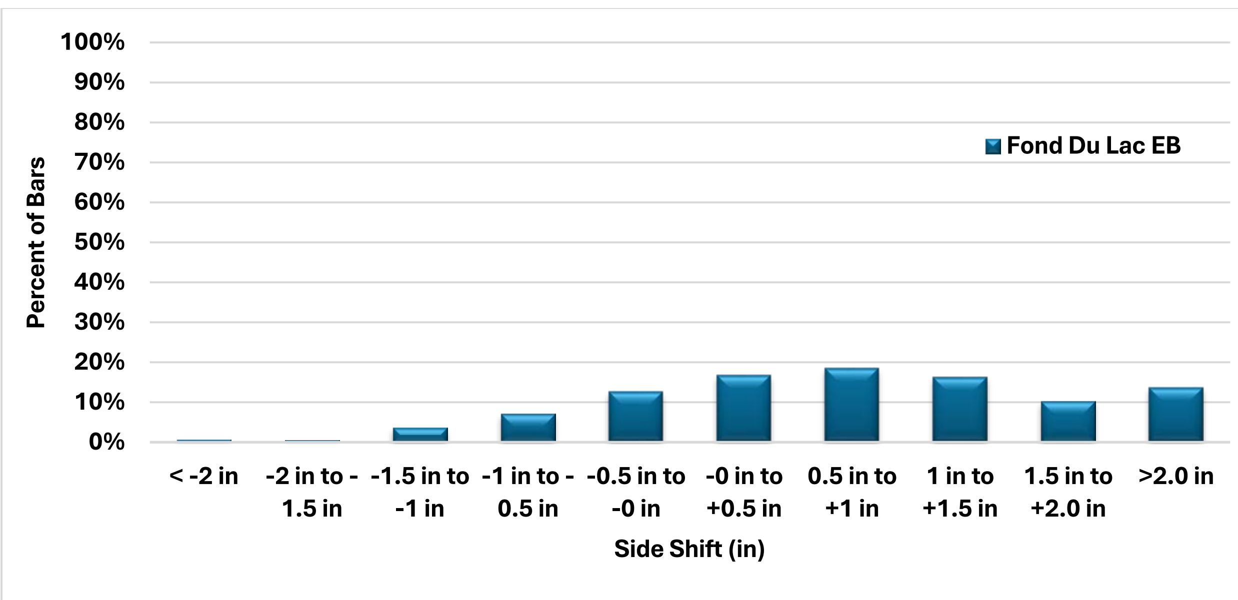

Figure 57. Longitudinal Translation distribution for Fond du Lac EB

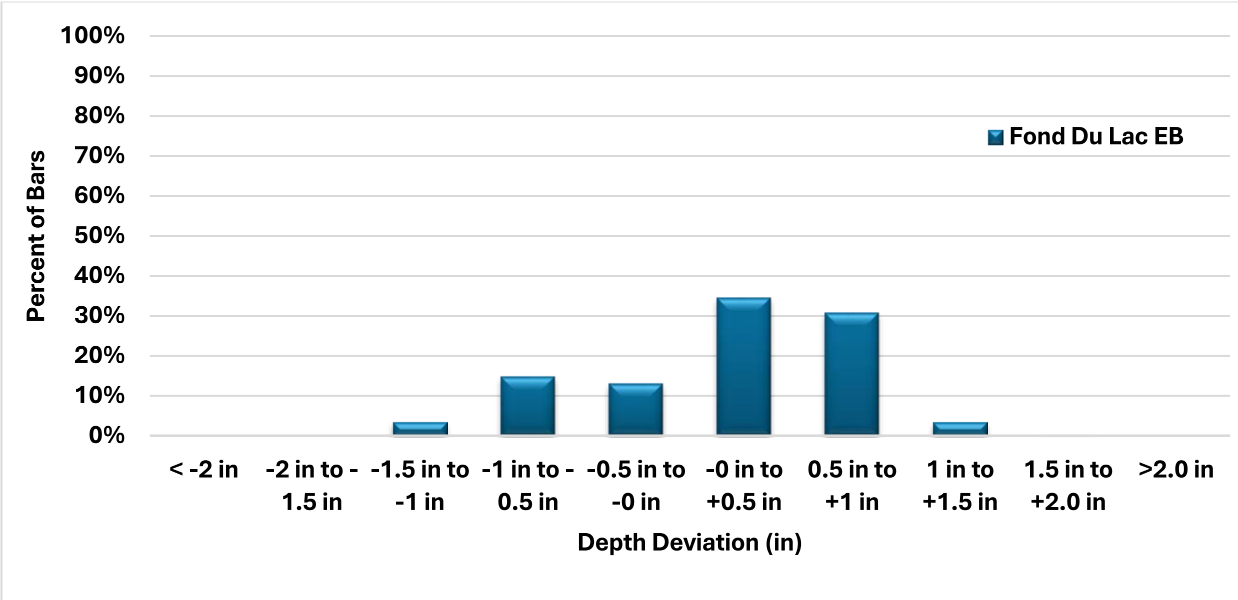

Figure 58. Vertical Translation distribution for Fond du Lac EB

Table 20. Dowel misalignment summary for Fond du Lac EB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Fond du Lac EB	-0.01	0.18	0.15	0.49	0.74	0.82	0.17	0.58

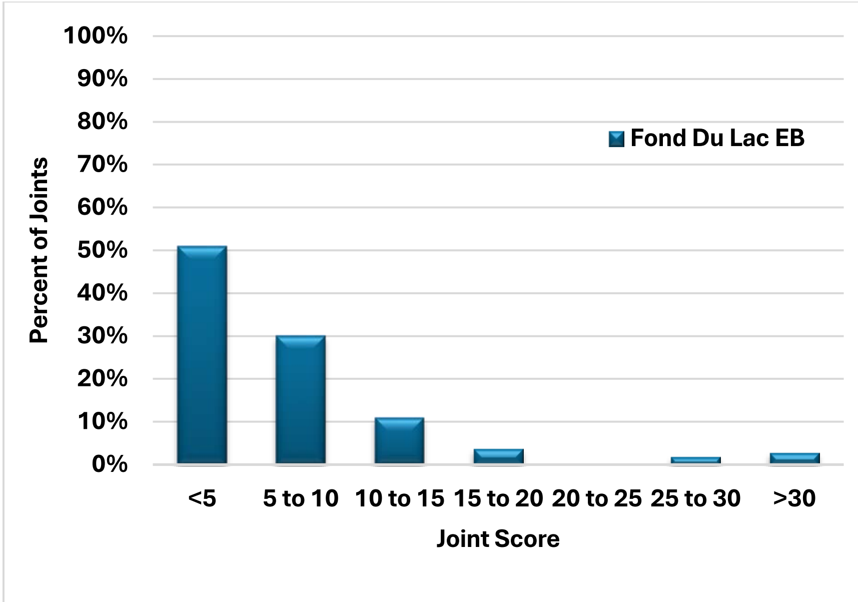

Figure 59. Joint score distribution for Fond du Lac EB

Table 21. Joint score and effective dowel diameter for Fond du Lac EB.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Fond du Lac EB	7.3	14.1	10	1.5	1.467	0.035	2.20

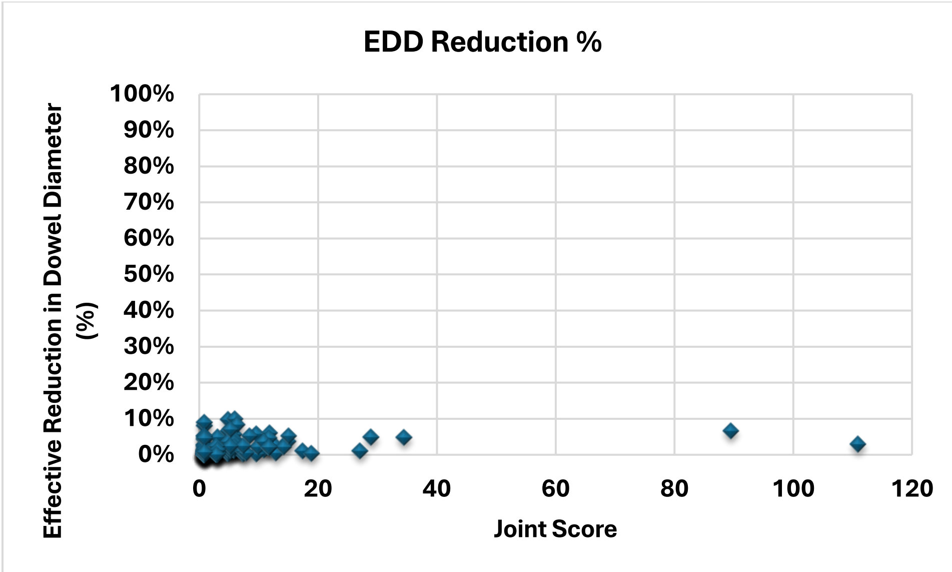

Figure 60. Joint score versus effective reduction in dowel diameter for Fond du Lac EB.

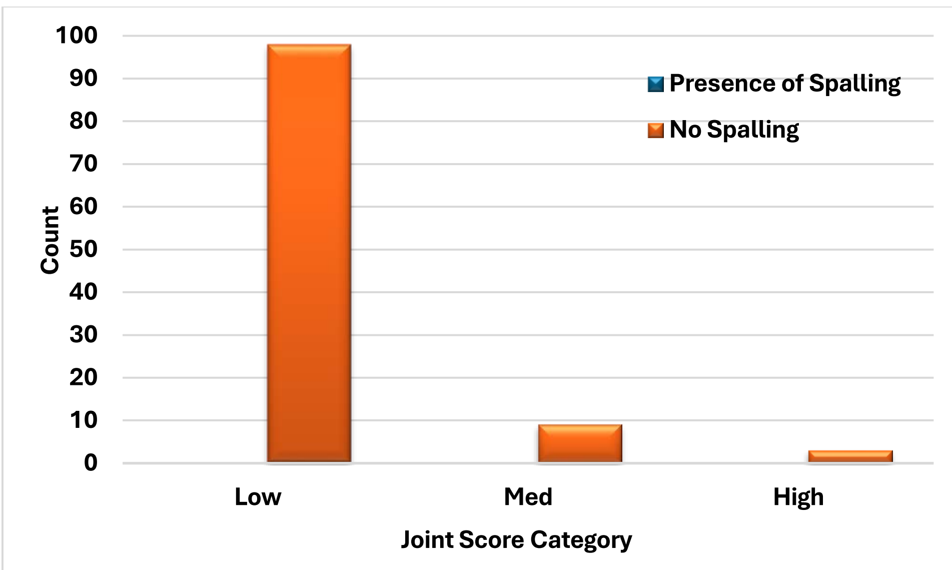

Figure 61. Joint score and presence of spalling for Fond du Lac EB.

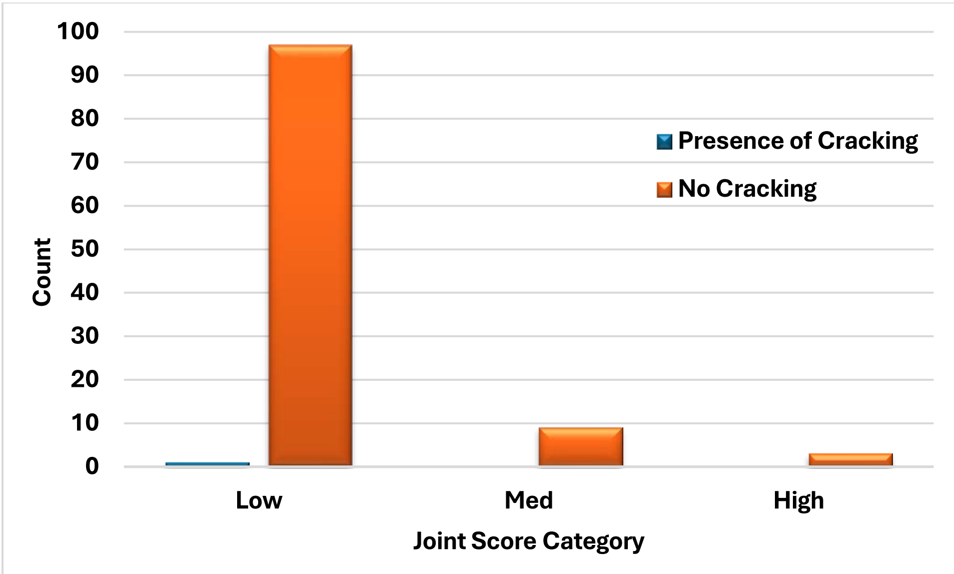

Figure 6238. Joint score and presence of cracking for Fond du Lac EB

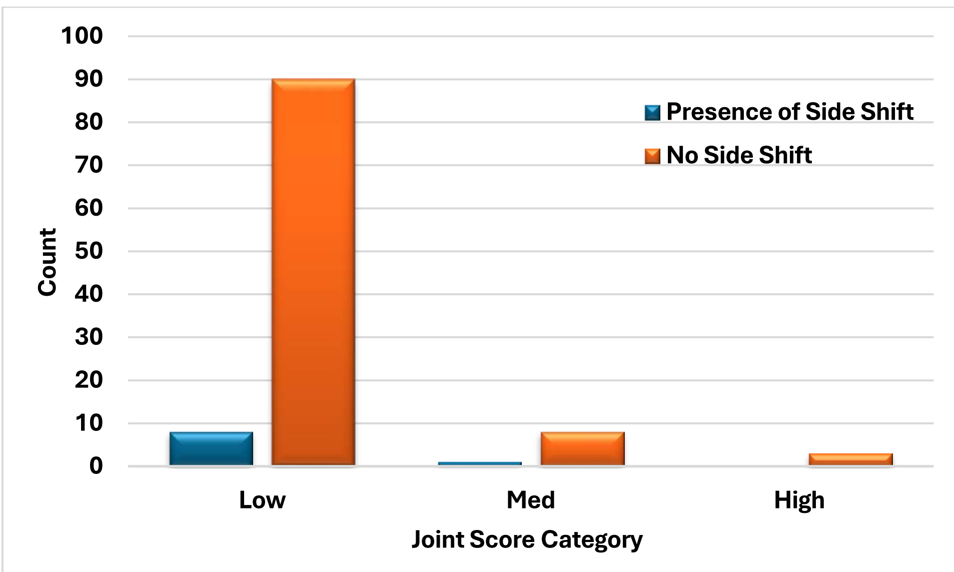

Figure 6339. Joint score and presence of side shift for Fond du Lac EB.

Fond du Lac WB

Table 22. Details of test sections in Fond du Lac WB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Fond du Lac WB	10	1.5	10/19/2023	14

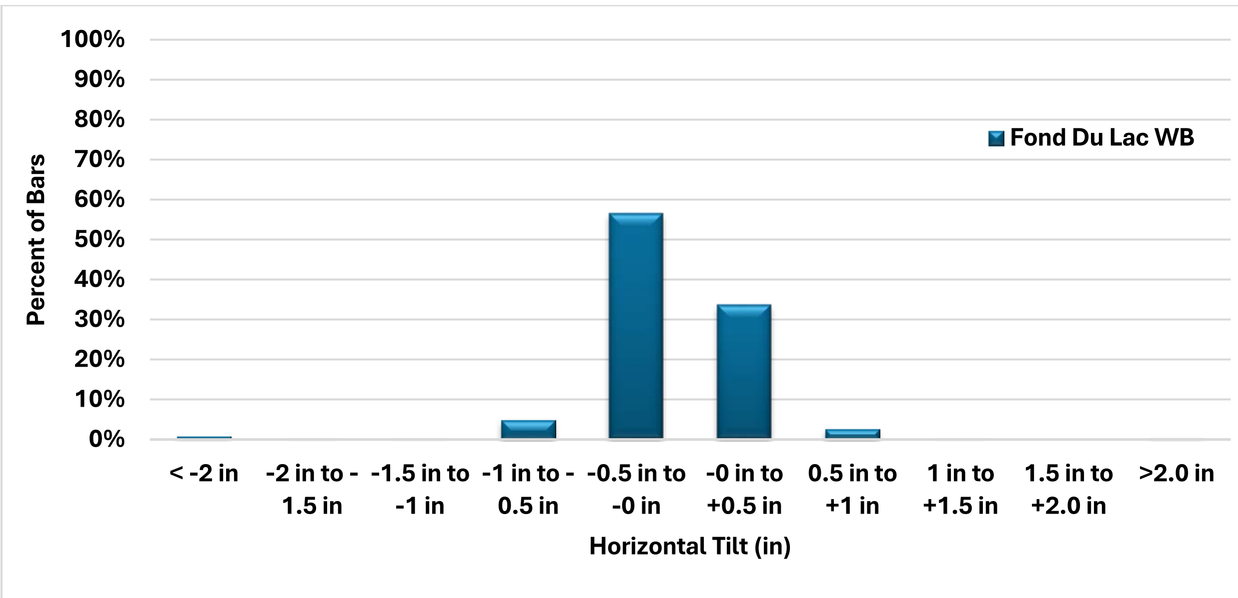

Figure 64. Horizontal Skew distribution for Fond du Lac WB

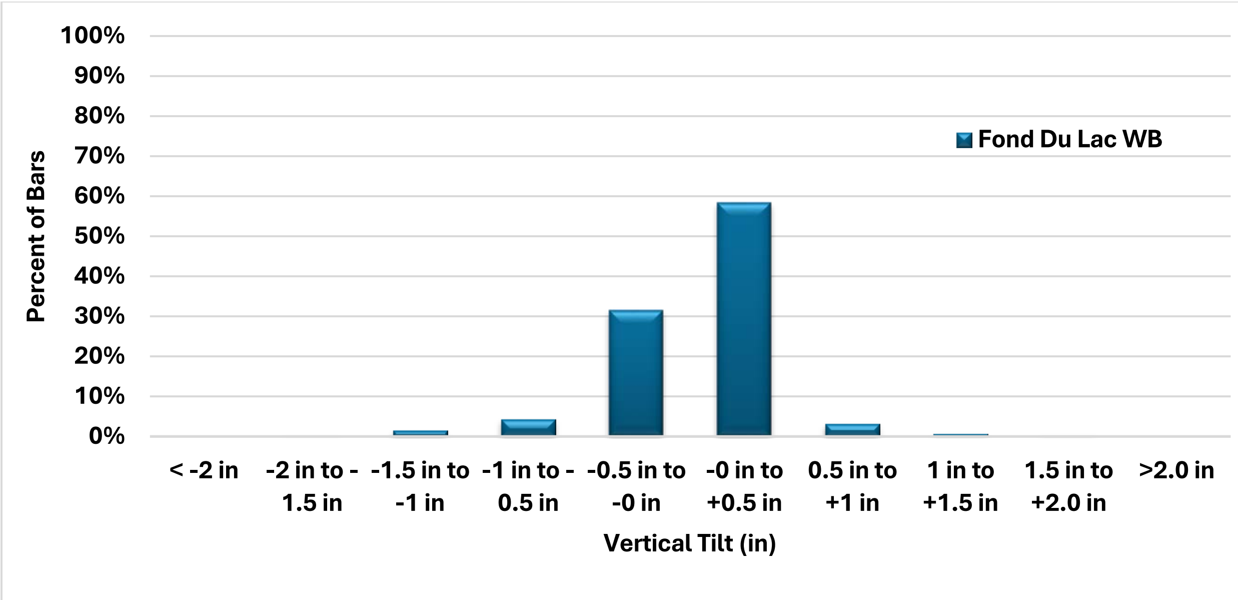

Figure 65. Vertical Tilt distribution for Fond du Lac WB.

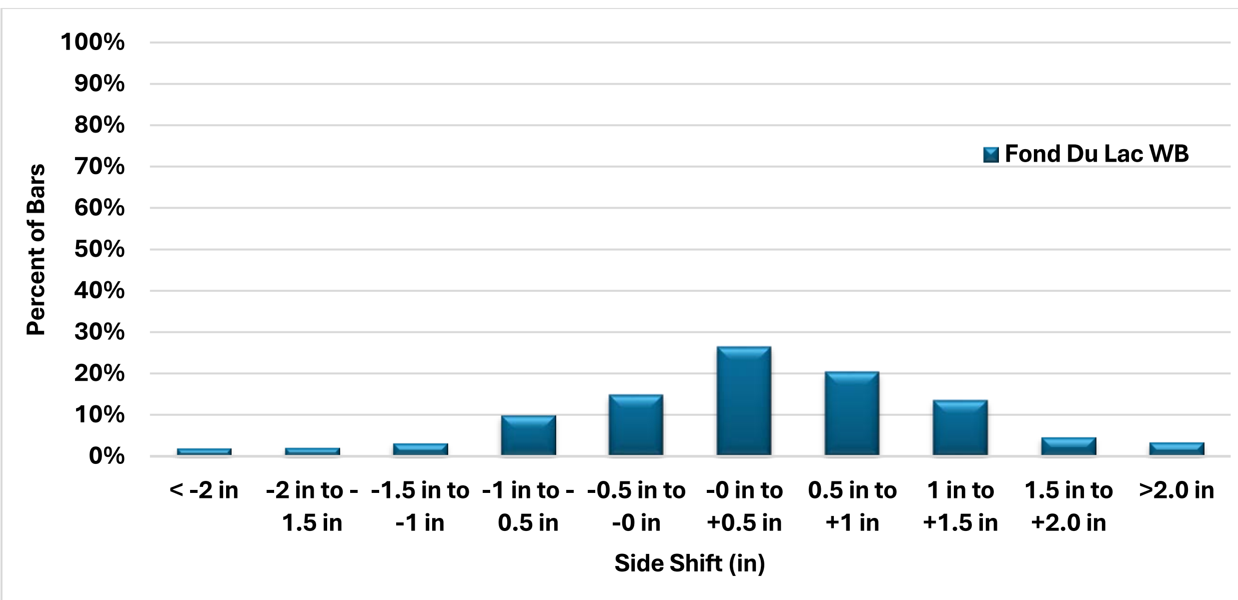

Figure 66. Longitudinal Translation distribution for Fond du Lac WB

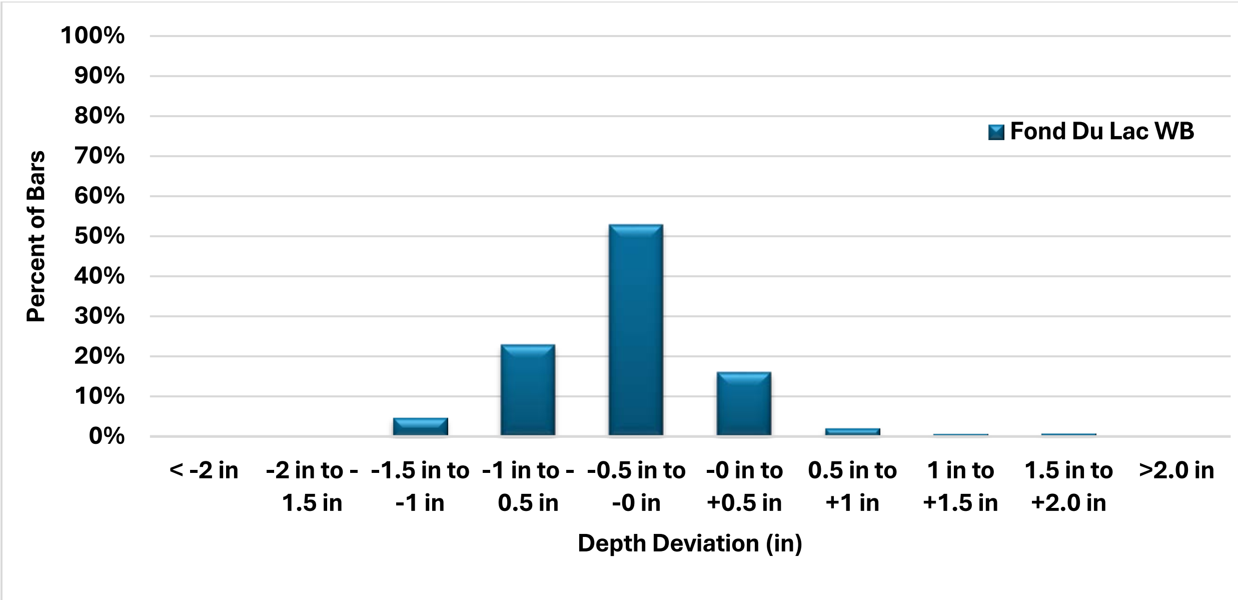

Figure 67. Vertical Translation distribution for Fond du Lac WB

Table 23. Dowel misalignment summary for Fond du Lac WB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Fond du Lac WB	-0.09	0.32	0.04	0.26	0.33	0.71	-0.29	0.44

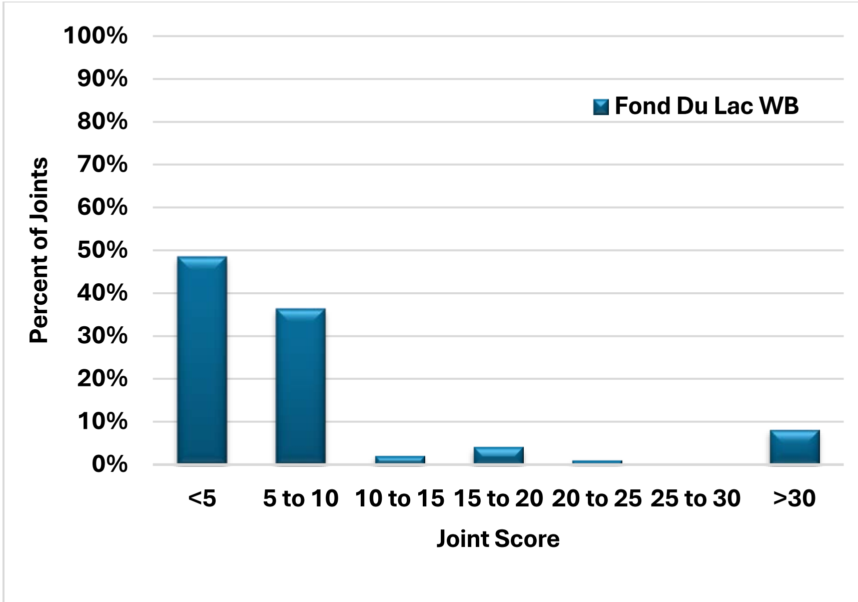

Figure 68. Joint score distribution for Fond du Lac WB

Table 24. Joint score and effective dowel diameter for Fond du Lac WB.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Fond du Lac WB	10.8	23.4	10	1.5	1.447	0.105	3.53

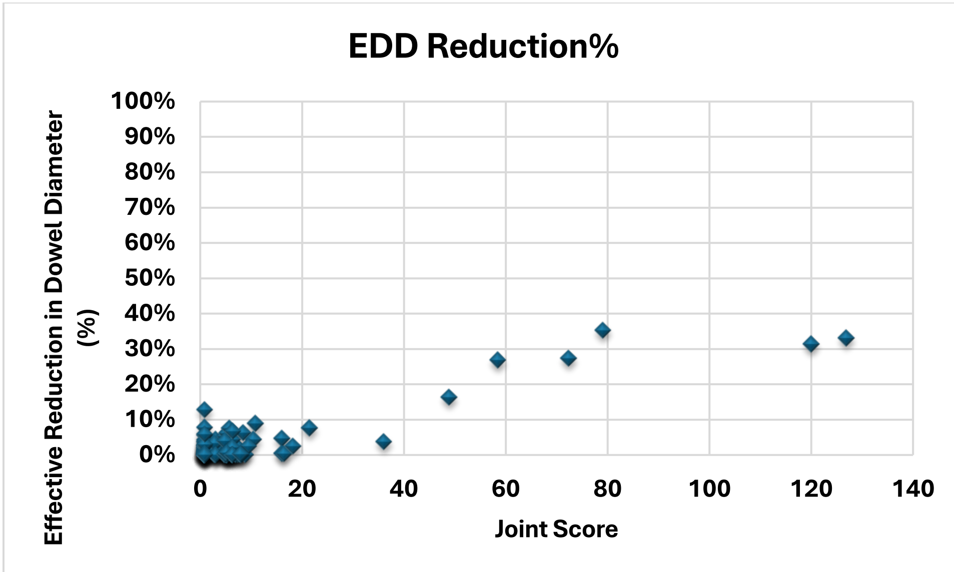

Figure 69. Joint score versus effective reduction in dowel diameter for Fond du Lac WB.

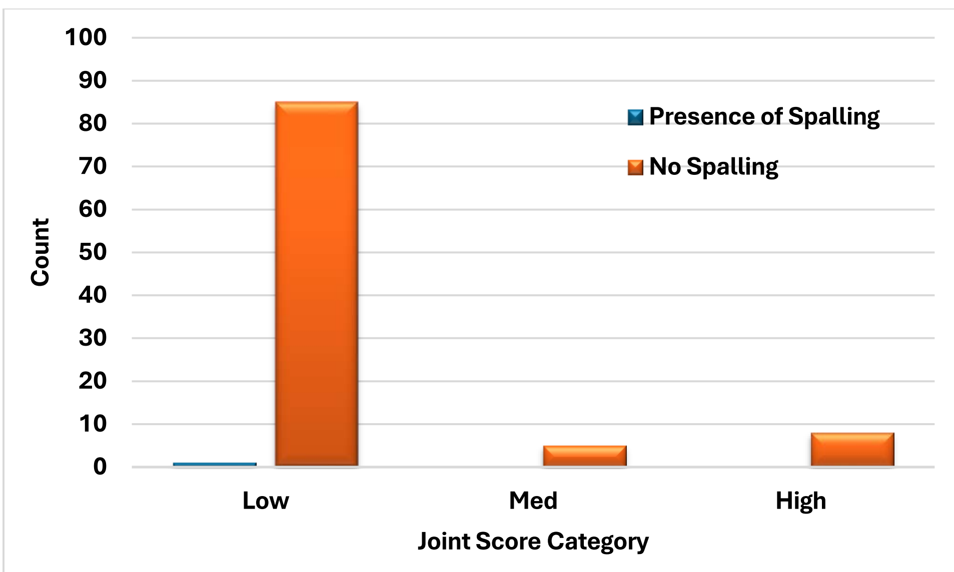

Figure 70. Joint score and presence of spalling for Fond du Lac WB.

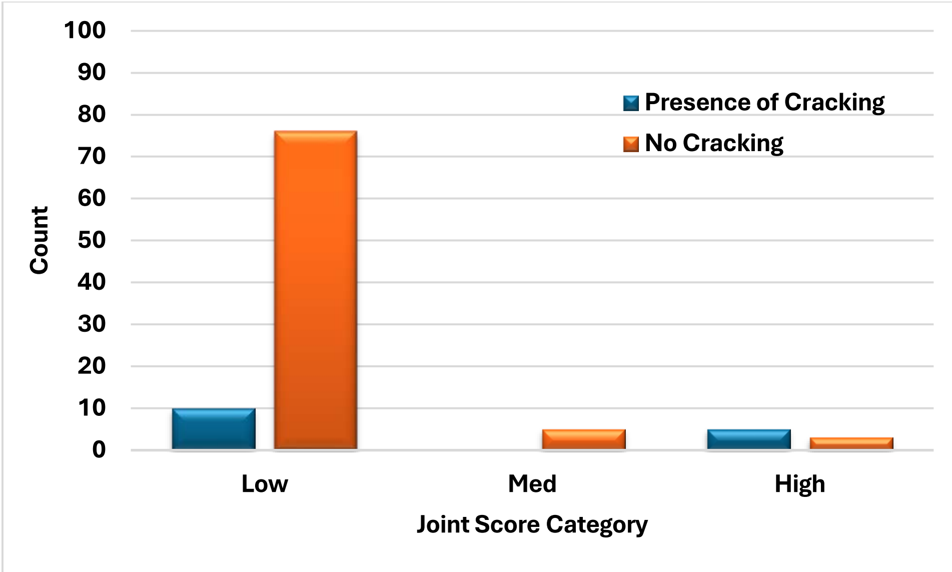

Figure 7140. Joint score and presence of cracking for Fond du Lac WB

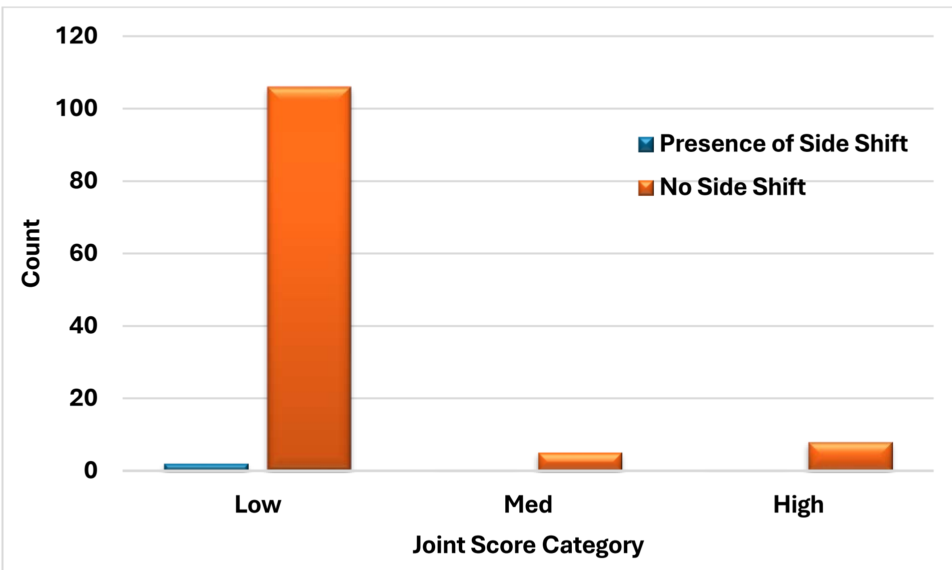

Figure 7241. Joint score and presence of side shift for Fond du Lac WB.

Jefferson EB

Table 25. Details of test sections in Jefferson EB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Jefferson EB	9	1.25	10/24/2023	12

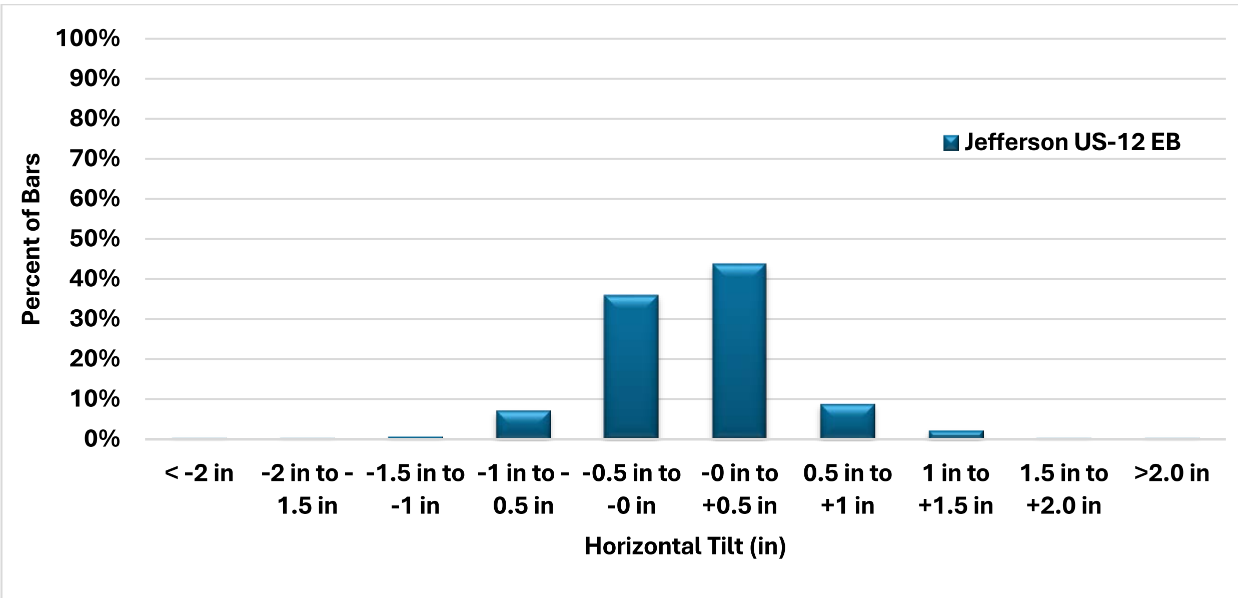

Figure 73. Horizontal Skew distribution for Jefferson EB

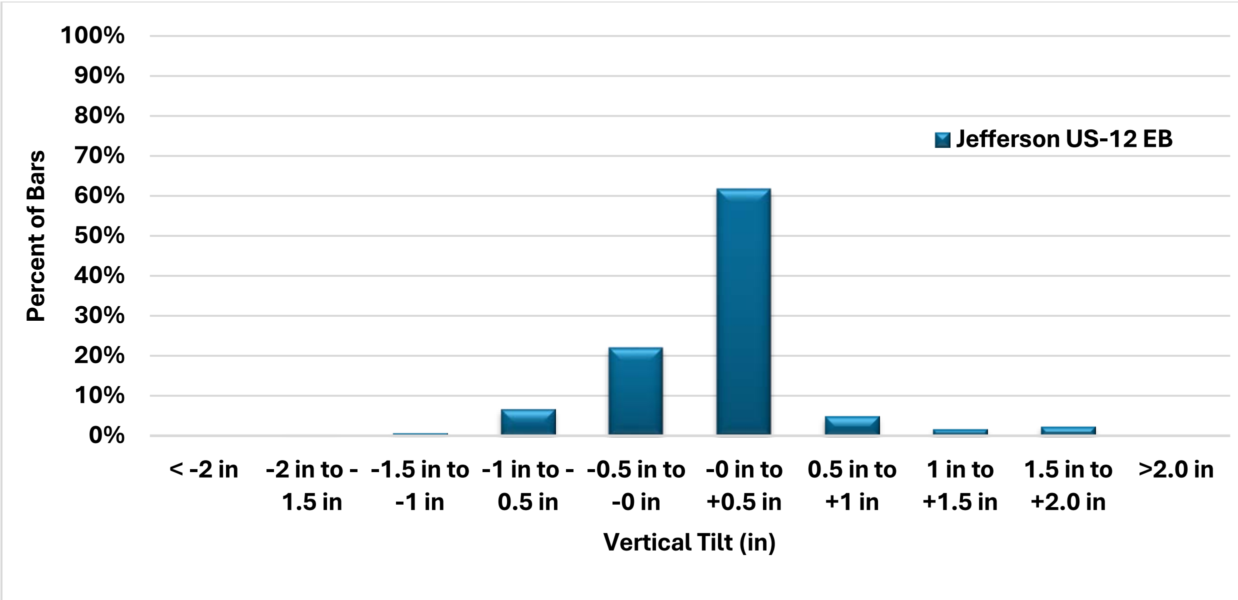

Figure 74. Vertical Tilt distribution for Jefferson EB

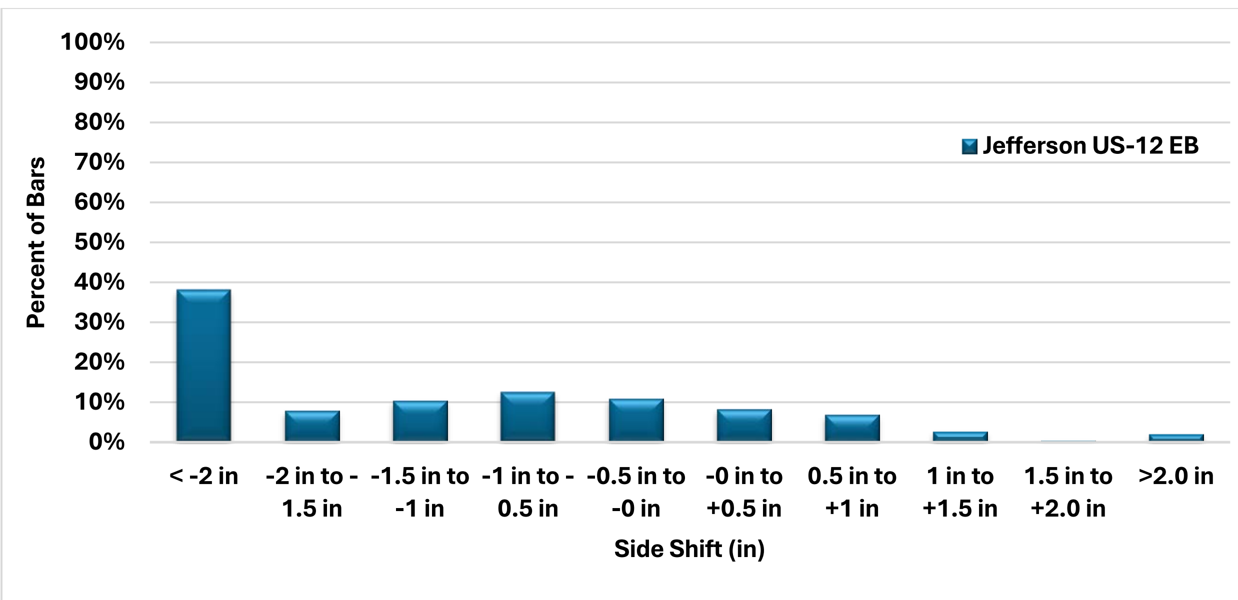

Figure 75. Longitudinal Translation distribution for Jefferson EB

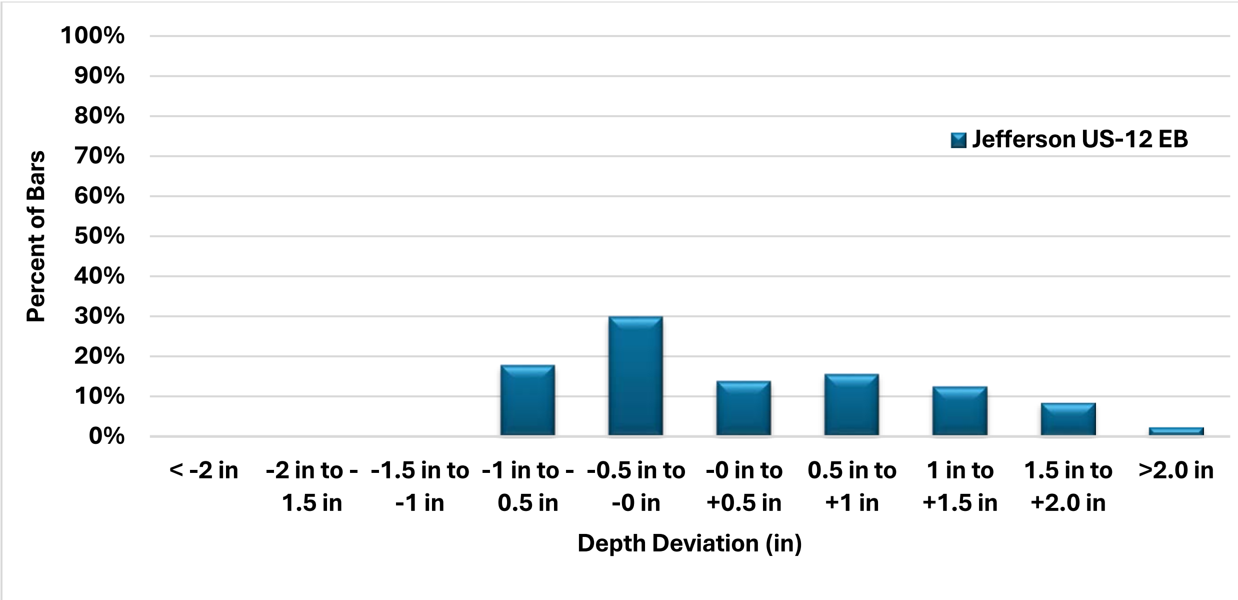

Figure 76. Vertical Translation distribution for Jefferson EB

Table 26. Dowel misalignment summary for Jefferson EB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Jefferson EB	0.03	0.39	0.02	0.37	-1.52	1.29	0.30	0.84

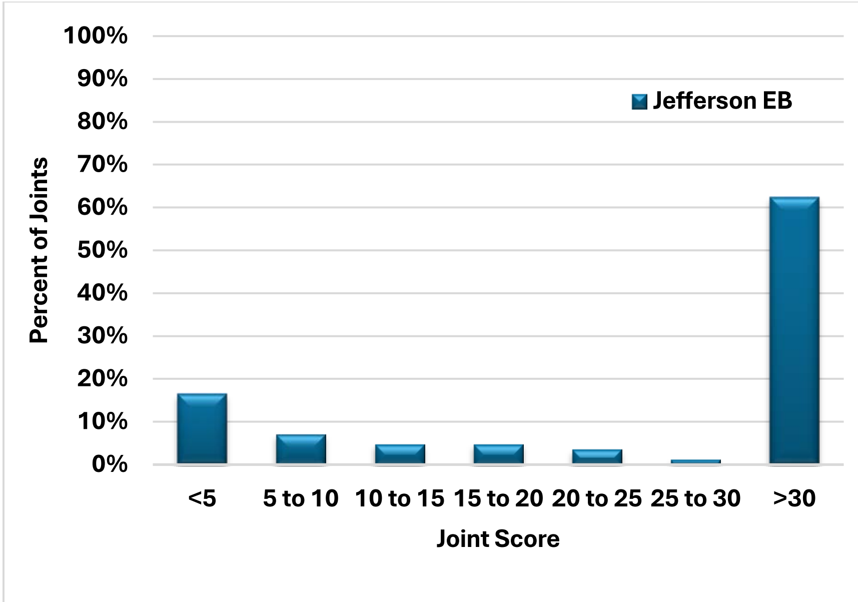

Figure 77. Joint score distribution for Jefferson EB

Table 27. Joint score and effective dowel diameter for Jefferson EB.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Jefferson EB	36.0	36.6	9	1.25	1.172	0.083	6.24

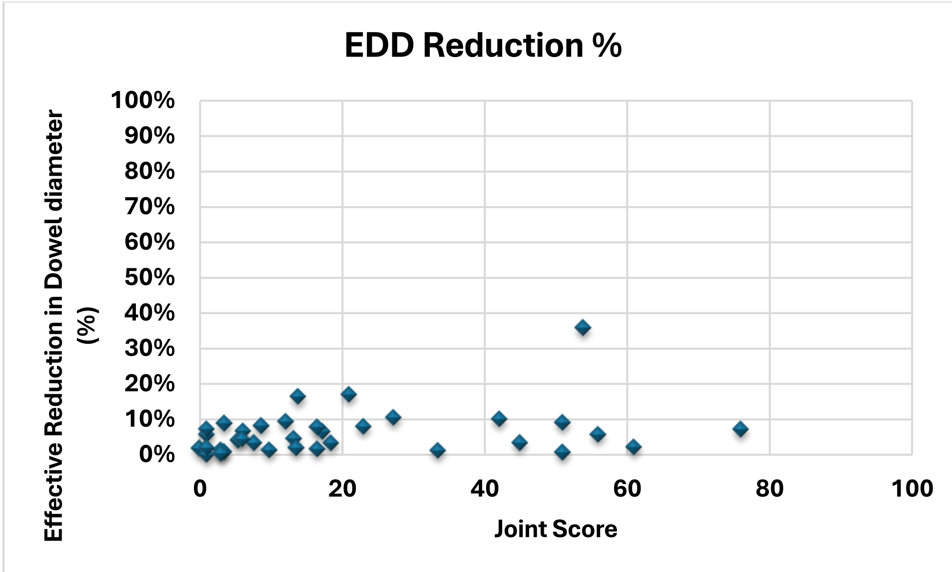

Figure 78. Joint score versus effective reduction in dowel diameter for Jefferson EB

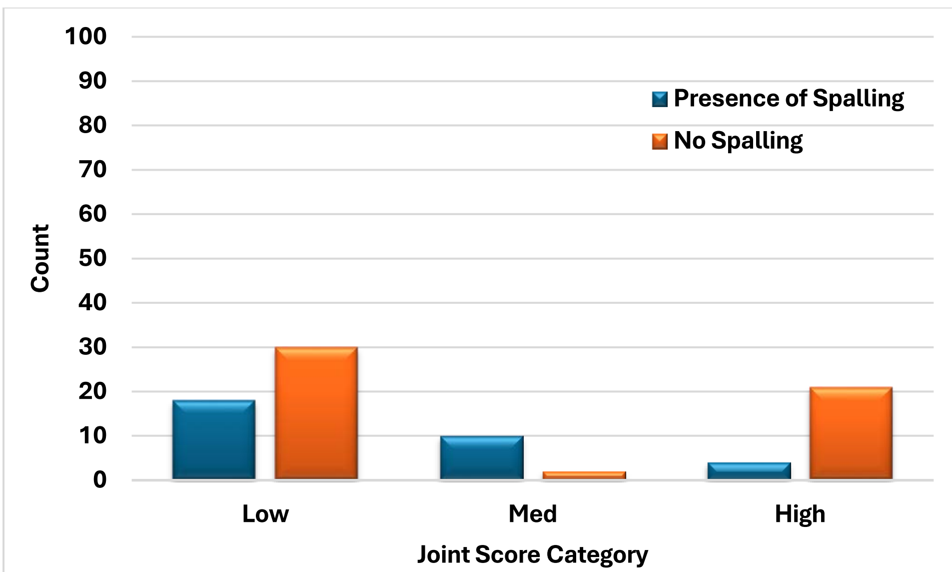

Figure 79. Joint score and presence of spalling for Jefferson EB

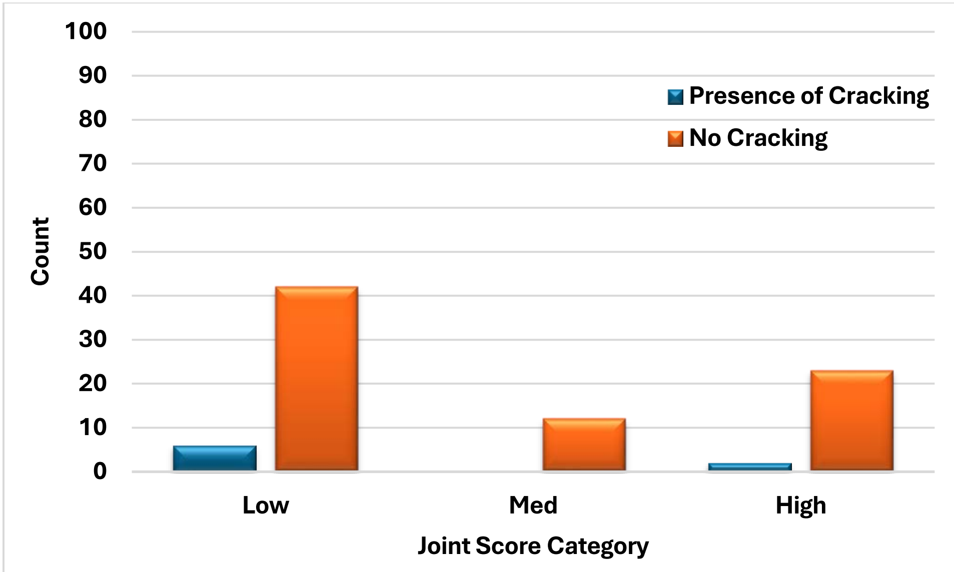

Figure 8042. Joint score and presence of cracking for Jefferson EB

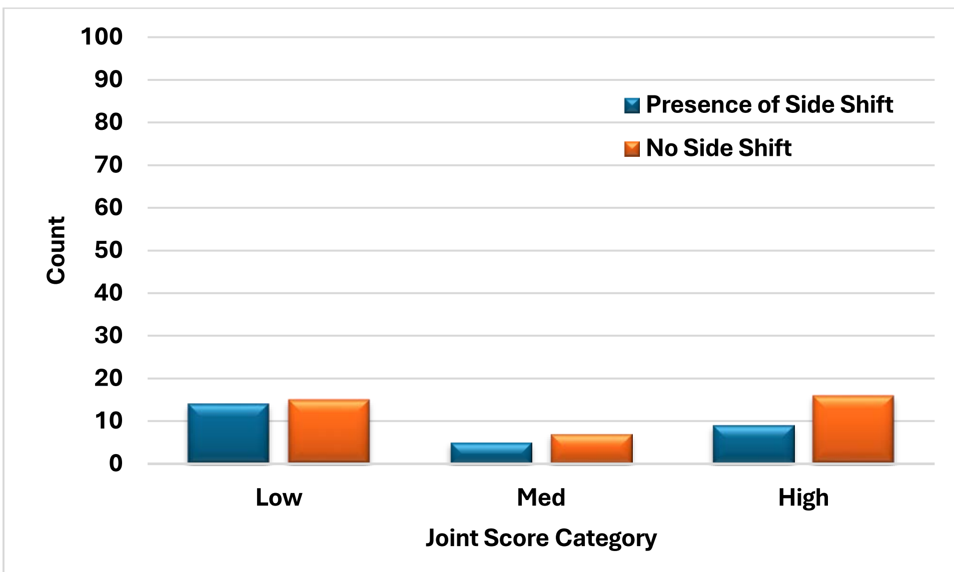

Figure 8143. Joint score and presence of side shift for Jefferson EB.

Jefferson WB

Table 28. Details of test sections in Jefferson WB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Jefferson WB	9	1.25	10/24/2023	12

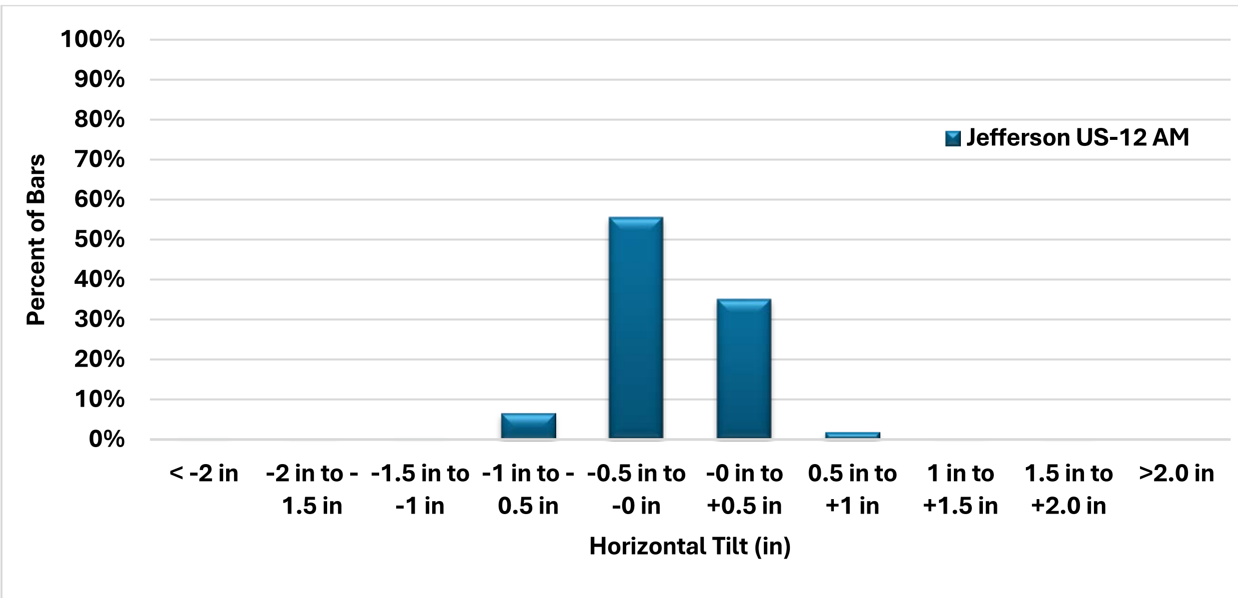

Figure 82. Horizontal Skew distribution for Jefferson WB

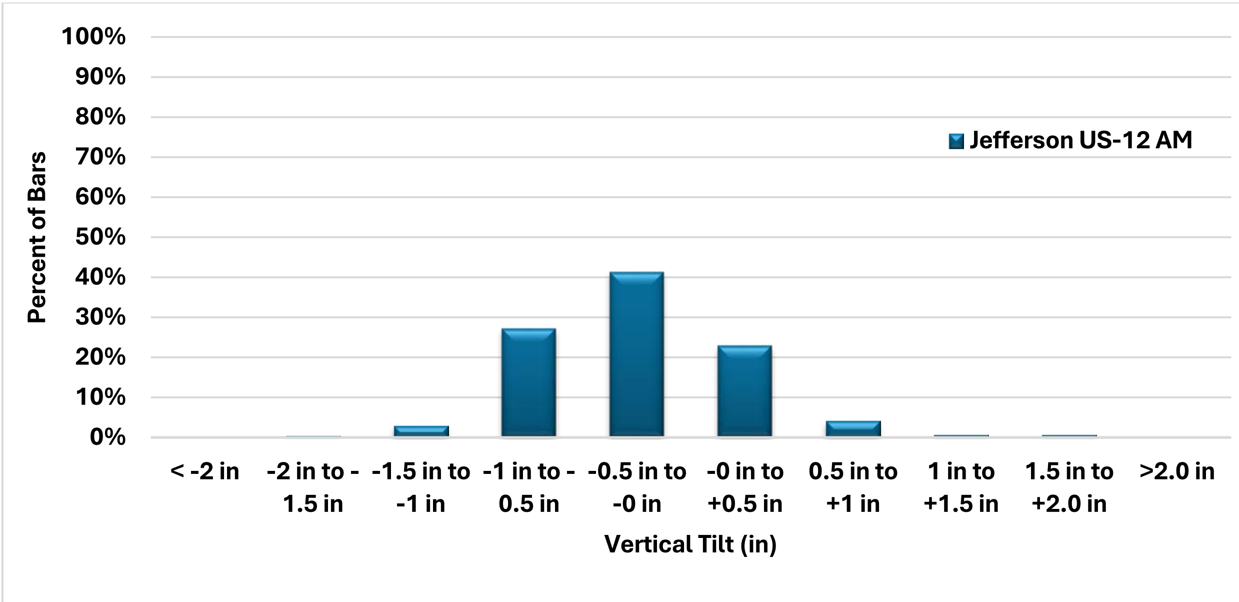

Figure 83. Vertical Tilt distribution for Jefferson WB

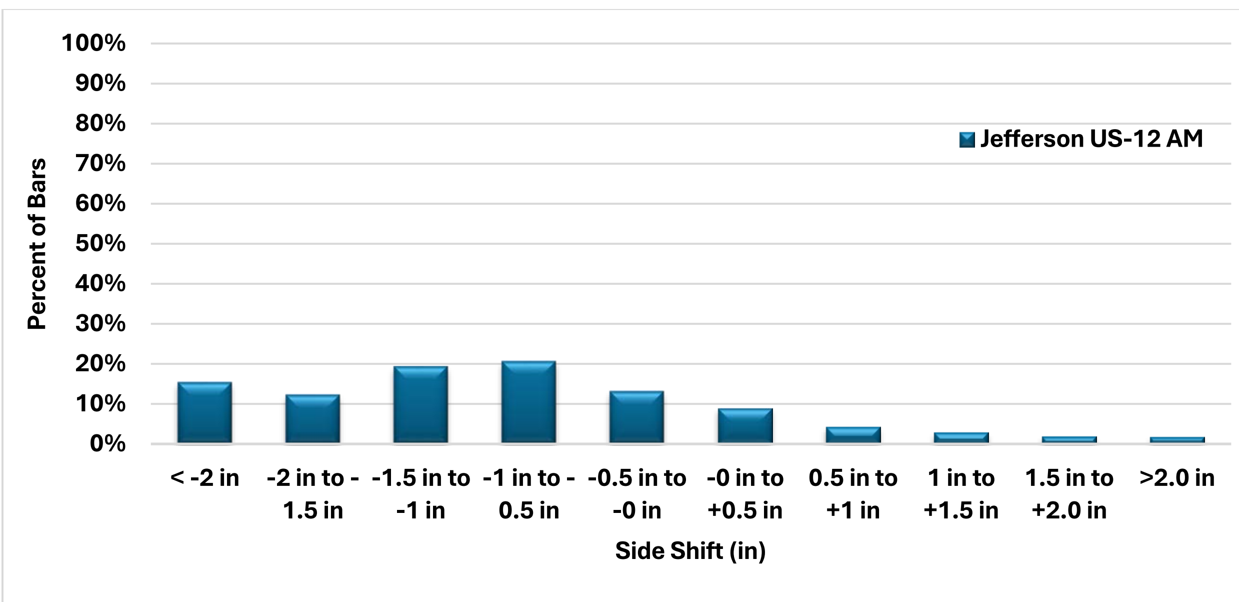

Figure 84. Longitudinal Translation distribution for Jefferson WB

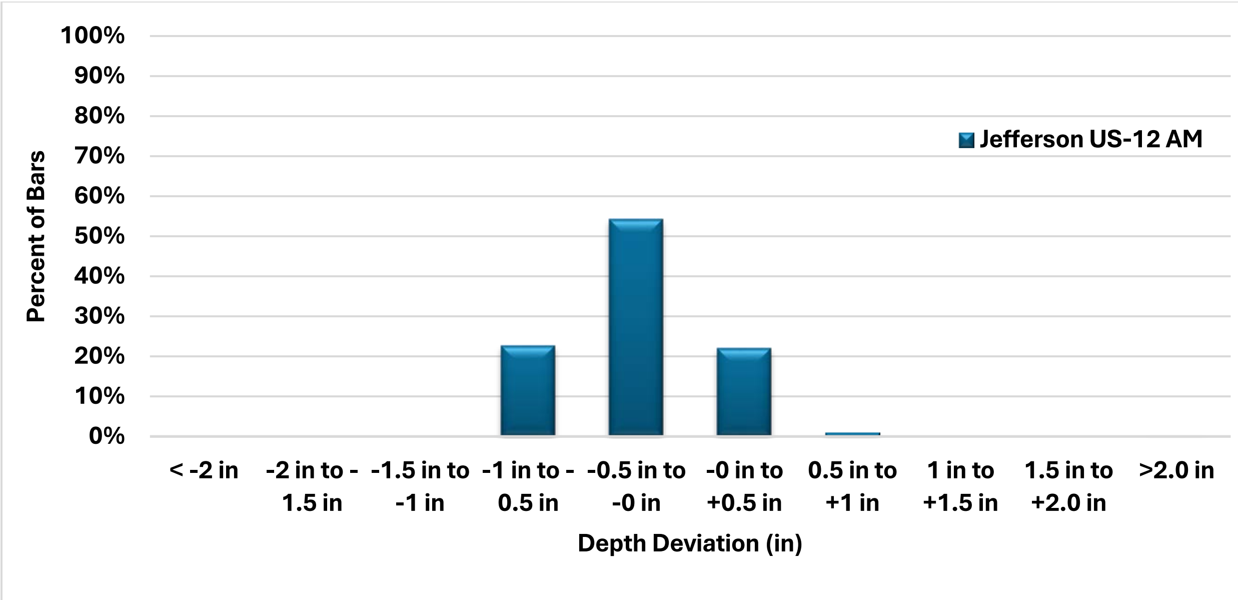

Figure 85. Vertical Translation distribution for Jefferson WB

Table 29. Dowel misalignment summary for Jefferson WB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Jefferson WB	-0.10	0.23	-0.24	0.31	-0.87	0.86	-0.25	0.36

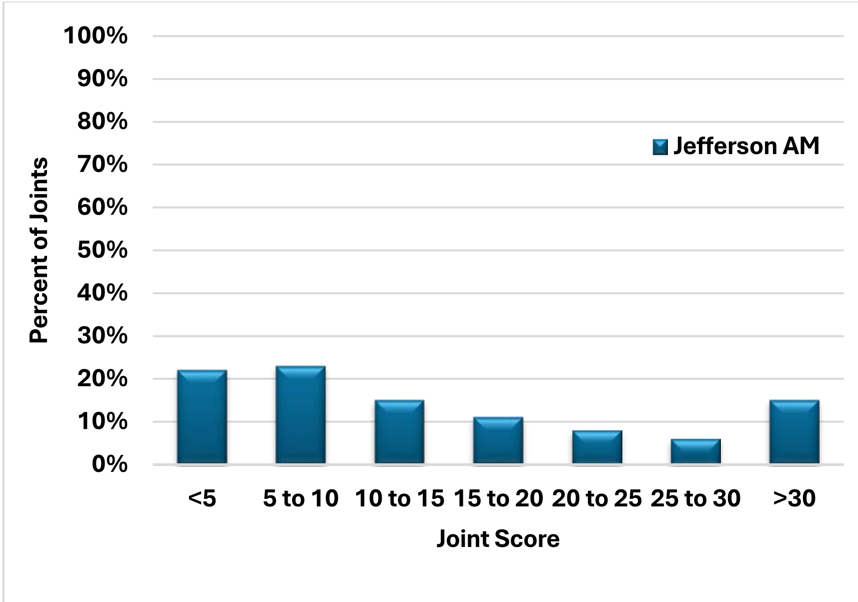

Figure 86. Joint score distribution for Jefferson WB

Table 30. Joint score and effective dowel diameter for Jefferson WB.

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Jefferson WB	15.9	18.2	9	1.25	1.206	0.041	3.52

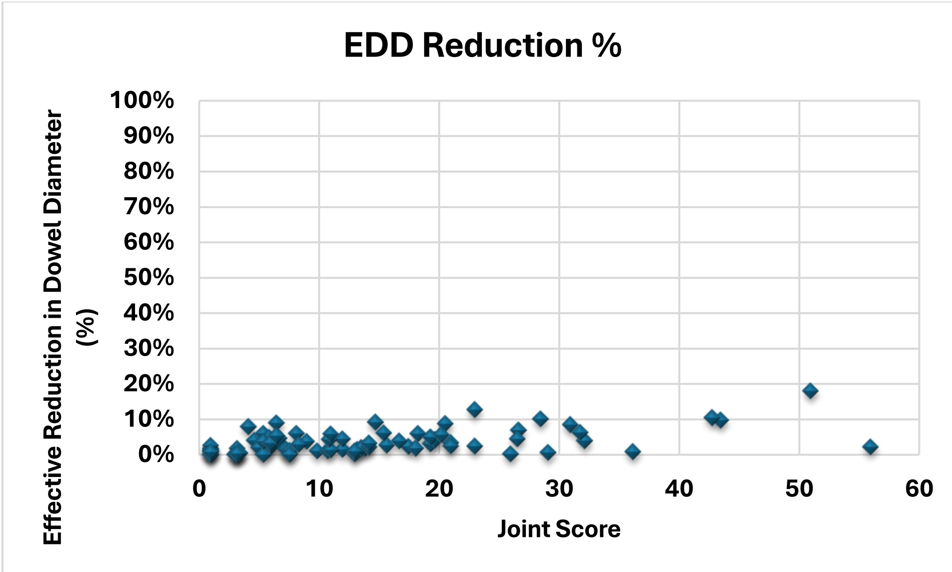

Figure 87. Joint score versus effective reduction in dowel diameter for Jefferson WB

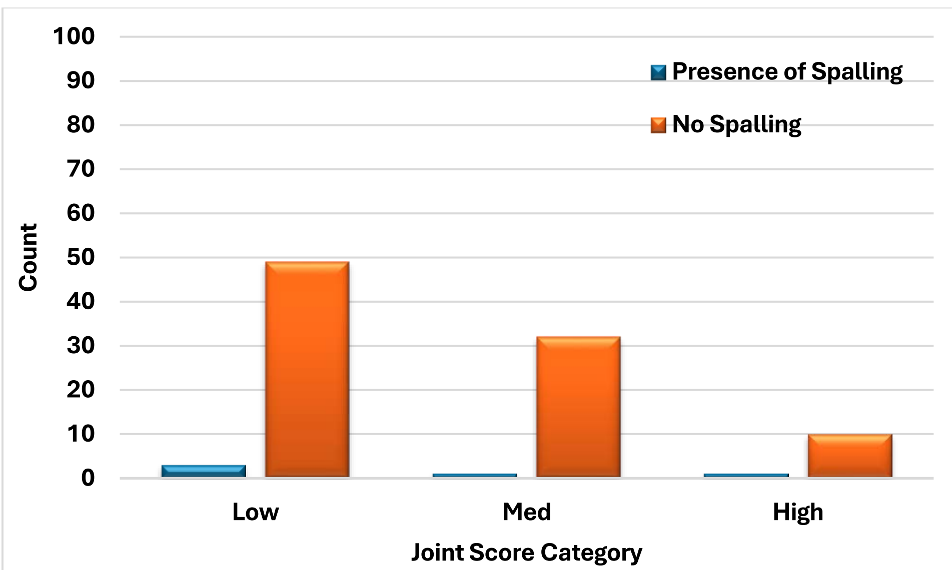

Figure 88. Joint score and presence of spalling for Jefferson WB

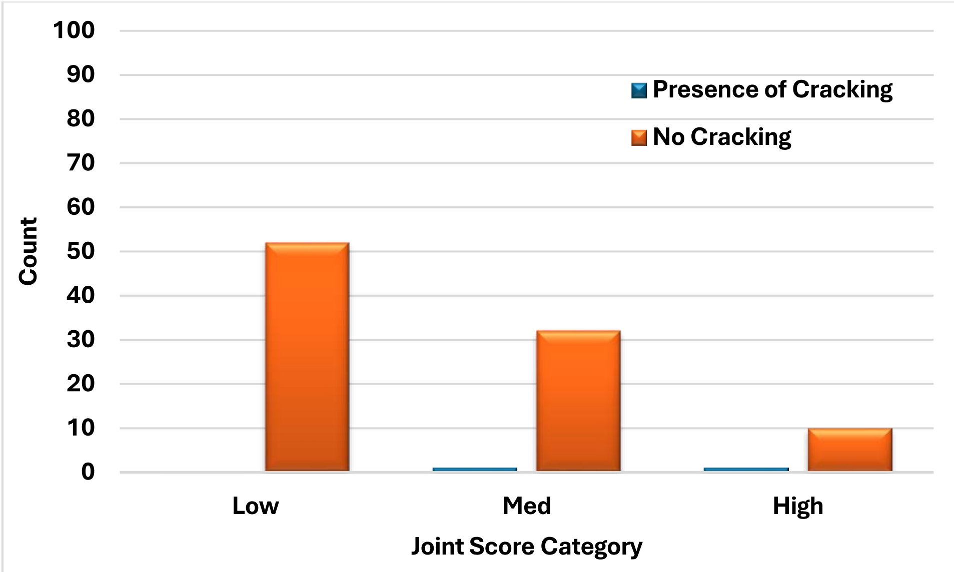

Figure 8944. Joint score and presence of cracking for Jefferson WB

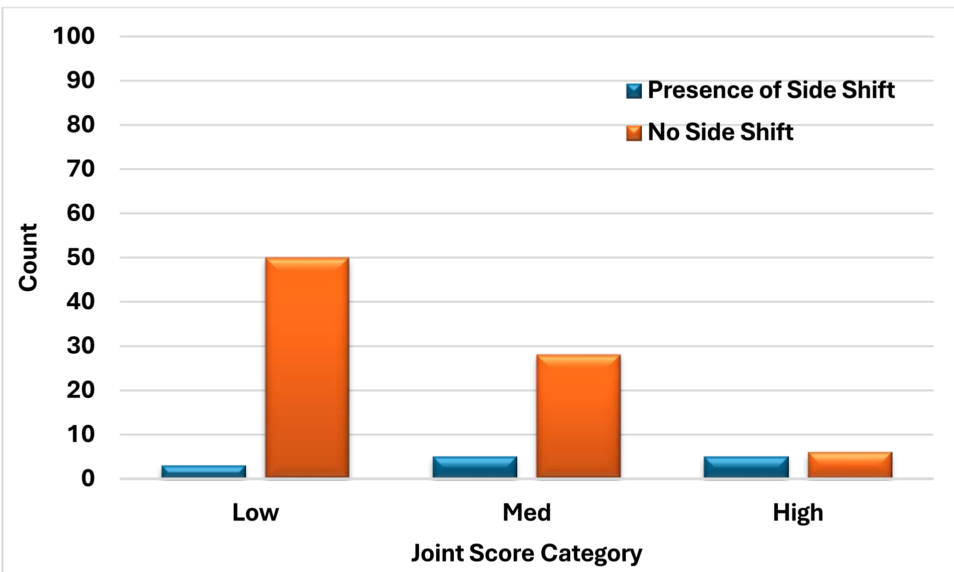

Figure 9045. Joint score and presence of side shift for Jefferson WB

Rock NB

Table 31. Details of test sections in Rock NB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Rock NB	9	1.25	10/25/2023	11

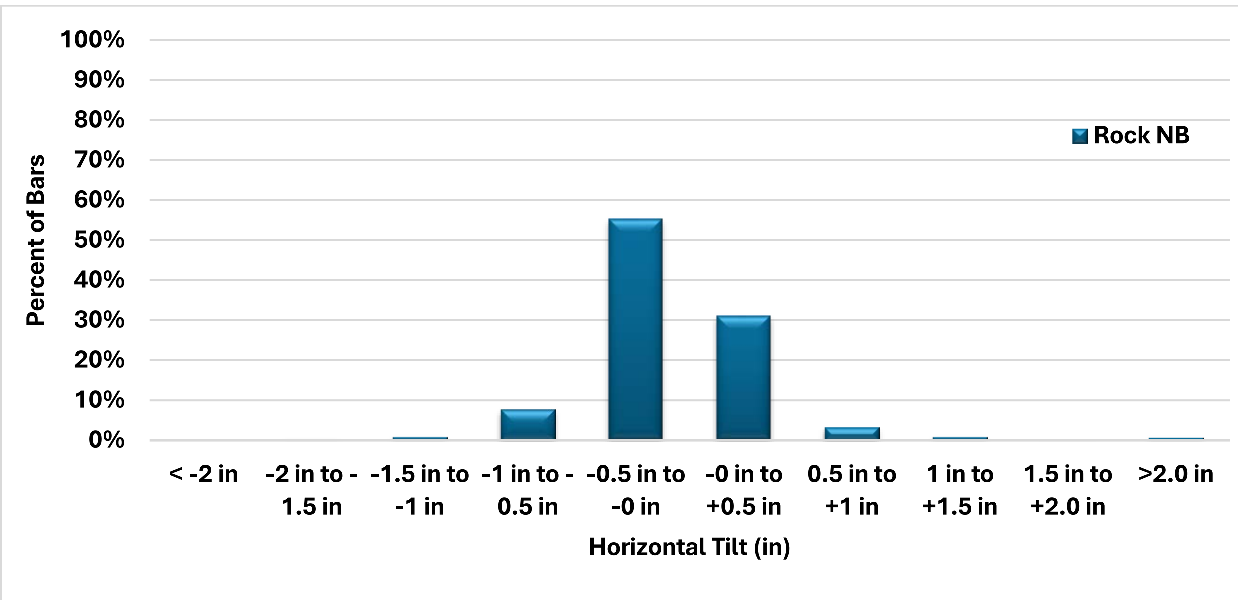

Figure 91. Horizontal Skew distribution for Rock NB

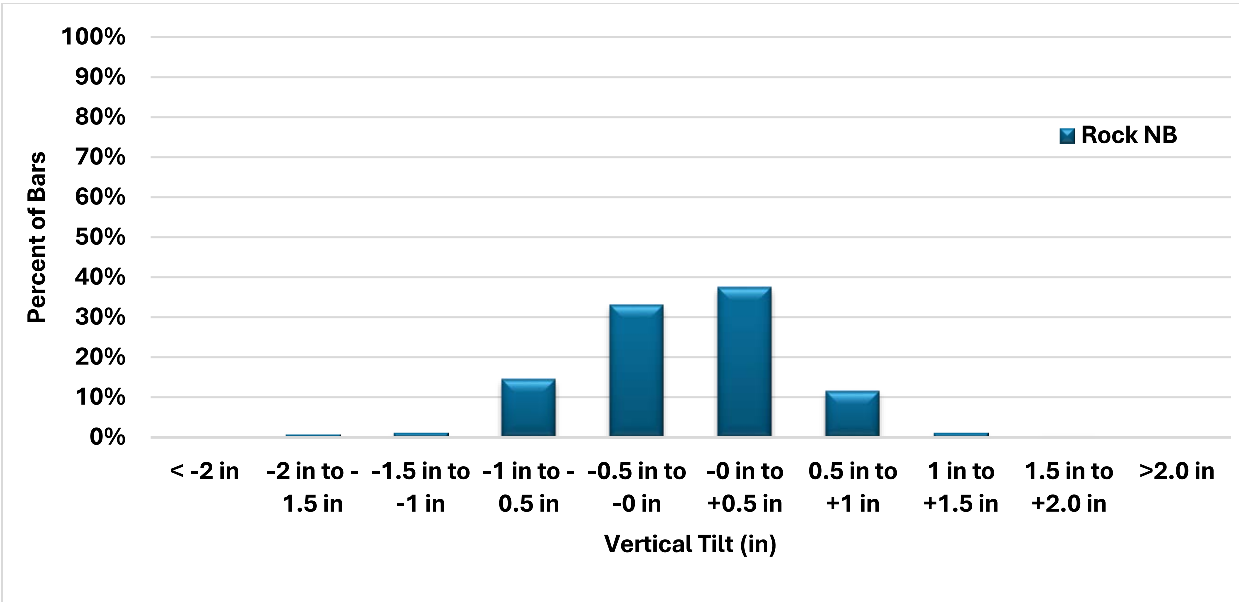

Figure 92. Vertical Tilt distribution for Rock NB

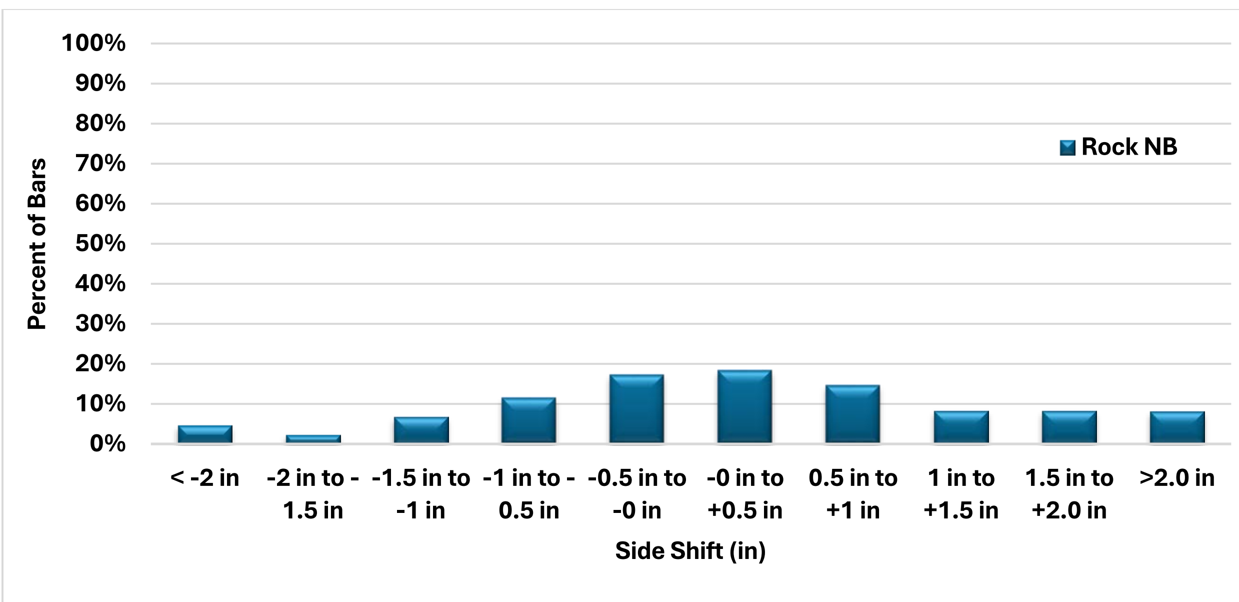

Figure 93. Longitudinal Translation distribution for Rock NB

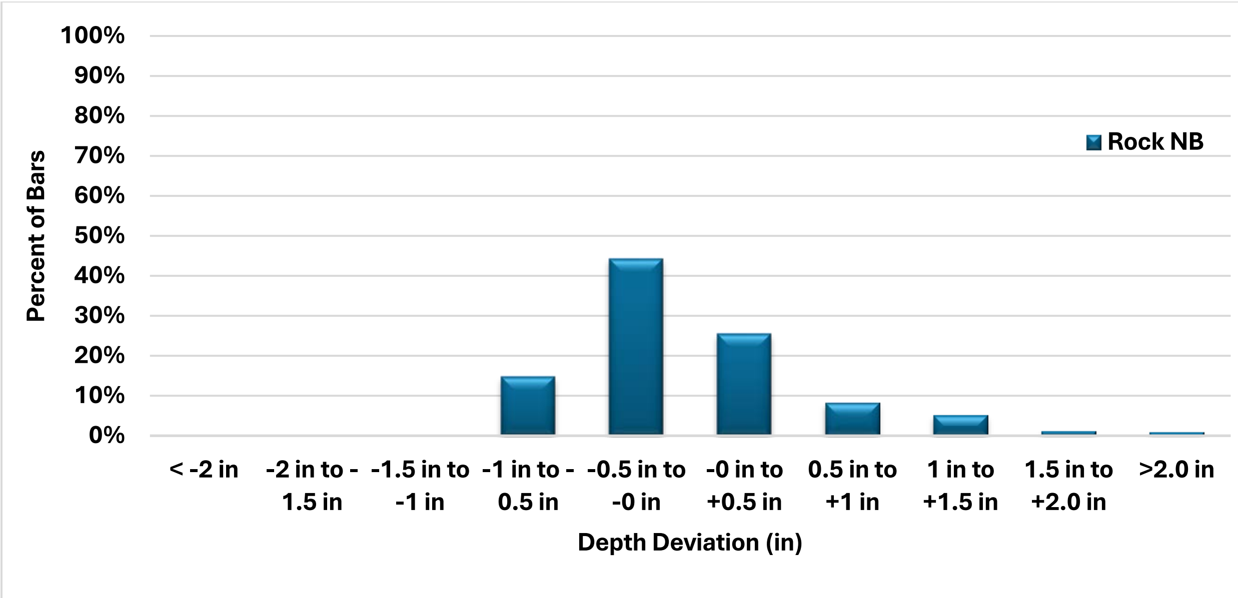

Figure 94. Vertical Translation distribution for Rock NB

Table 32. Dowel misalignment summary for Rock NB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Rock NB	-0.0910	0.30	-0.04	0.30	0.21	0.90	0.01	0.57

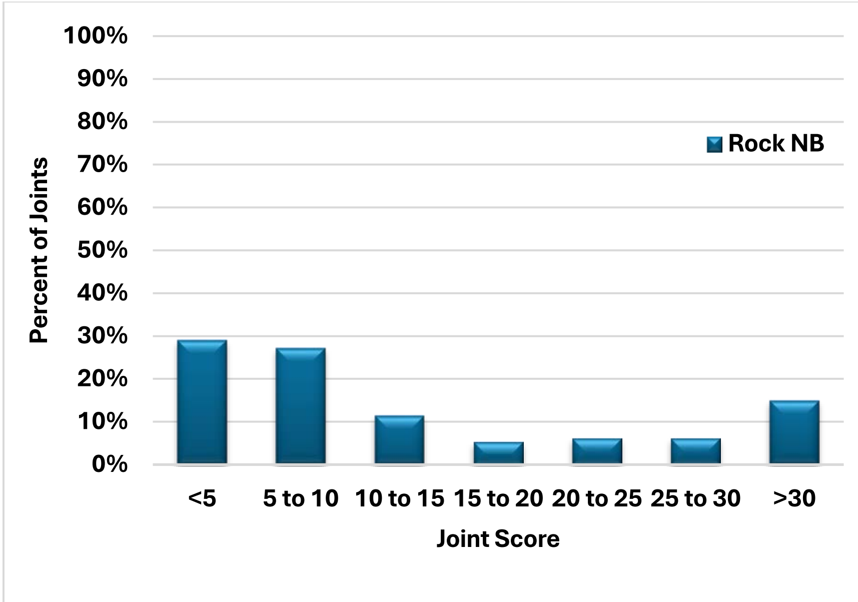

Figure 95. Joint score distribution for Rock NB

Table 33. Joint score and effective dowel diameter for Rock NB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Rock NB	14.0	16.9	9	1.25	1.197	0.13	4.24

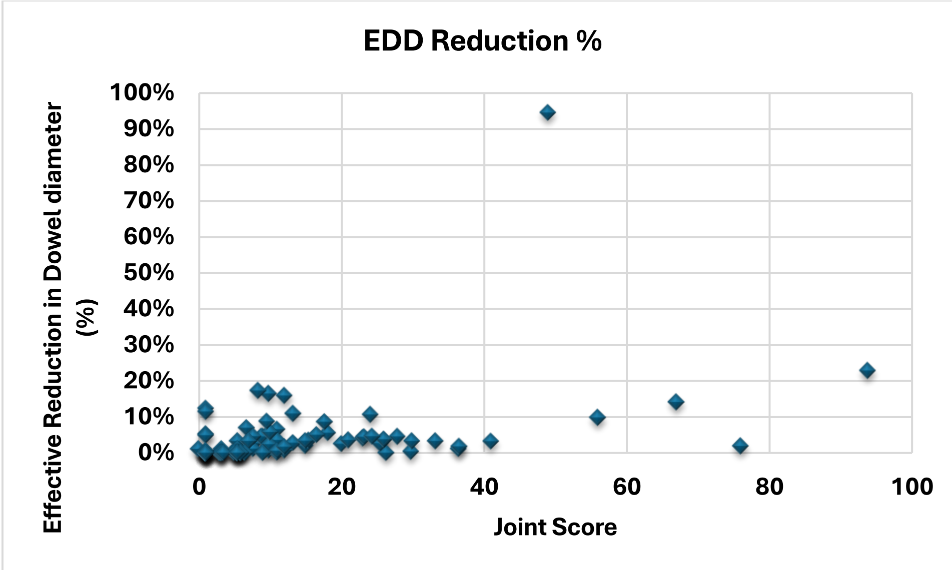

Figure 96. Joint score versus effective reduction in dowel diameter for Rock NB

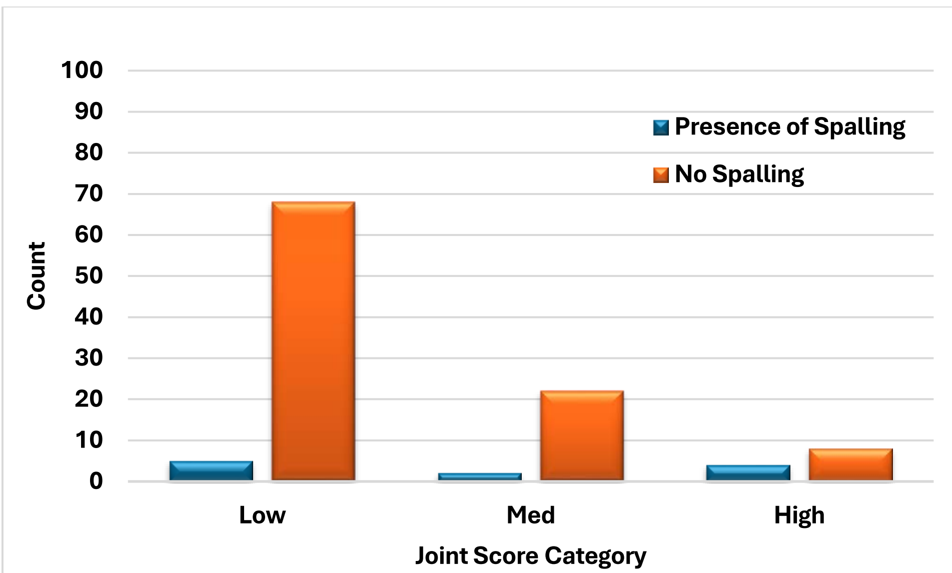

Figure 97. Joint score and presence of spalling for Rock NB

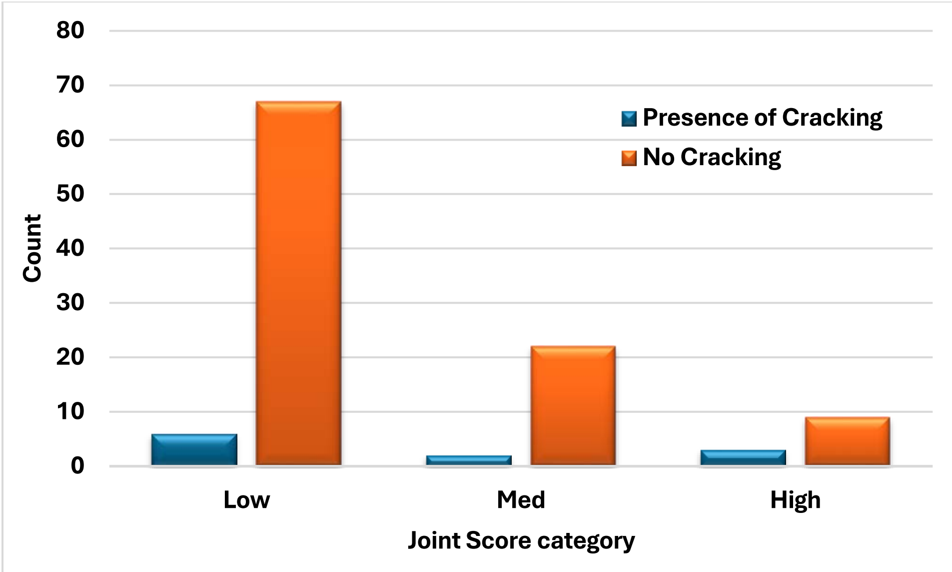

Figure 9846. Joint score and presence of cracking for Rock NB

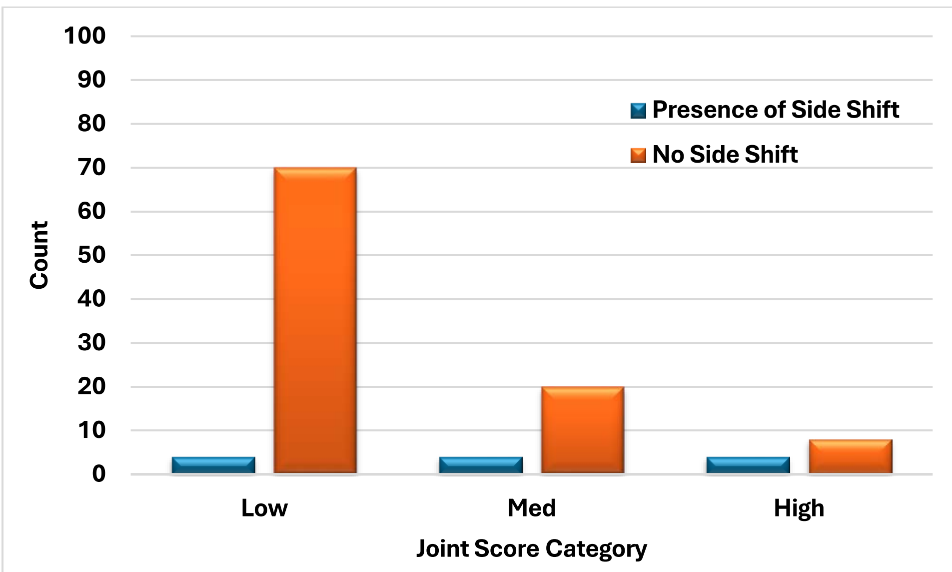

Figure 9947. Joint score and presence of side shift for Rock NB

Rock WB

Table 34. Details of test sections in Rock WB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
Rock WB	9	1.25	10/25/2023	11

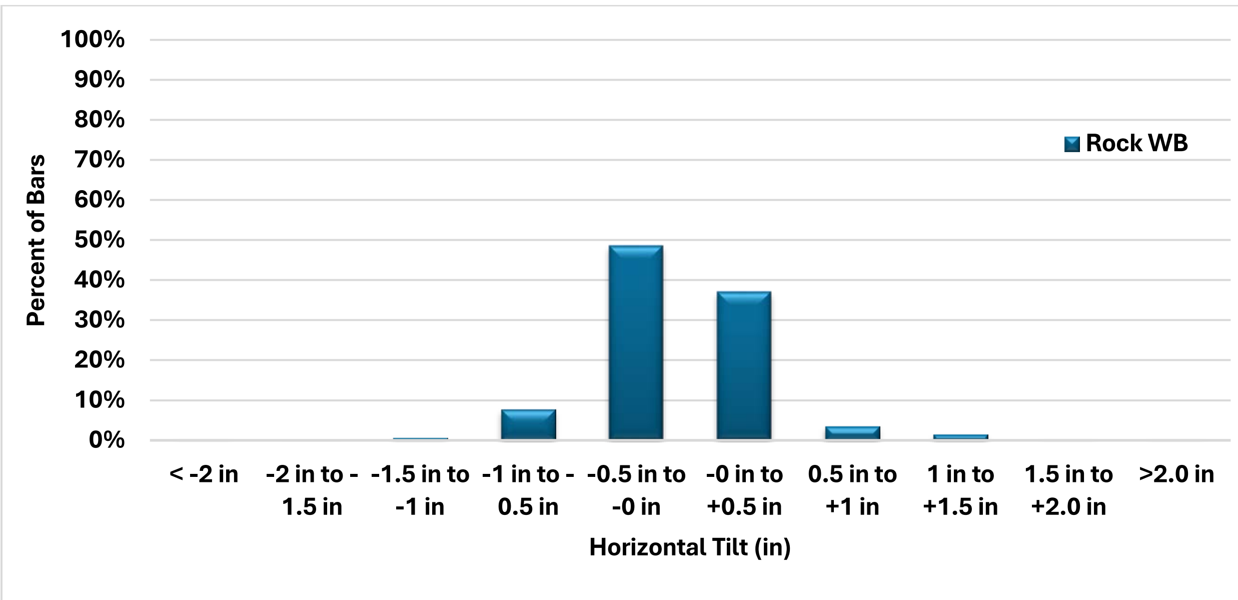

Figure 100. Horizontal Skew distribution for Rock WB

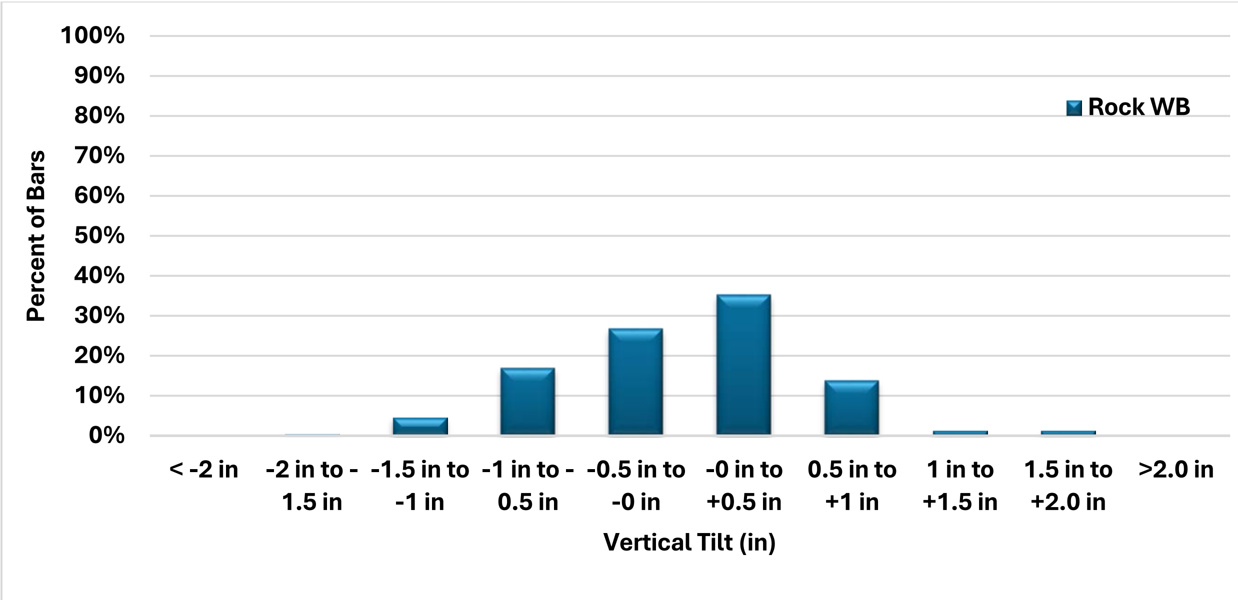

Figure 101. Vertical Tilt distribution for Rock WB

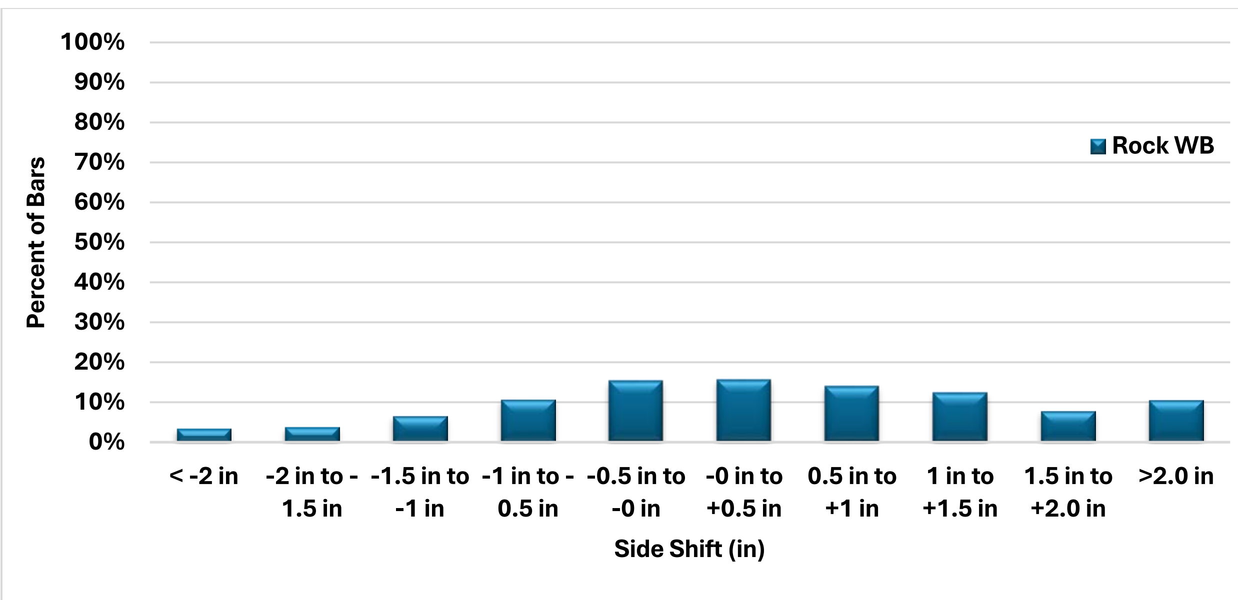

Figure 102. Longitudinal Translation distribution for Rock NB

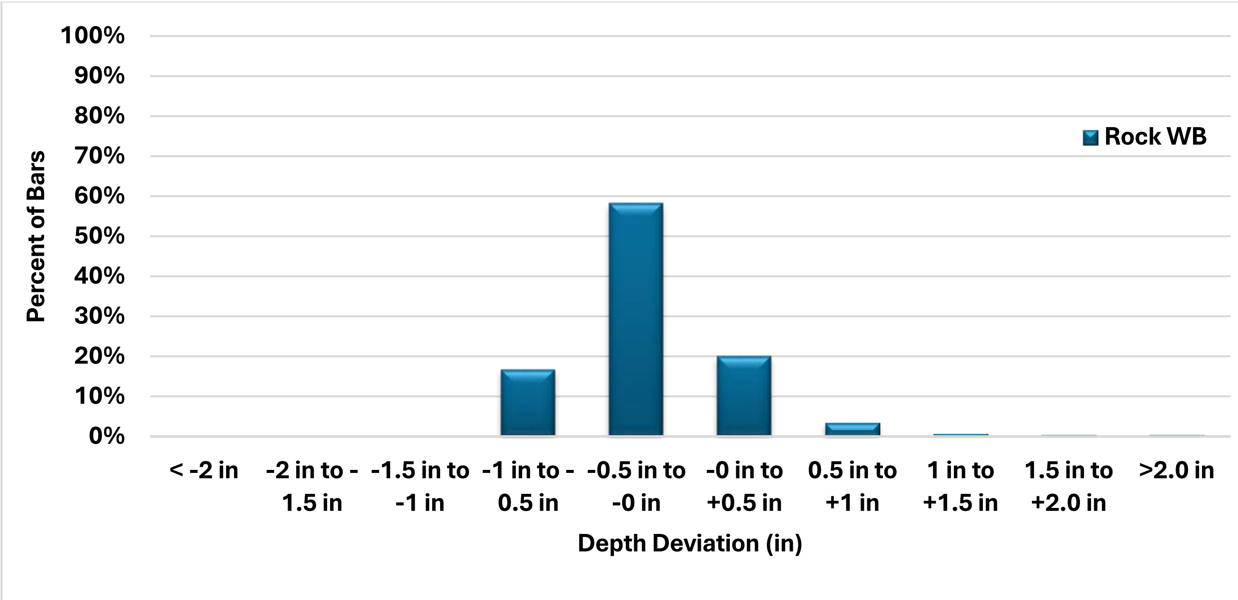

Figure 103. Vertical Translation distribution for Rock WB

Table 35. Dowel misalignment summary for Rock WB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Rock WB	-0.06	0.29	-0.04	0.35	0.34	0.86	-0.16	0.42

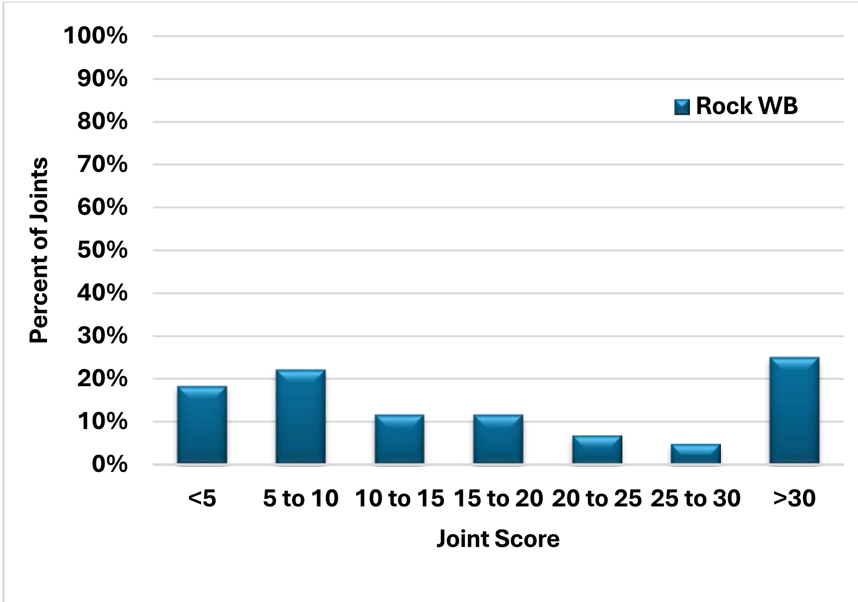

Figure 104. Joint score distribution for Rock WB

Table 36. Joint score and effective dowel diameter for Rock WB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
Rock WB	17.3	14.9	9	1.25	1.196	0.092	4.32

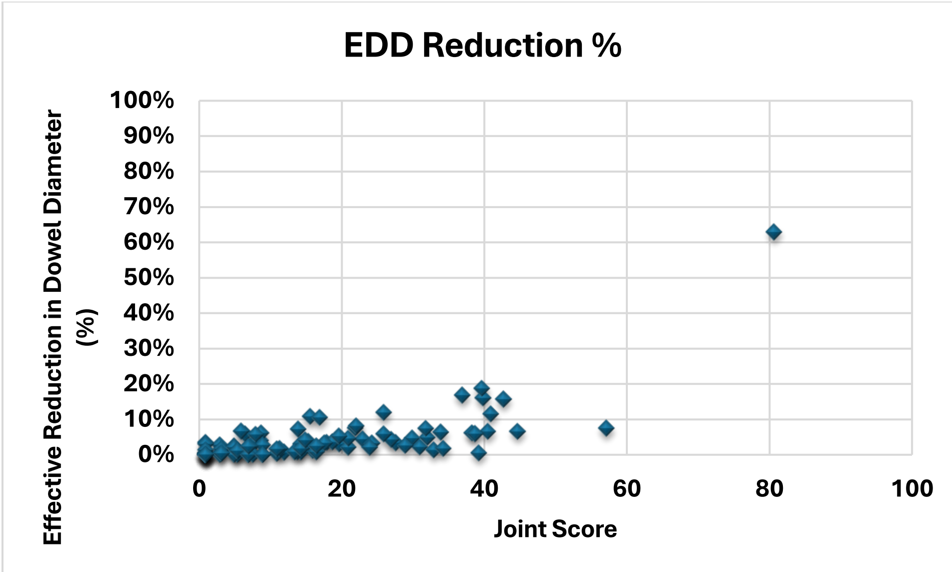

Figure 105. Joint score versus effective reduction in dowel diameter for Rock WB

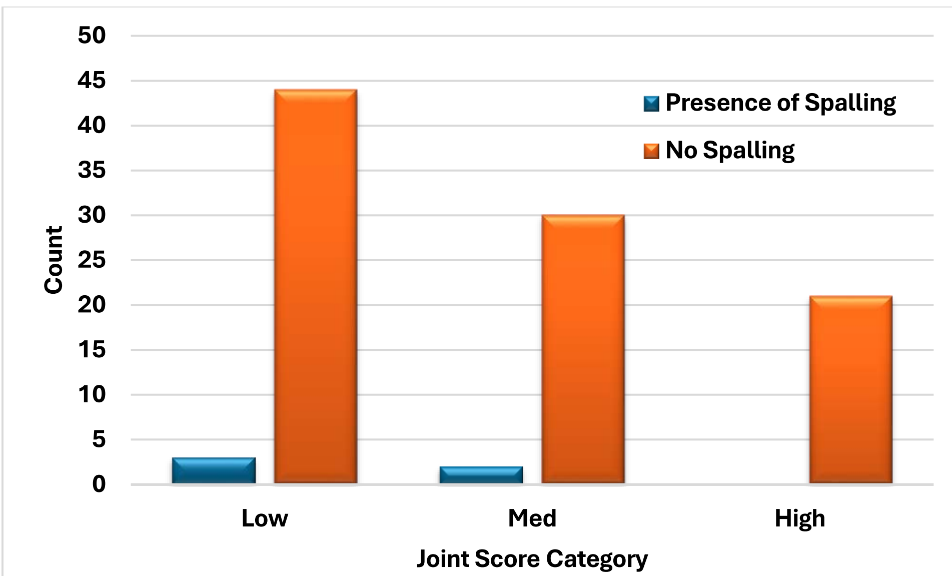

Figure 106. Joint score and presence of spalling for Rock WB

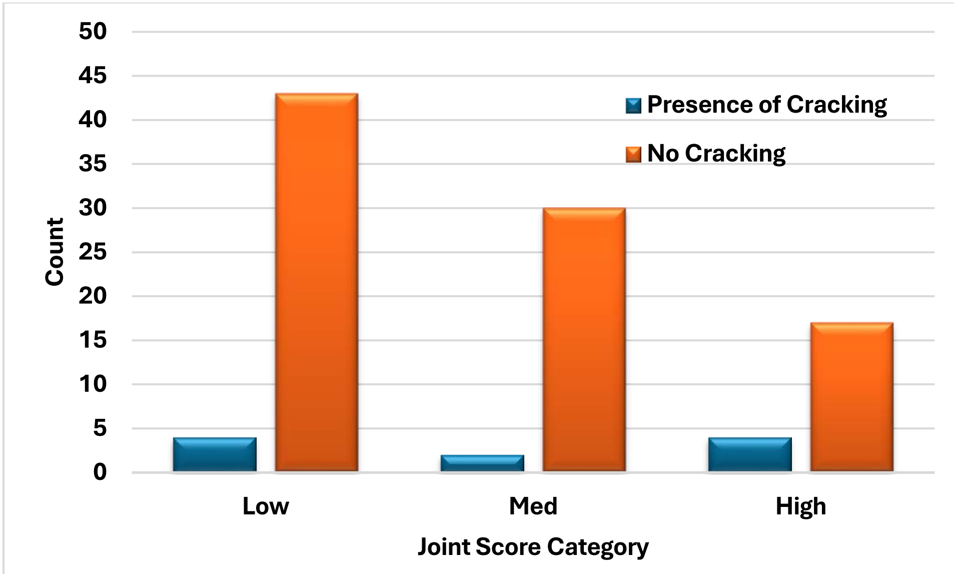

Figure 10748. Joint score and presence of cracking for Rock WB

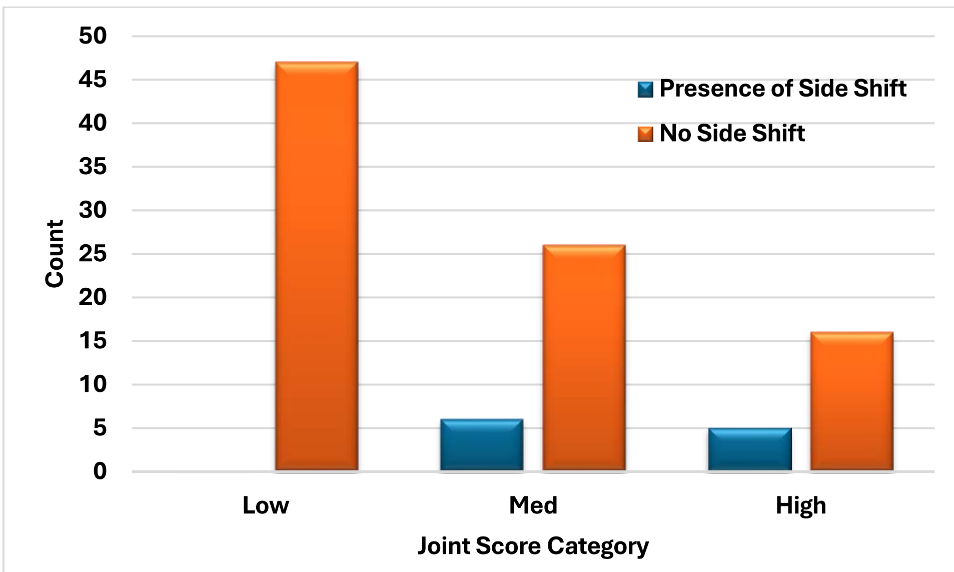

Figure 10849. Joint score and presence of side shift for Rock WB

STH 82 EB

Table 37. Details of test sections in STH 82 EB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
STH 82 EB	10	1.25		12

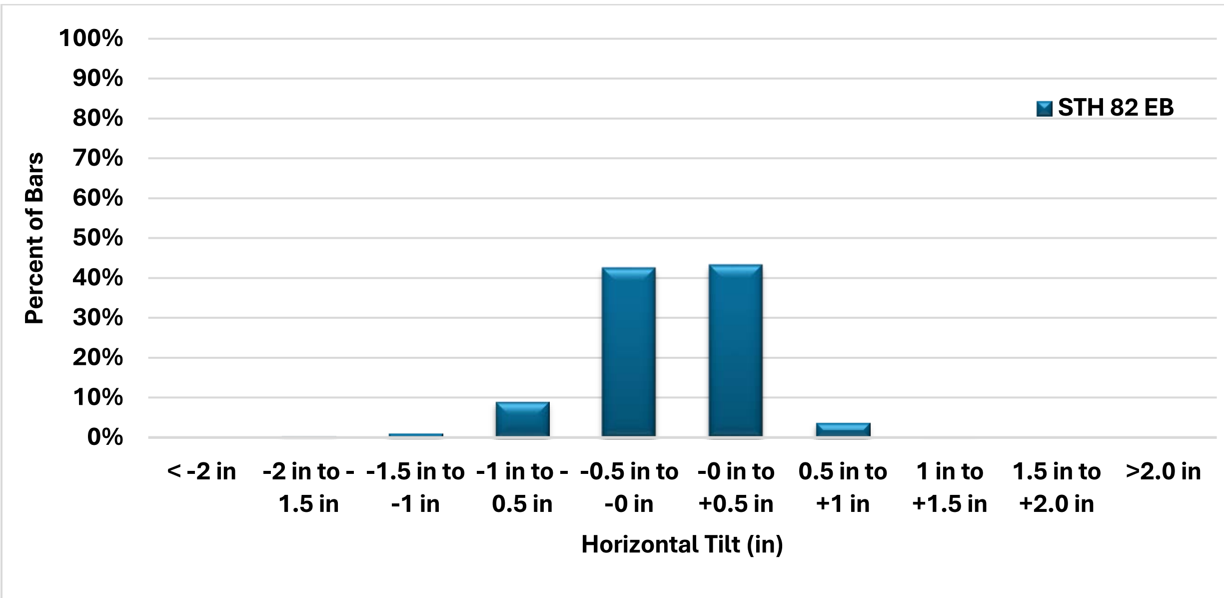

Figure 109. Horizontal Skew distribution for STH 82 EB

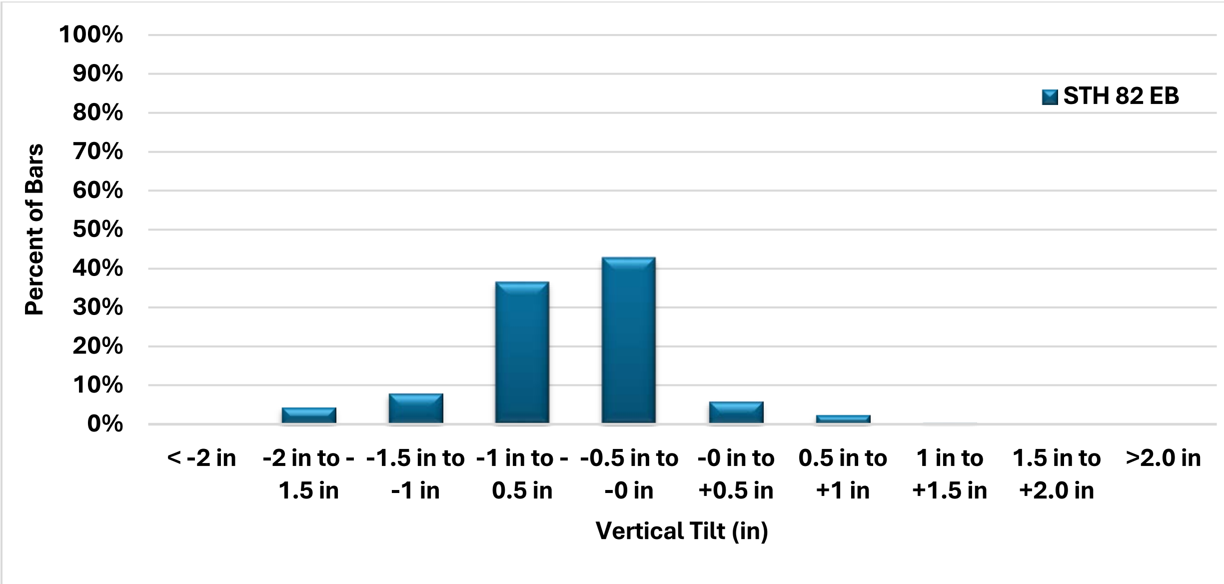

Figure 110. Vertical Tilt distribution for STH 82 EB

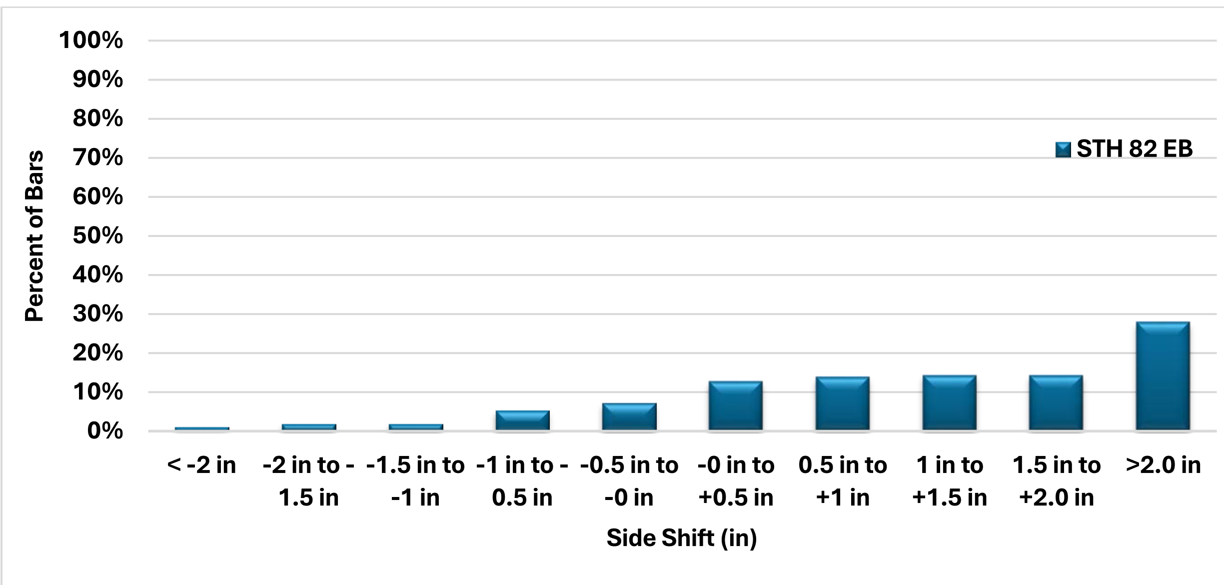

Figure 111. Longitudinal Translation distribution for STH 82 EB

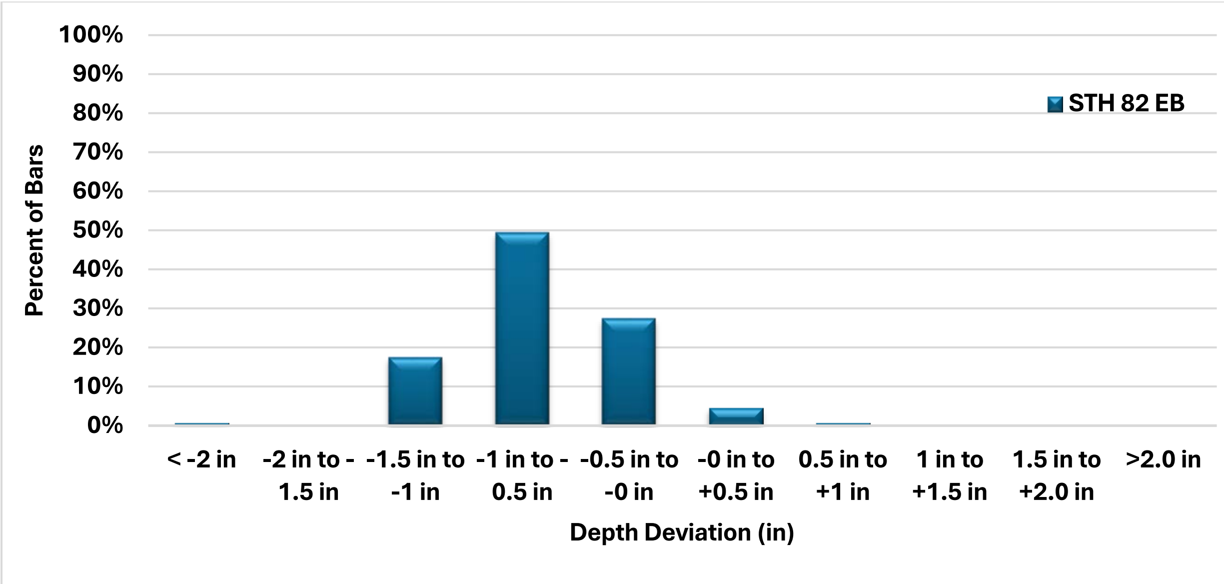

Figure 112. Vertical Translation distribution for STH 82 EB

Table 38. Dowel misalignment summary for STH 82 EB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
STH 82 EB	-0.06	0.24	-0.52	0.38	1.28	1.12	-0.68	0.52

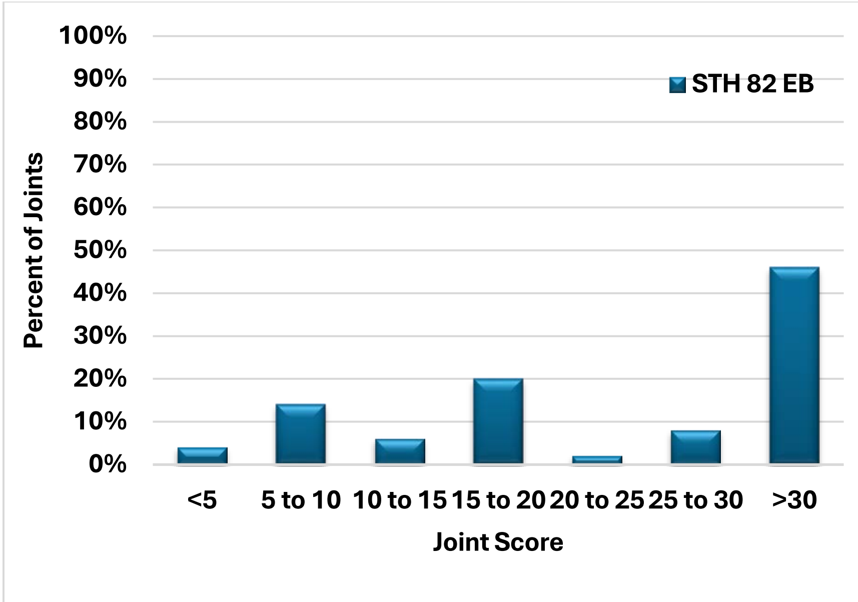

Figure 113. Joint score distribution for STH 82 EB

Table 39. Joint score and effective dowel diameter for STH 82 EB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
STH 82 EB	31.0	20.31	10	1.25	1.221	0.031	2.32

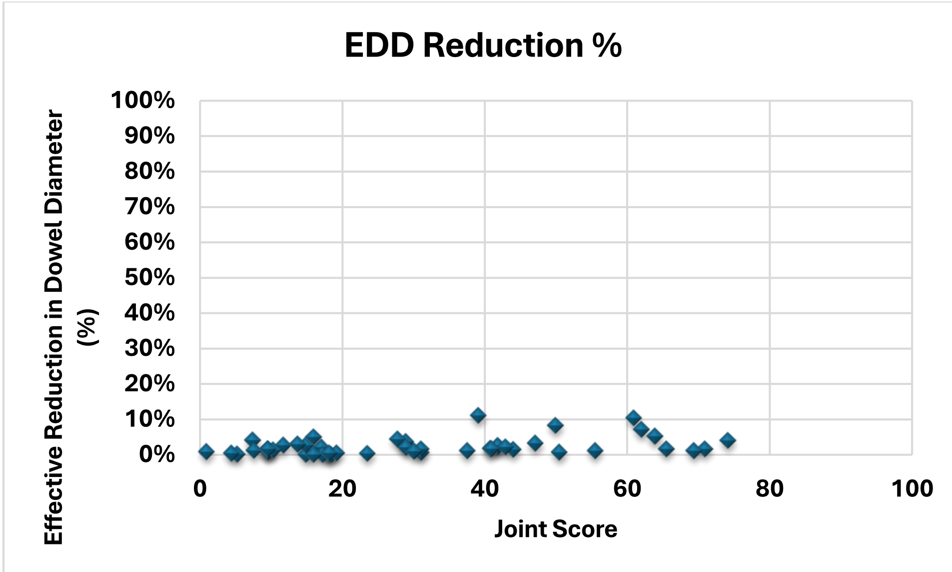

Figure 114. Joint score versus effective reduction in dowel diameter for STH 82 EB

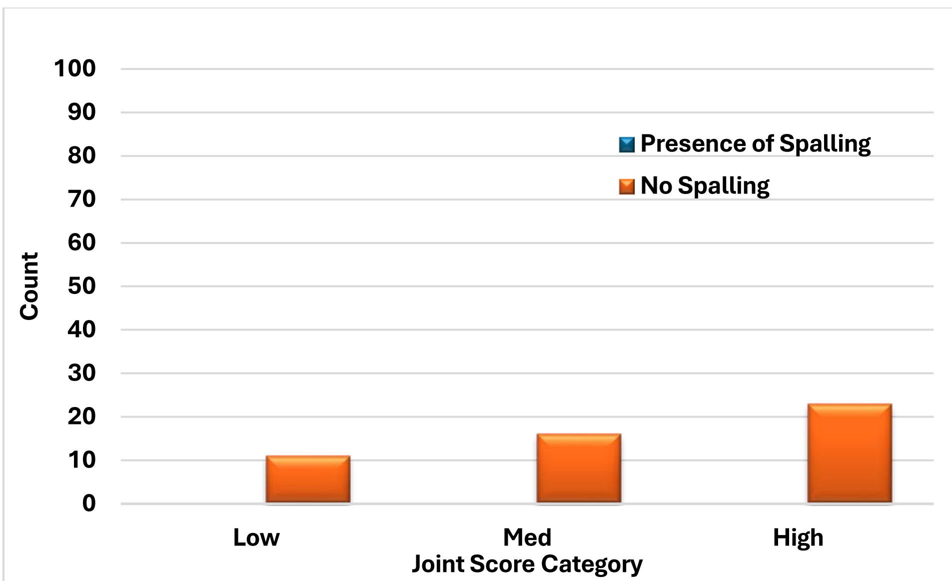

Figure 115. Joint score and presence of spalling for STH 82 EB

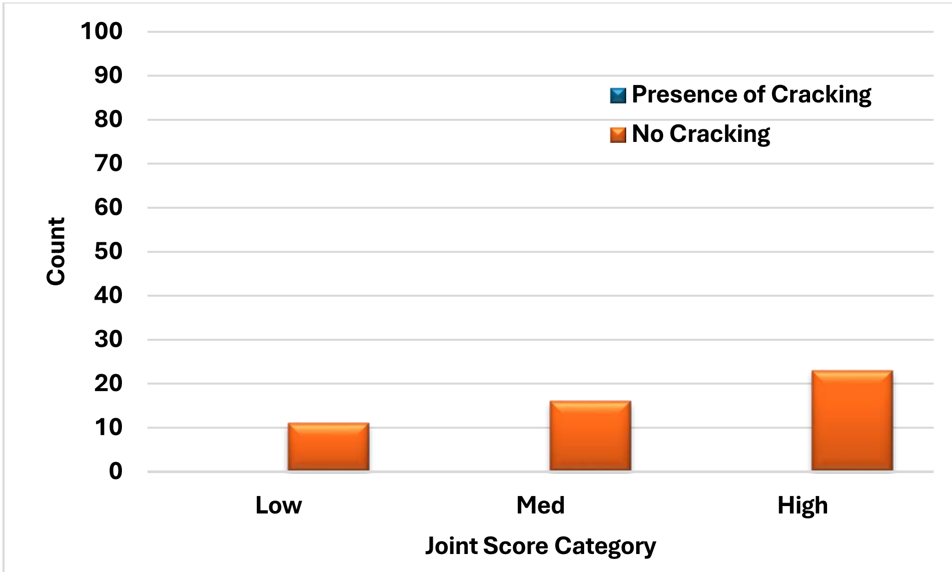

Figure 11650. Joint score and presence of cracking for STH 82 EB

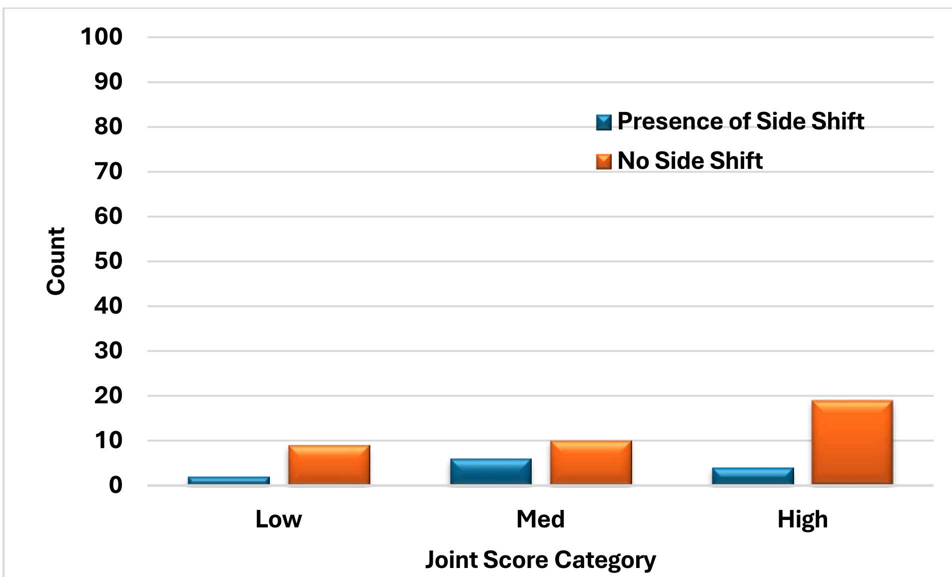

Figure 11751. Joint score and presence of side shift for STH 82 EB

STH 82 EB 5_25

Table 40. Details of test sections in STH 82 EB 5_25

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
STH 82 EB 5_25	10	1.25		12

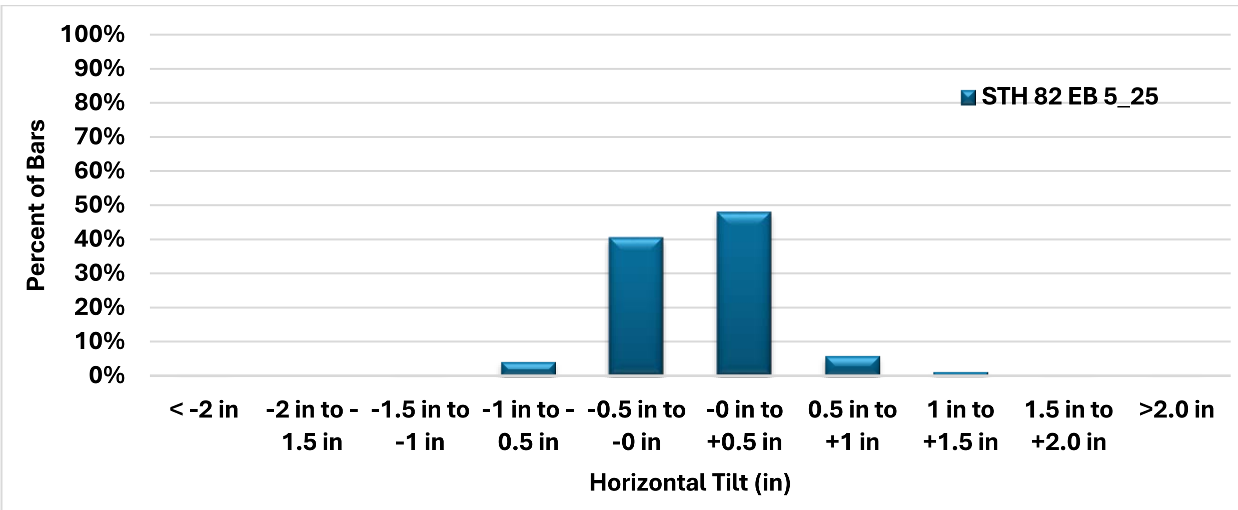

Figure 118. Horizontal Skew distribution for STH 82 EB 5_25

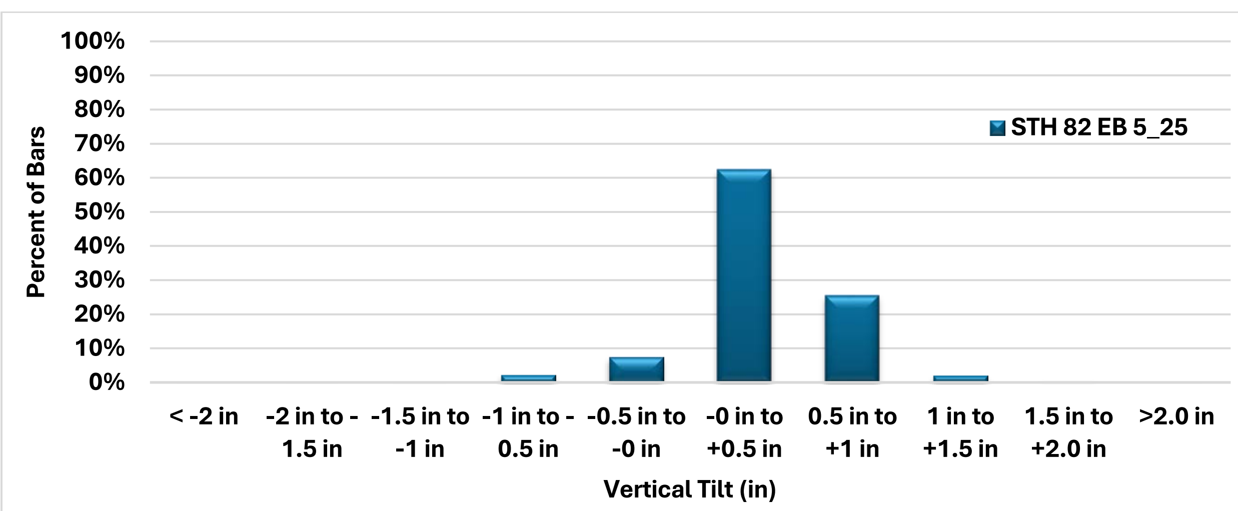

Figure 119. Vertical Tilt distribution for STH 82 EB 5_25

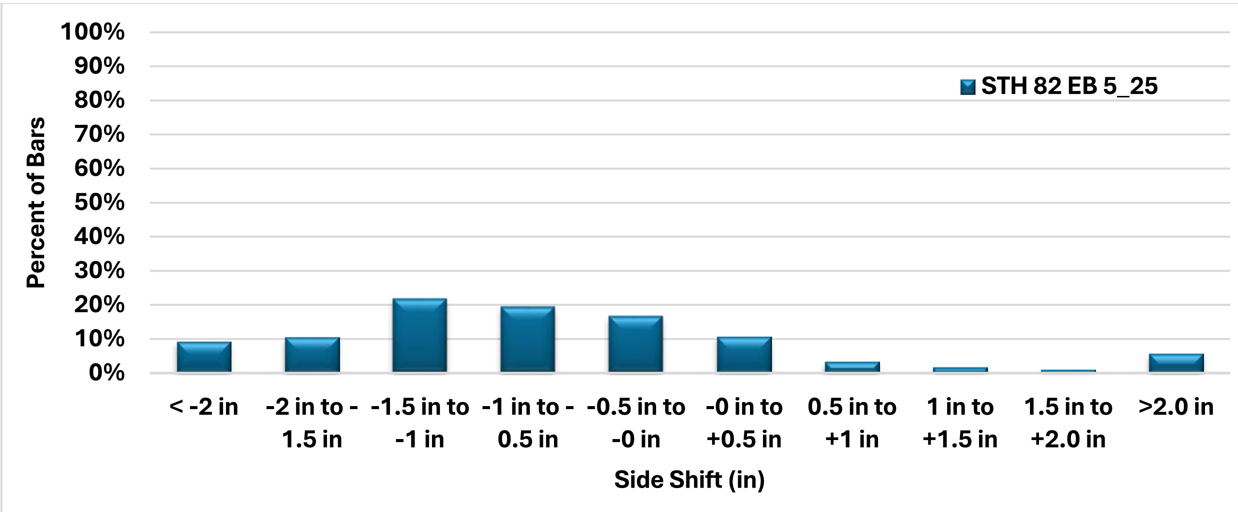

Figure 120. Longitudinal Translation distribution for STH 82 EB 5_25

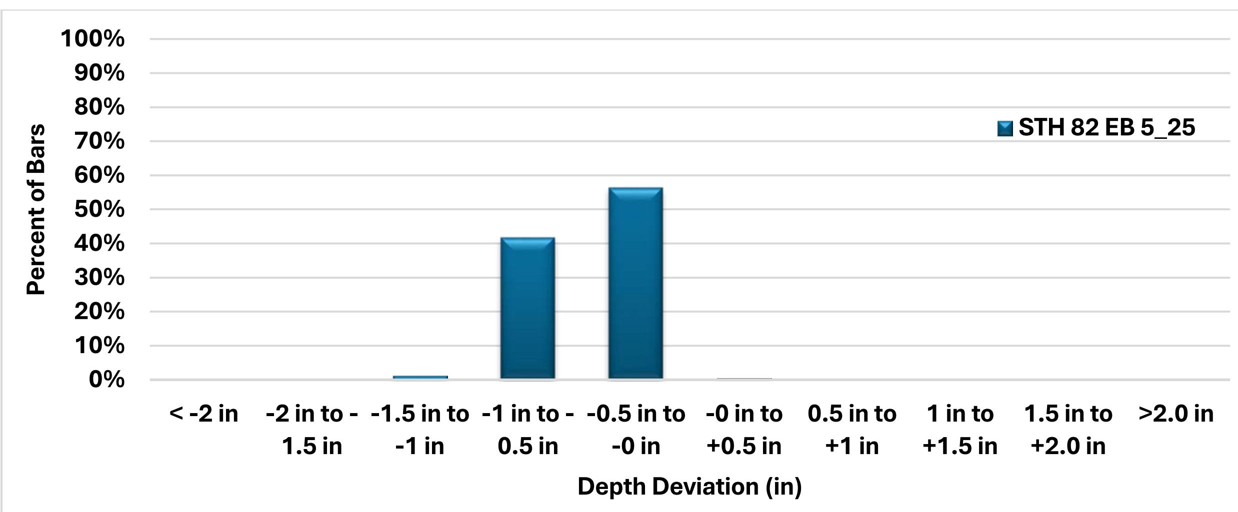

Figure 121. Vertical Translation distribution for STH 82 EB 5_25

Table 41. Dowel misalignment summary for STH 82 EB 5_25

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
STH 82 EB 5_25	-0.03	0.25	0.34	0.25	-0.62	0.85	-0.47	0.21

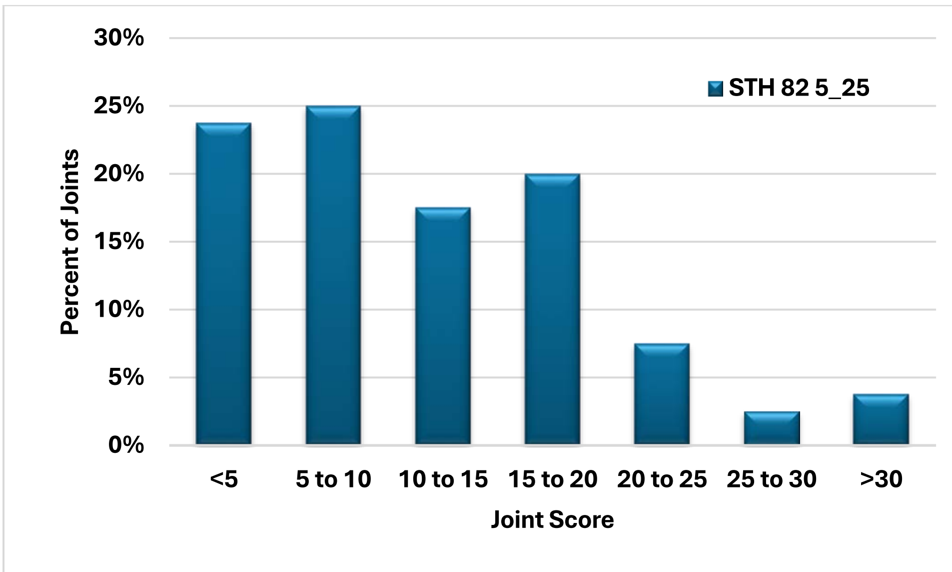

Figure 122. Joint score distribution for STH 82 EB 5_25

Table 42. Joint score and effective dowel diameter for STH 82 EB 5_25

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
STH 82 EB 5_25	12.3	11.8	10	1.25	1.224	0.044	2.08

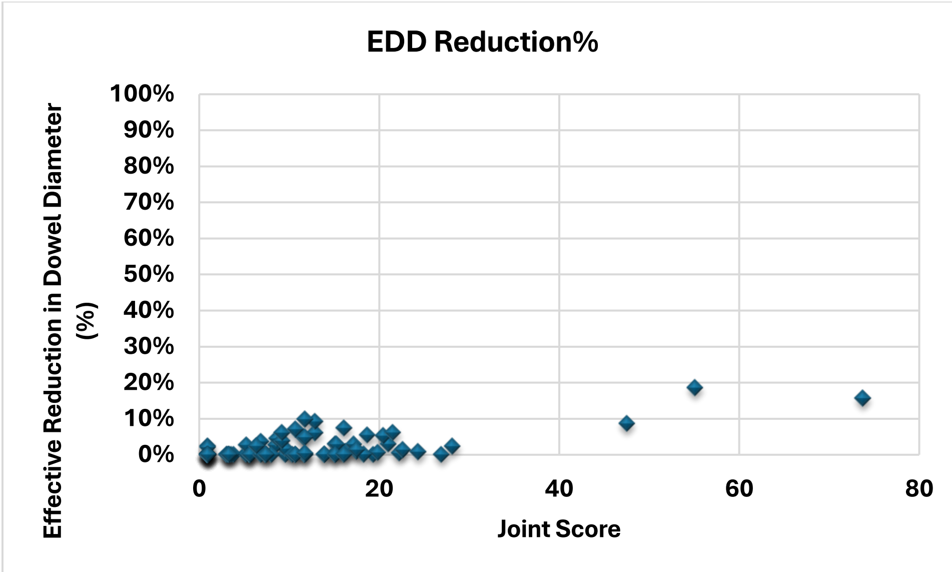

Figure 123. Joint score versus effective reduction in dowel diameter for STH 82 EB 5_25

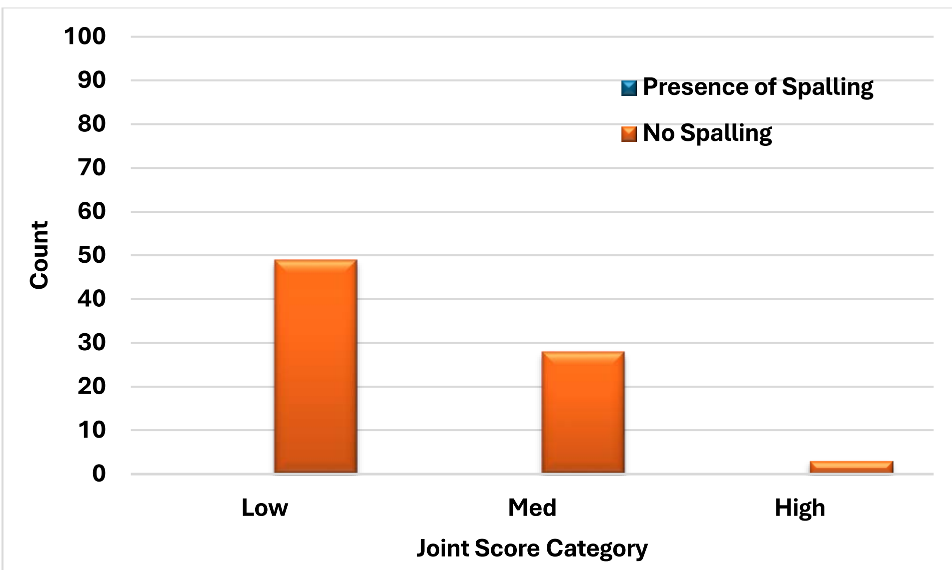

Figure 124. Joint score and presence of spalling for STH 82 EB 5_25

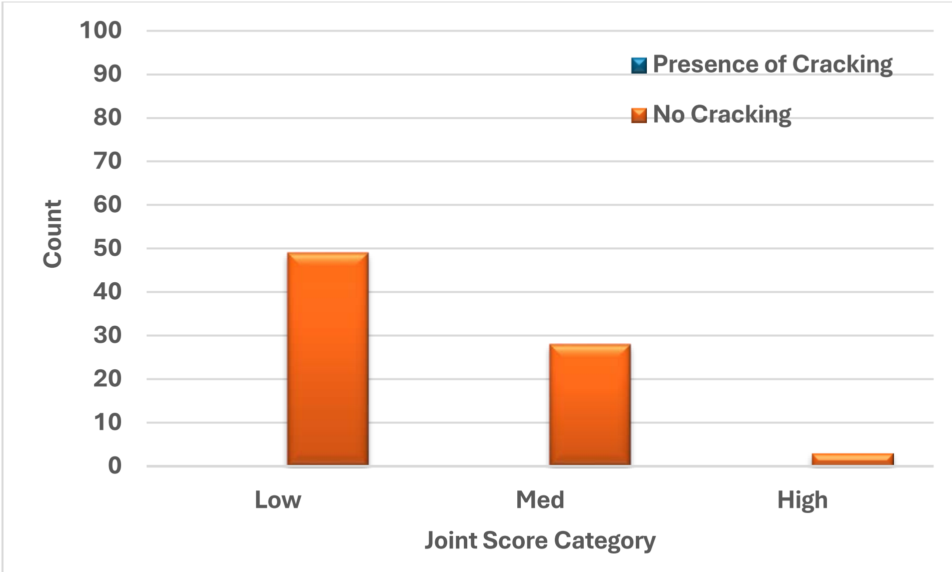

Figure 12552. Joint score and presence of cracking for STH 82 EB 5_25

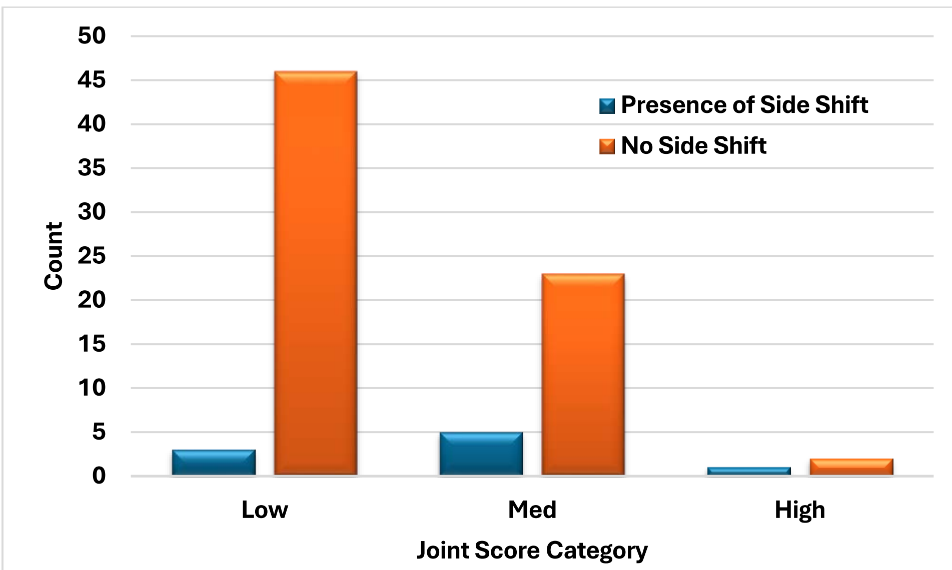

Figure 12653. Joint score and presence of side shift for STH 82 EB 5_25

US 53 NB

Table 43. Details of test sections in US 53 NB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
US 53 NB	9.5	1.25		14

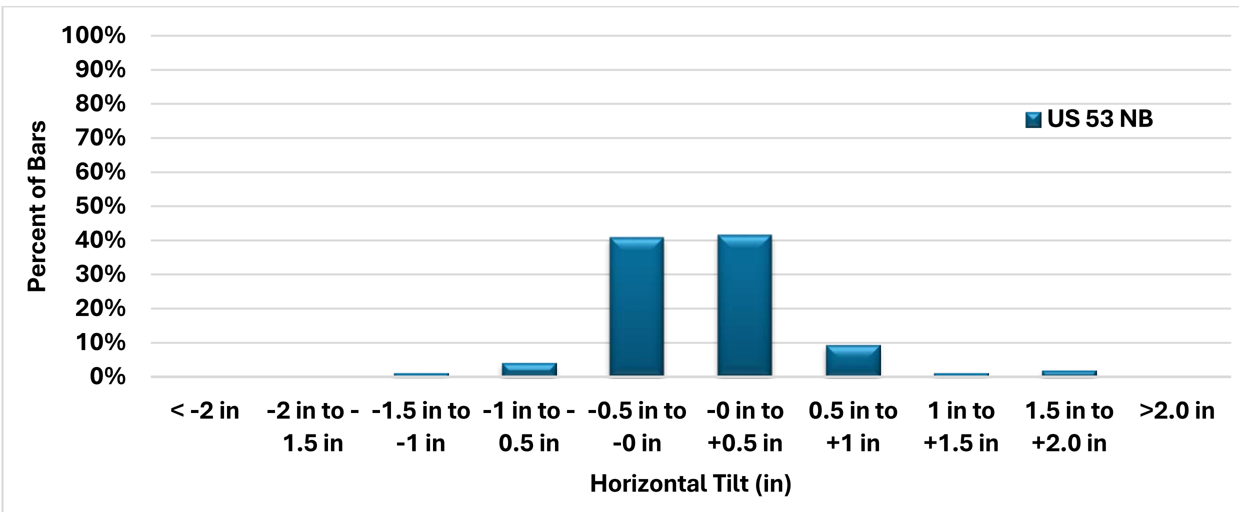

Figure 127. Horizontal Skew distribution for US 53 NB

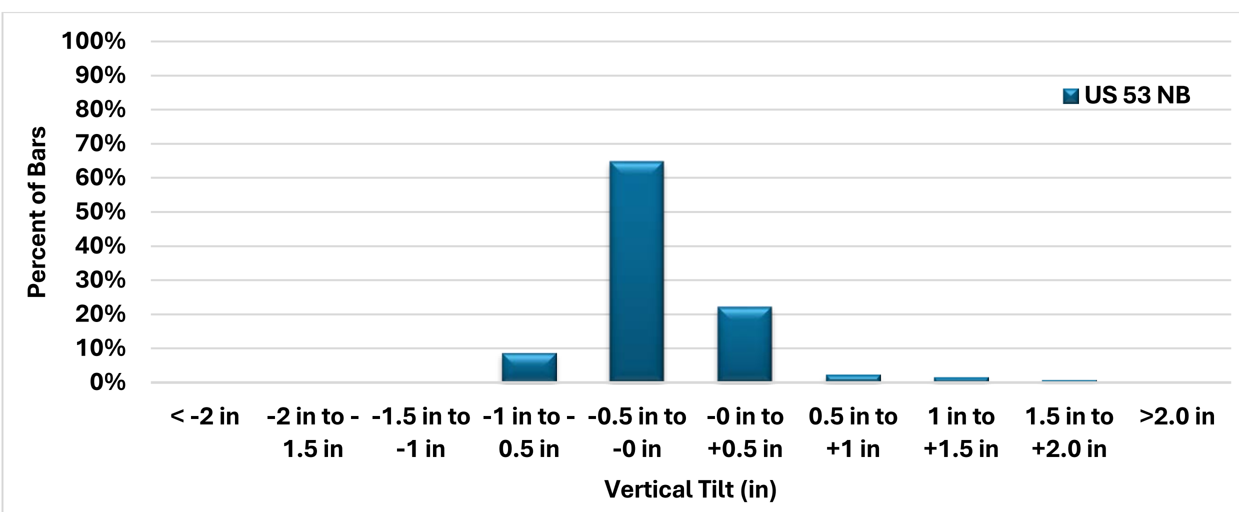

Figure 128. Vertical Tilt distribution for US 53 NB

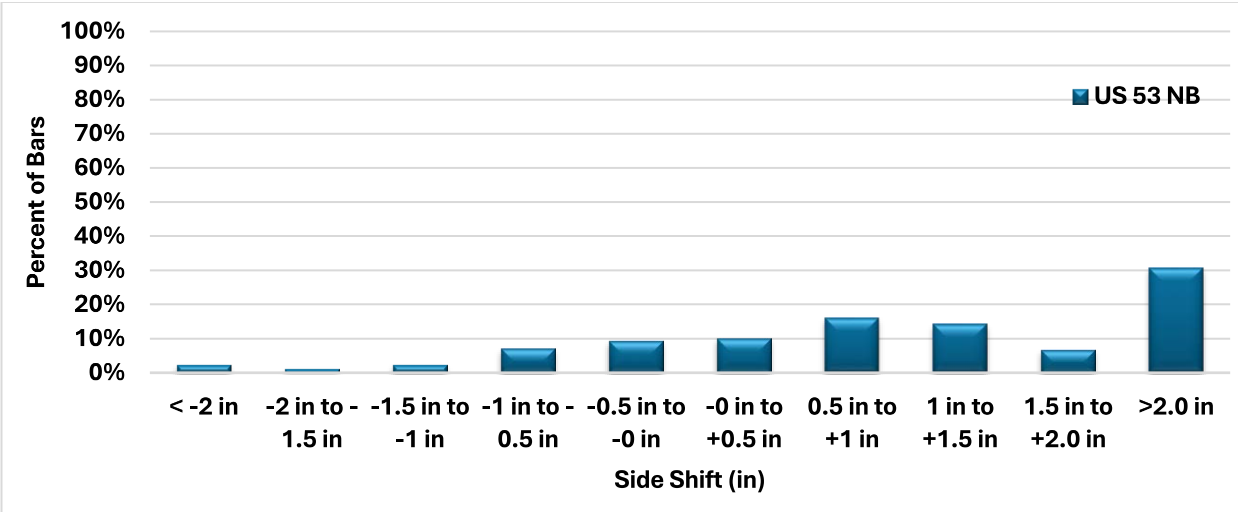

Figure 129. Longitudinal Translation distribution for US 53 NB

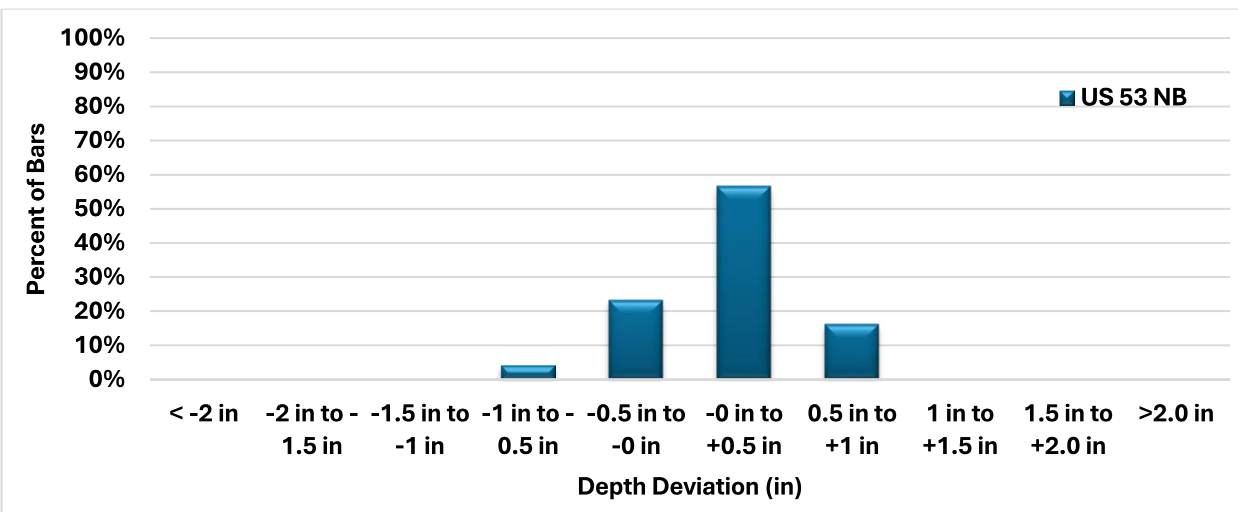

Figure 130. Vertical Translation distribution for US 53 NB

Table 44. Dowel misalignment summary for US 53 NB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
US 53 NB	0.05	0.32	-0.11	0.25	1.24	1.31	0.17	0.35

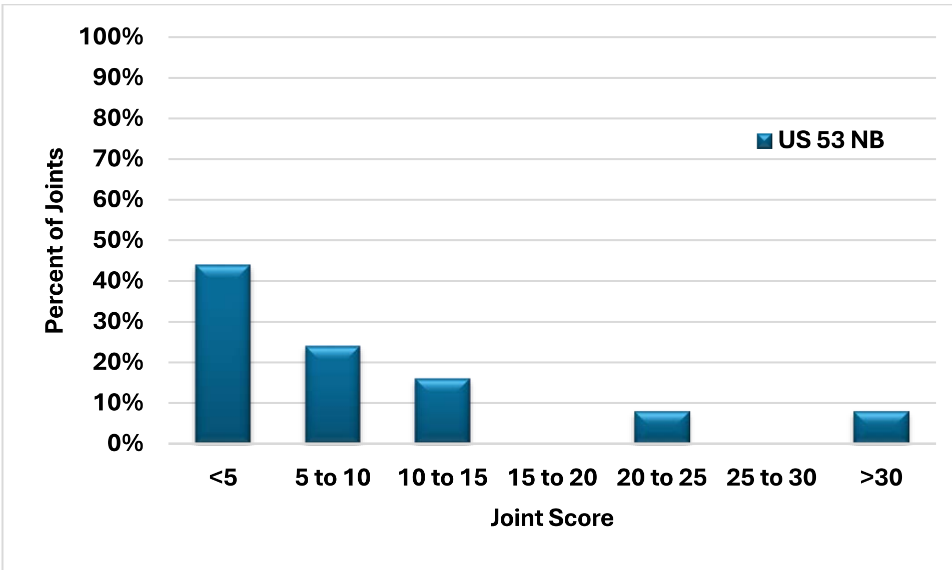

Figure 131. Joint score distribution for US 53 NB

Table 45. Joint score and effective dowel diameter for US 53 NB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
US 53 NB	12.9	23.8	9.5	1.25	1.192	0.084	4.64

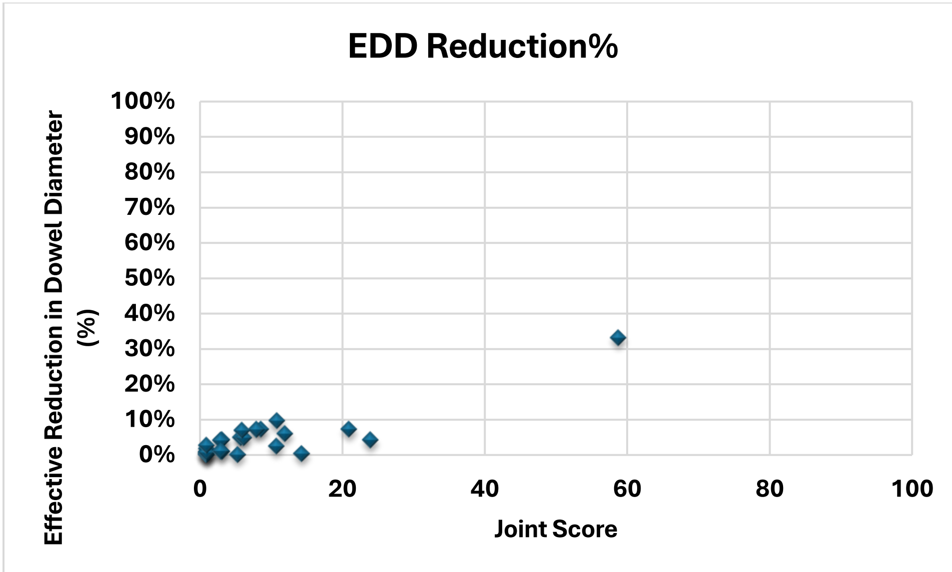

Figure 132. Joint score versus effective reduction in dowel diameter for US 53 NB

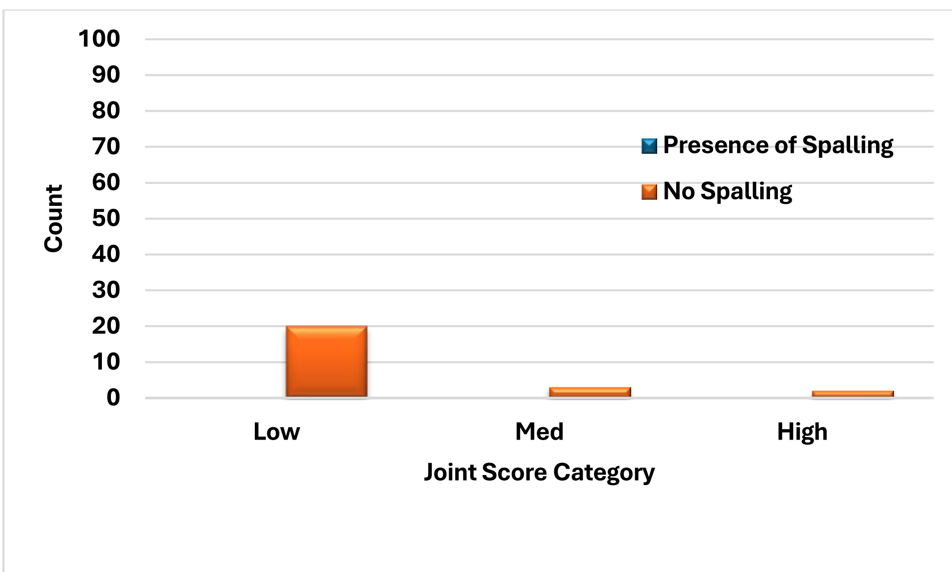

Figure 133. Joint score and presence of spalling for US 53 NB

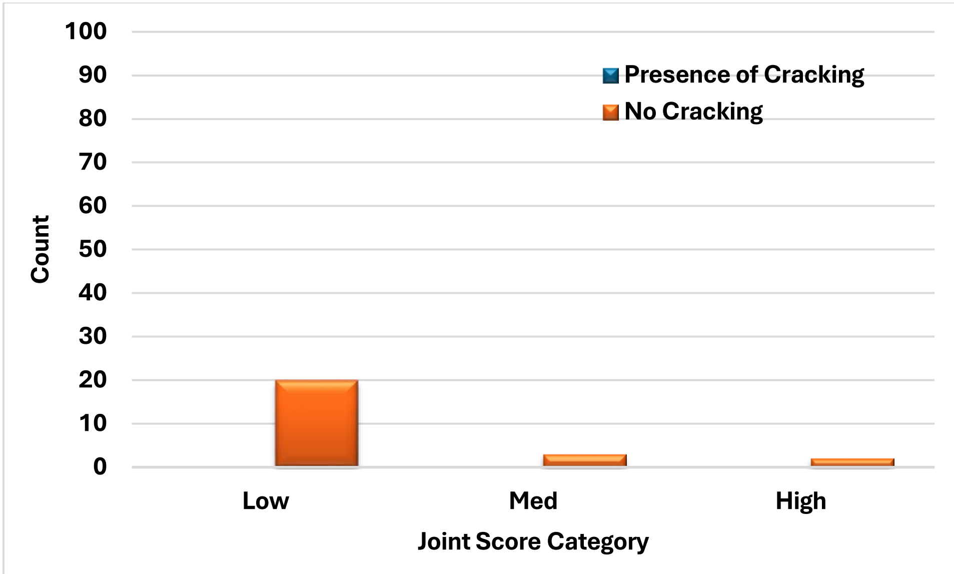

Figure 13454. Joint score and presence of cracking for US 53 NB

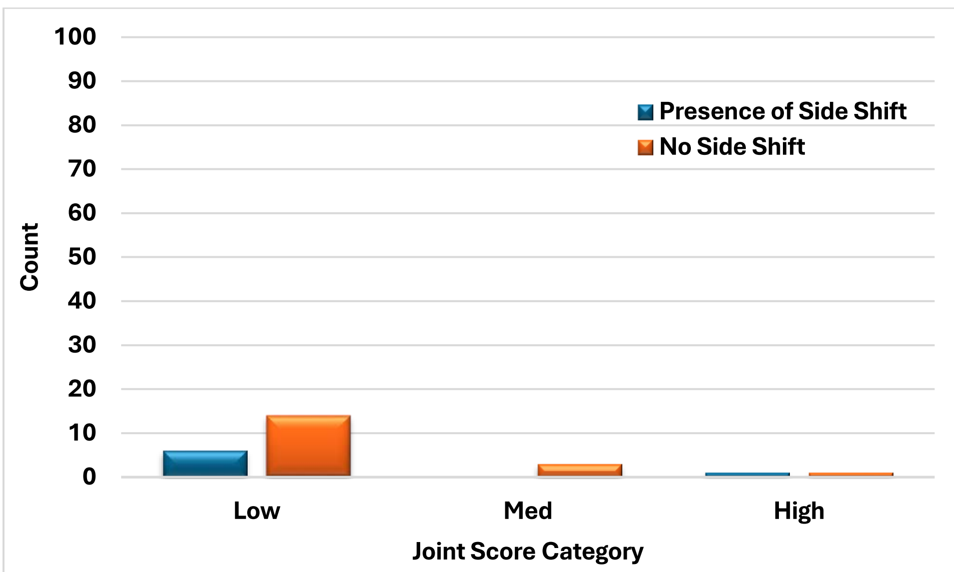

Figure 13555. Joint score and presence of side shift for US 53 NB

STH 29 WB

Table 46. Details of test sections in STH 29 WB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
STH 29 WB	10	1.5		12

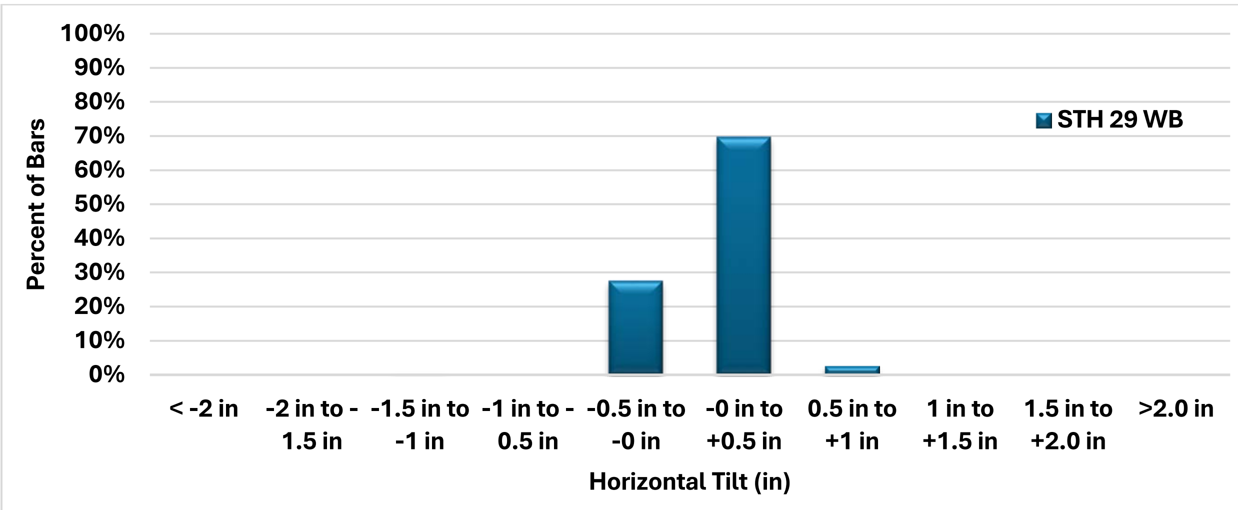

Figure 136. Horizontal Skew distribution for STH 29 WB

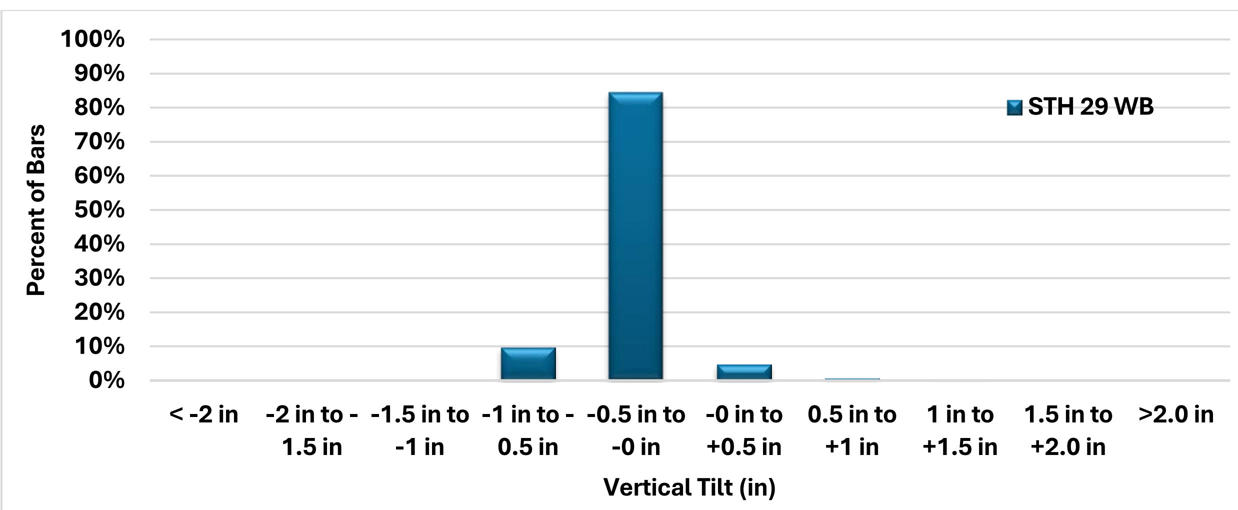

Figure 137. Vertical Tilt distribution for STH 29 WB

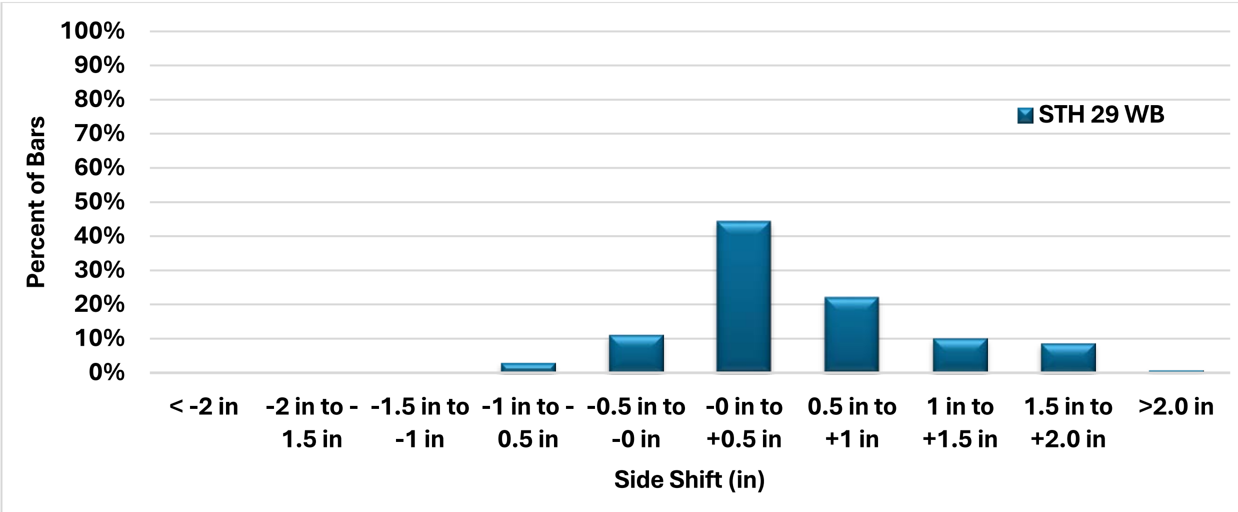

Figure 138. Longitudinal Translation distribution for STH 29 WB

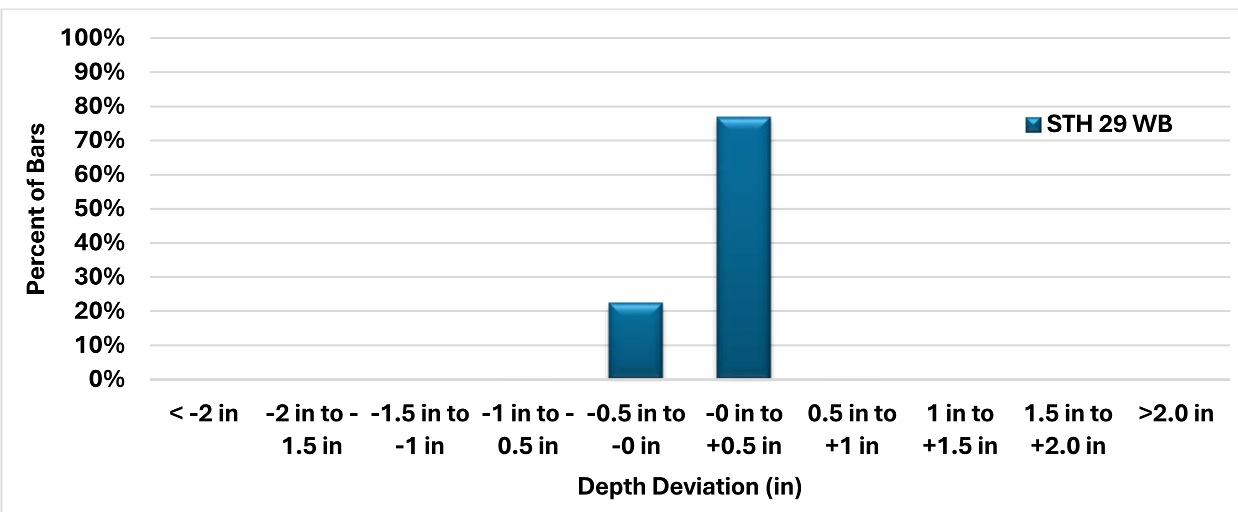

Figure 139. Vertical Translation distribution for STH 29 WB

Table 47. Dowel misalignment summary for STH 29 WB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
STH 29 WB	0.08	0.15	-0.28	0.16	-0.87	0.50	0.51	0.15

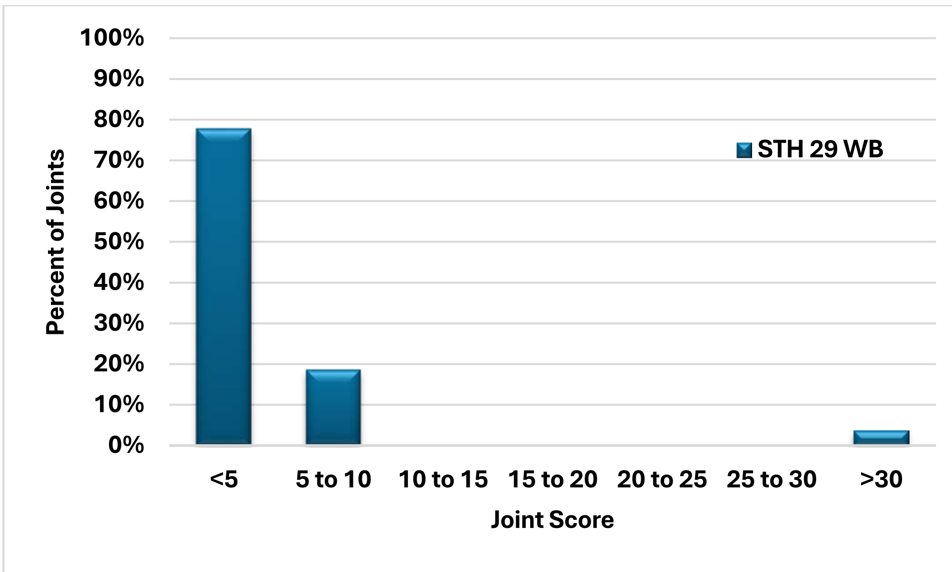

Figure 140. Joint score distribution for STH 29 WB

Table 48. Joint score and effective dowel diameter for STH 29 WB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
STH 29 WB	6.4	21.0	10	1.5	1.350	0.31	10.00

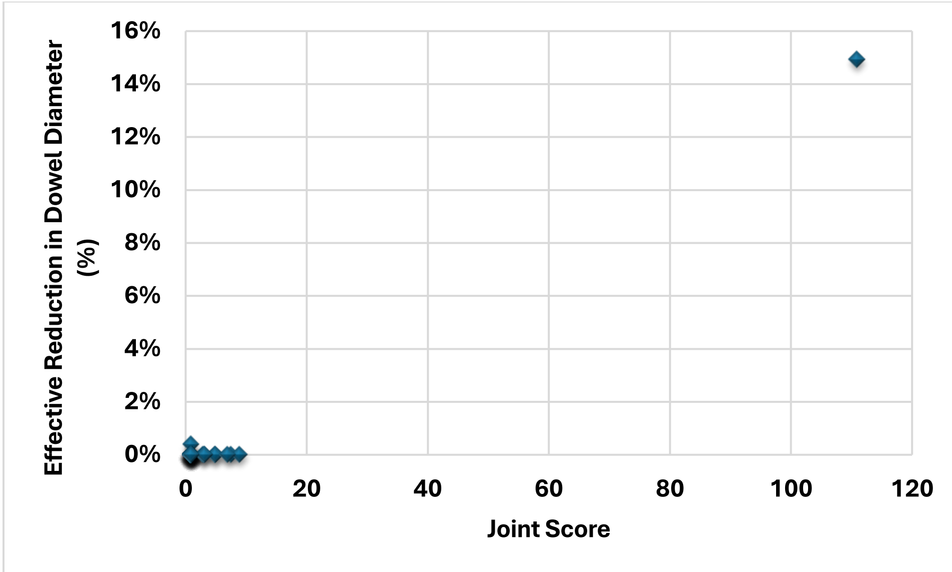

Figure 141. Joint score versus effective reduction in dowel diameter for STH 29 WB

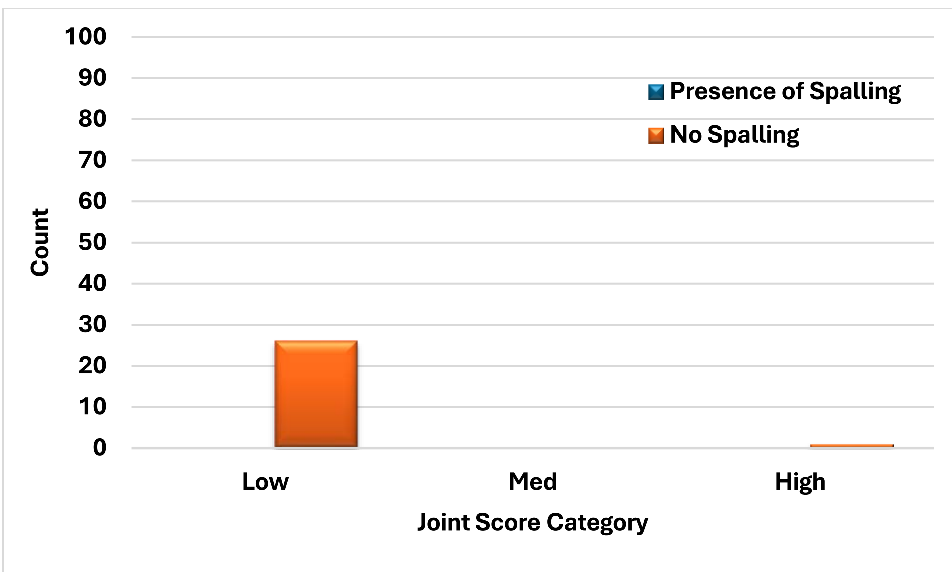

Figure 142. Joint score and presence of spalling for STH 29 WB

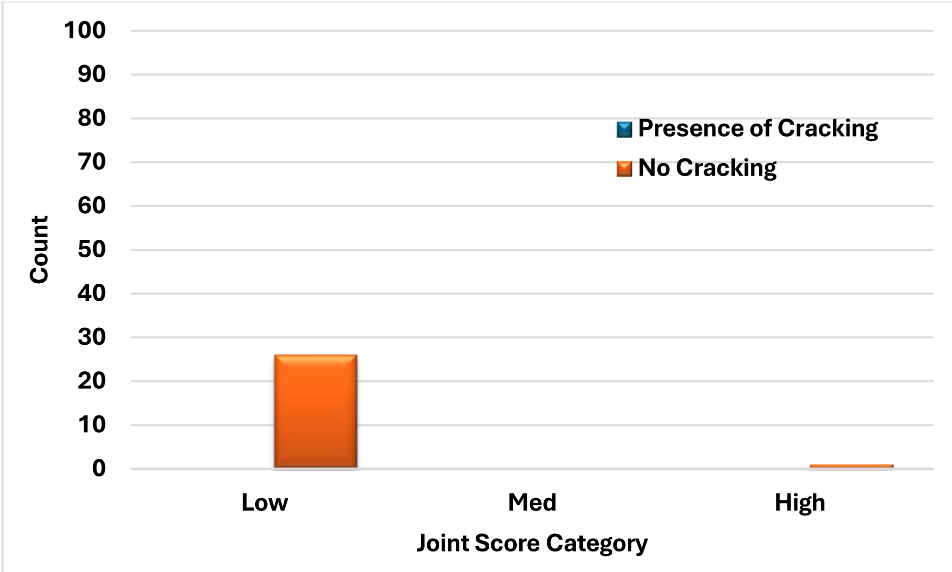

Figure 14356. Joint score and presence of cracking for STH 29 WB

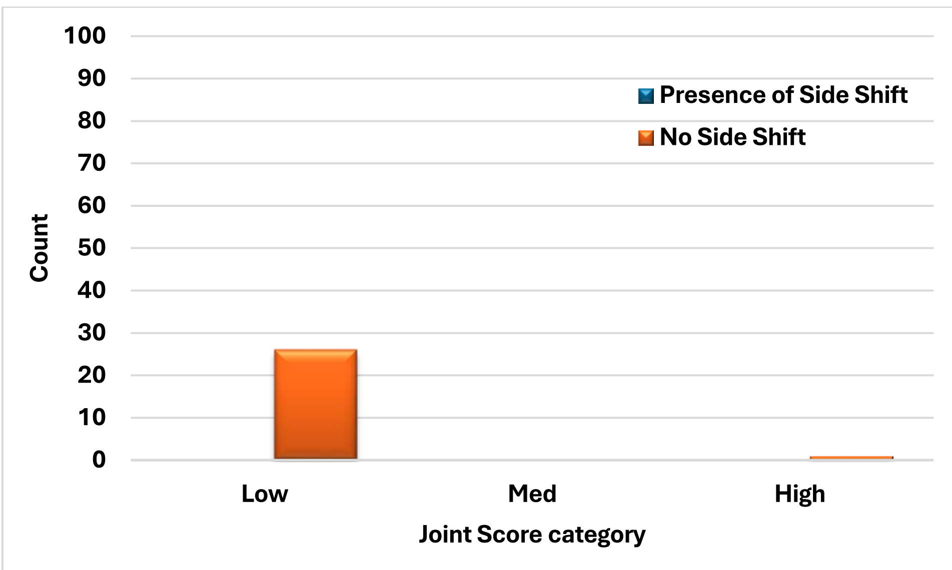

Figure 14457. Joint score and presence of side shift for STH 29 WB.

I 94 EB Dane County

Table 49. Details of test sections in I 94 EB Dane County

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
I 94 EB Dane County	7	1.5		15

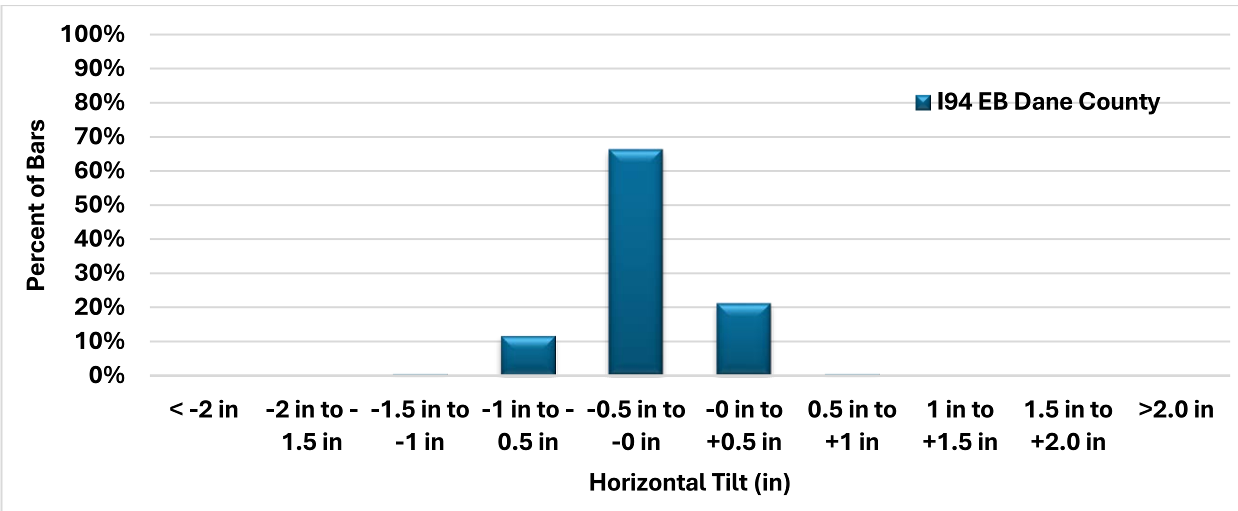

Figure 145. Horizontal Skew distribution for I 94 EB Dane County

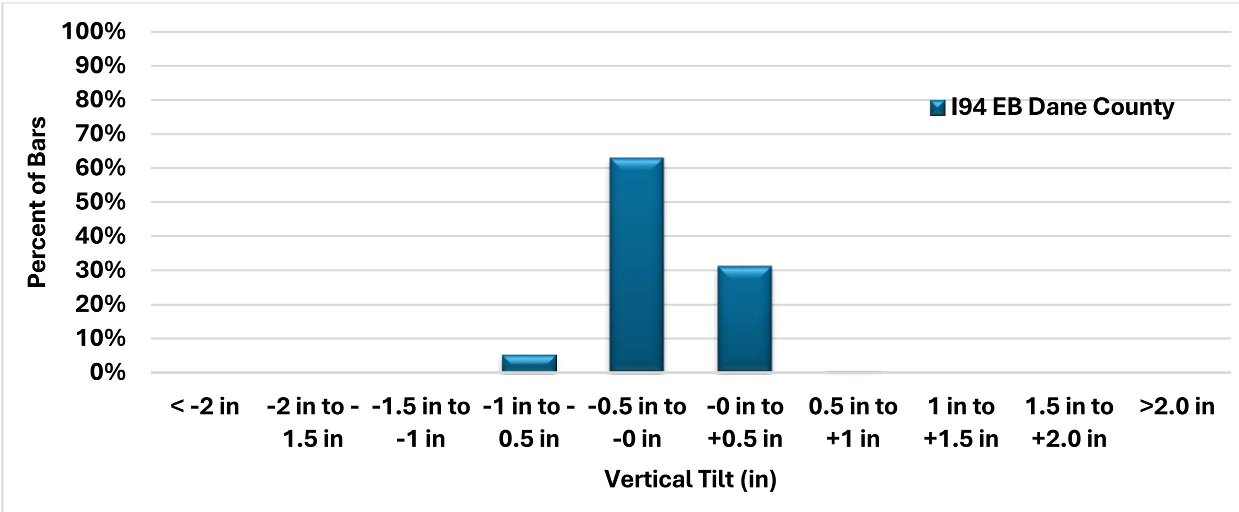

Figure 146. Vertical Tilt distribution for I 94 EB Dane County

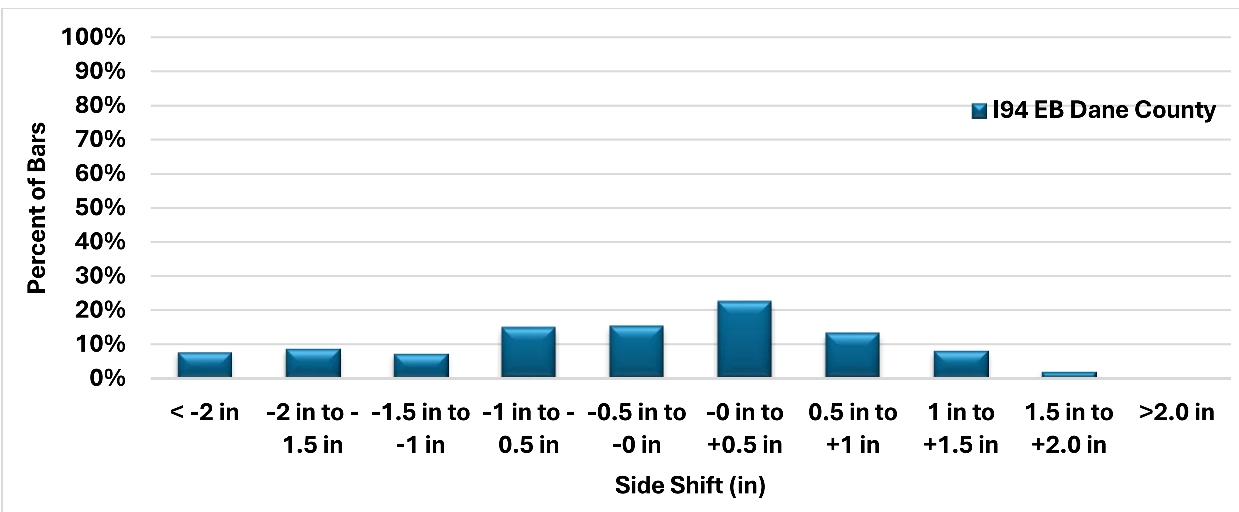

Figure 147. Longitudinal Translation distribution for I 94 EB Dane County

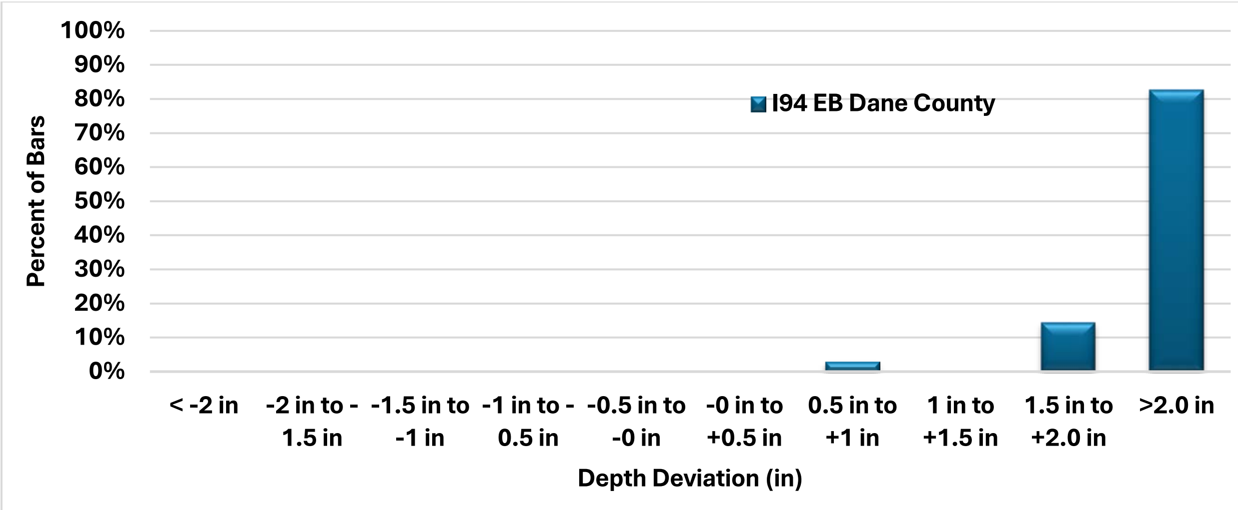

Figure 148. Vertical Translation distribution for I 94 EB Dane County

Table 50. Dowel misalignment summary for I 94 EB Dane County

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
Rock NB	-0.20	0.20	-0.11	0.15	-0.29	0.68	2.42	0.50

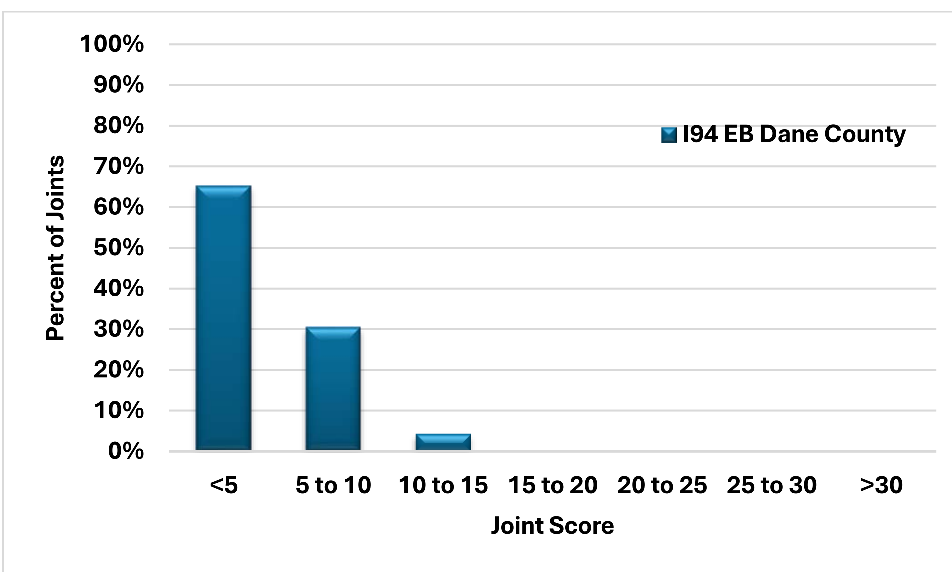

Figure 149. Joint score distribution for I 94 EB Dane County

Table 51. Joint score and effective dowel diameter for I 94 EB Dane County

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
I 94 EB Dane County	4.1	3.7	7	1.5	1.349	0.113	10.07

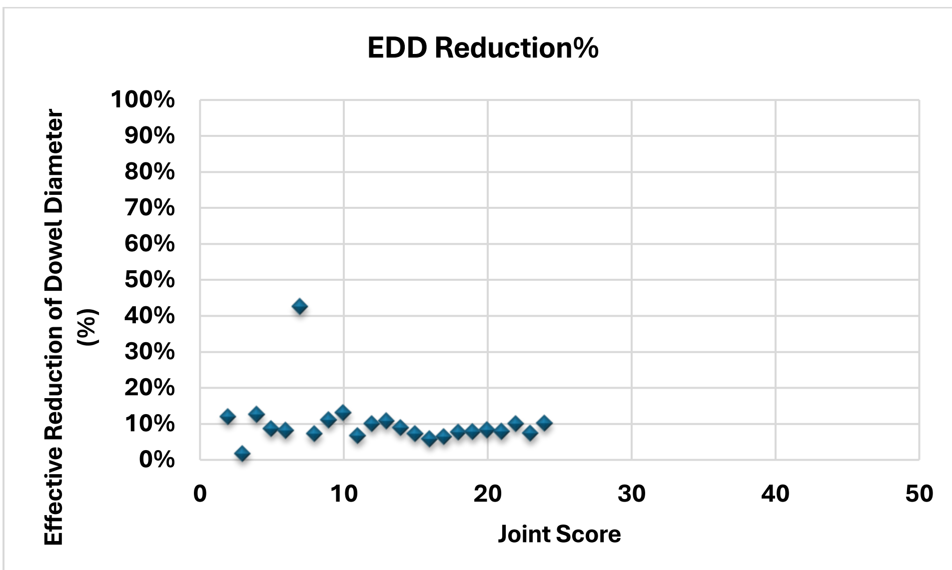

Figure 150. Joint score versus effective reduction in dowel diameter for I 94 EB Dane County

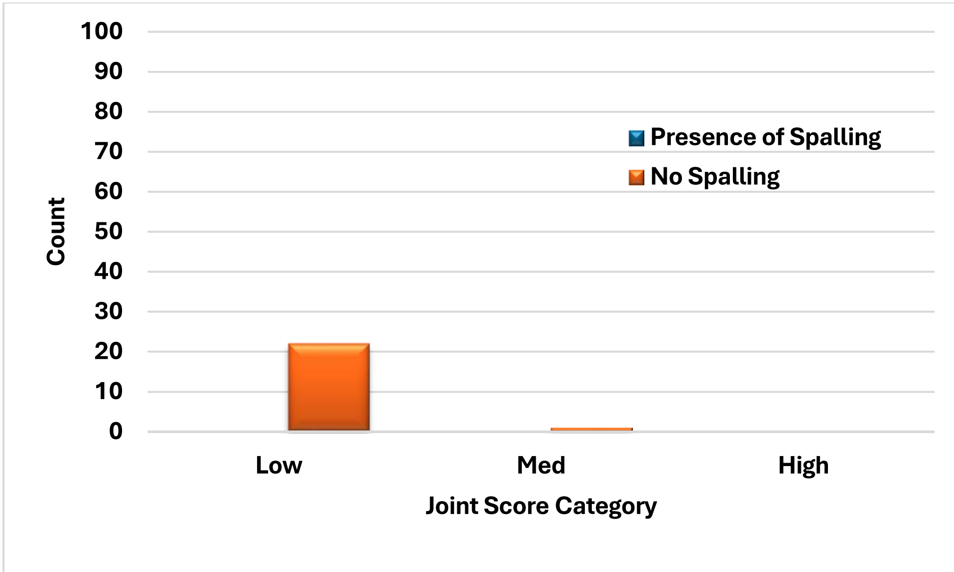

Figure 151. Joint score and presence of spalling for I 94 EB Dane County

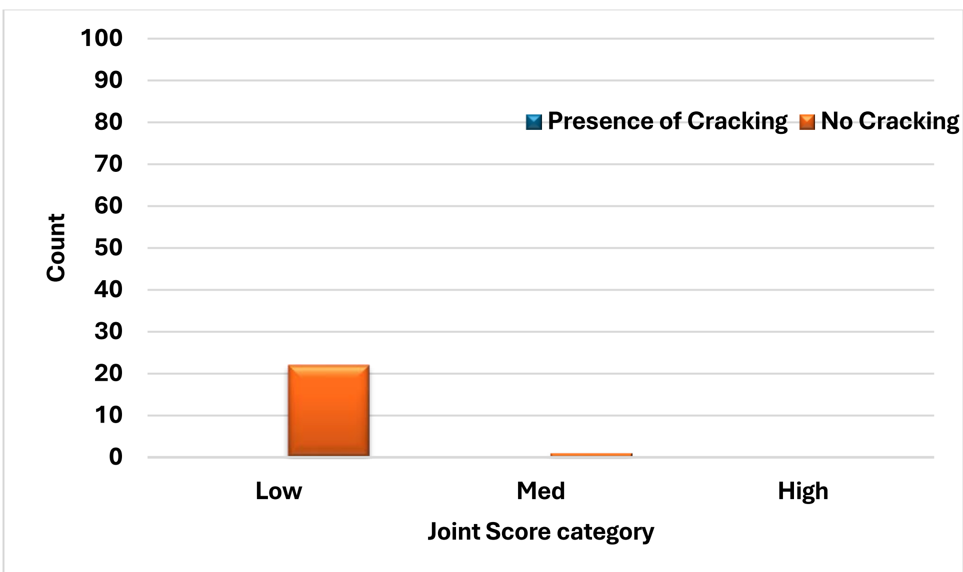

Figure 15258. Joint score and presence of cracking for I 94 EB Dane County

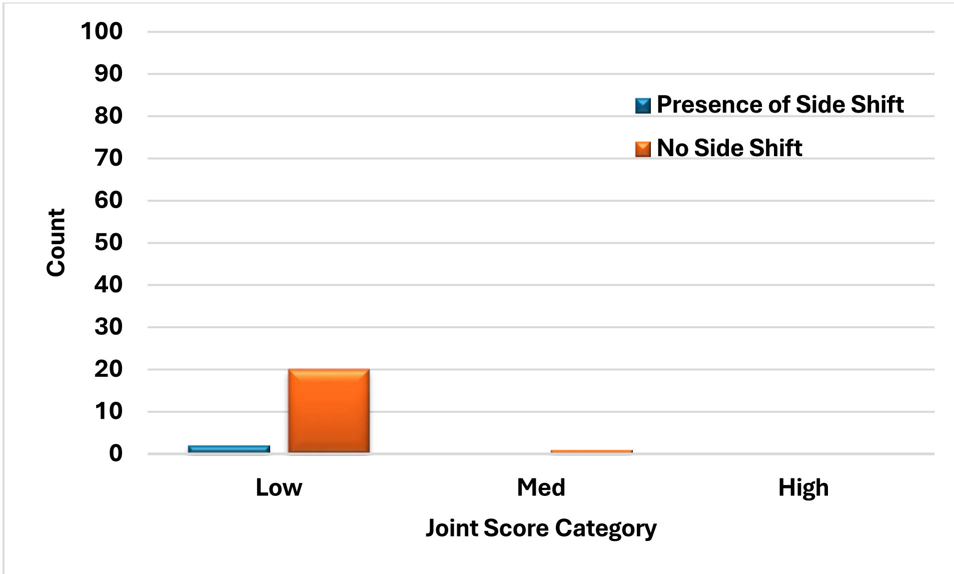

Figure 15359. Joint score and presence of side shift for I 94 EB Dane County

139 SB Columbia County

Table 52. Details of test sections in 139 SB Columbia County

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
139 SB Columbia County	10	1.5		12

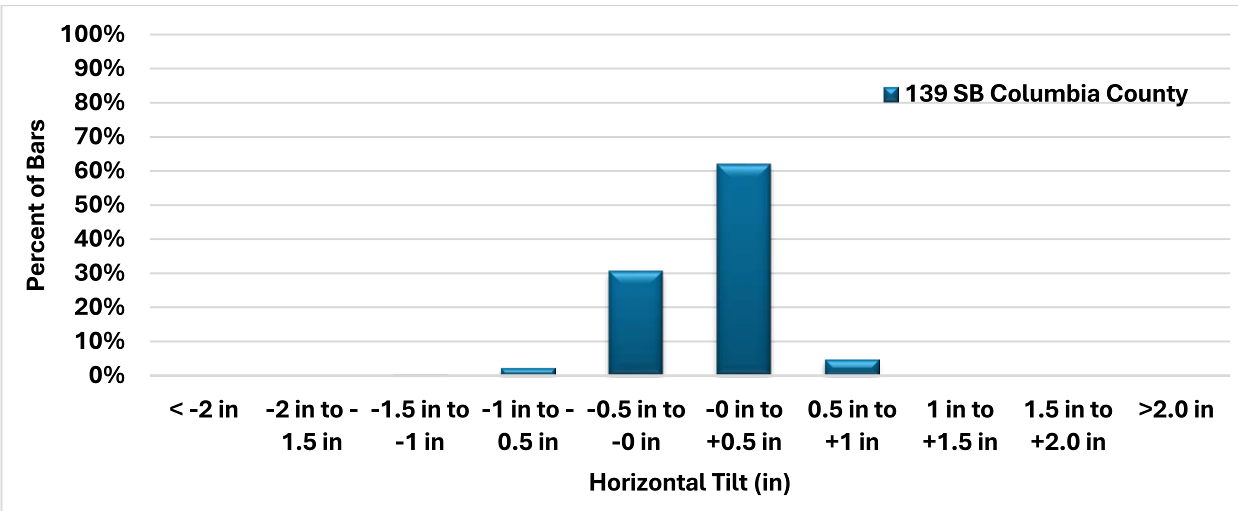

Figure 154. Horizontal Skew distribution for 139 SB Columbia County

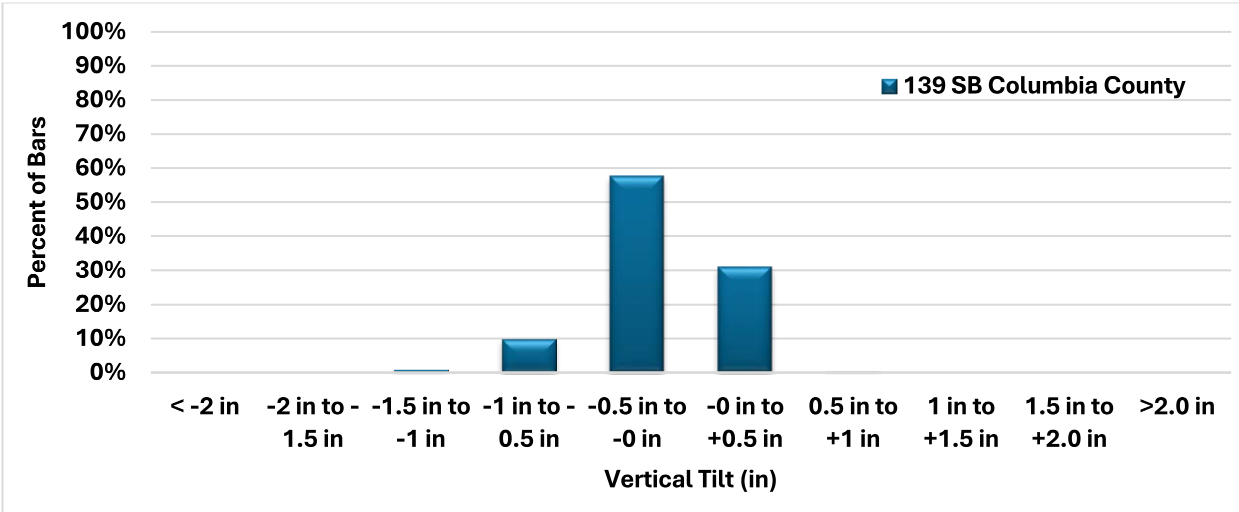

Figure 155. Vertical Tilt distribution for 139 SB Columbia County

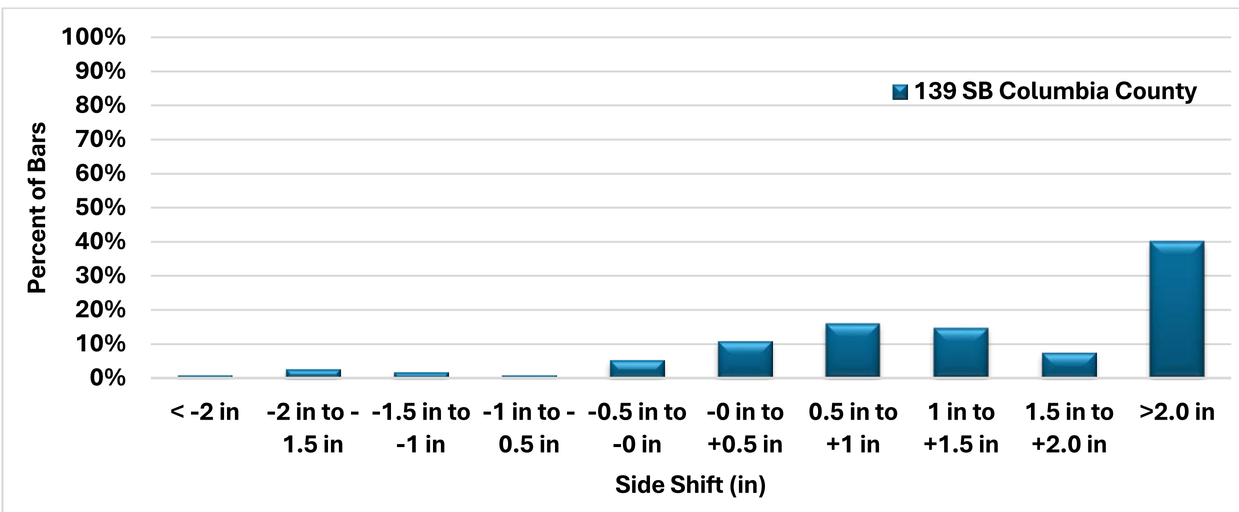

Figure 156. Longitudinal Translation distribution for 139 SB Columbia County

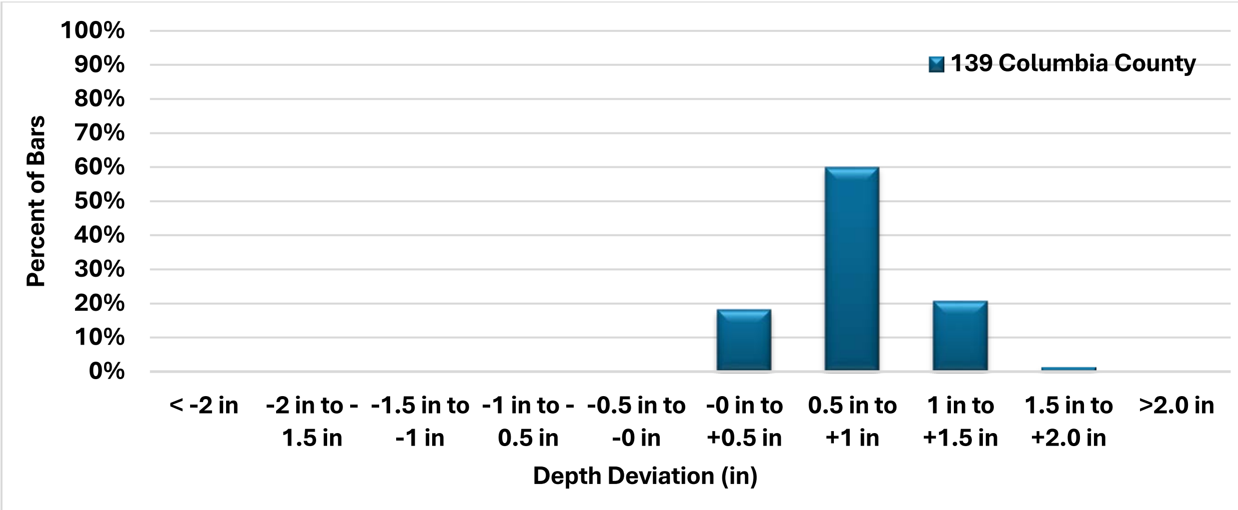

Figure 157. Vertical Translation distribution for 139 SB Columbia County

Table 53. Dowel misalignment summary for 139 SB Columbia County

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
139 SB Columbia County	0.08	0.18	-0.17	0.21	1.43	1.04	0.77	0.31

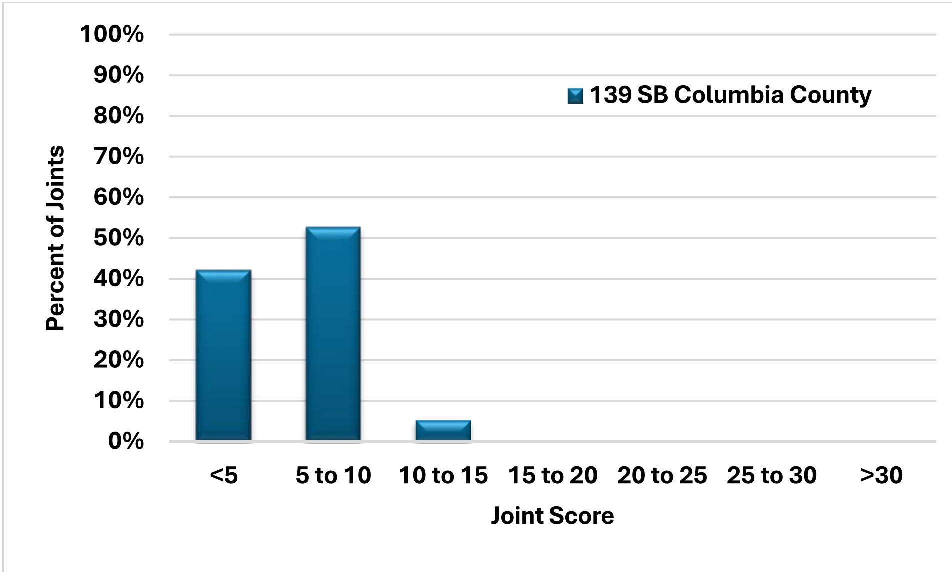

Figure 158. Joint score distribution for 139 SB Columbia County

Table 54. Joint score and effective dowel diameter for 139 SB Columbia County

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
139 SB Columbia County	5.3	3.6	10	1.5	1.394	0.037	7.07

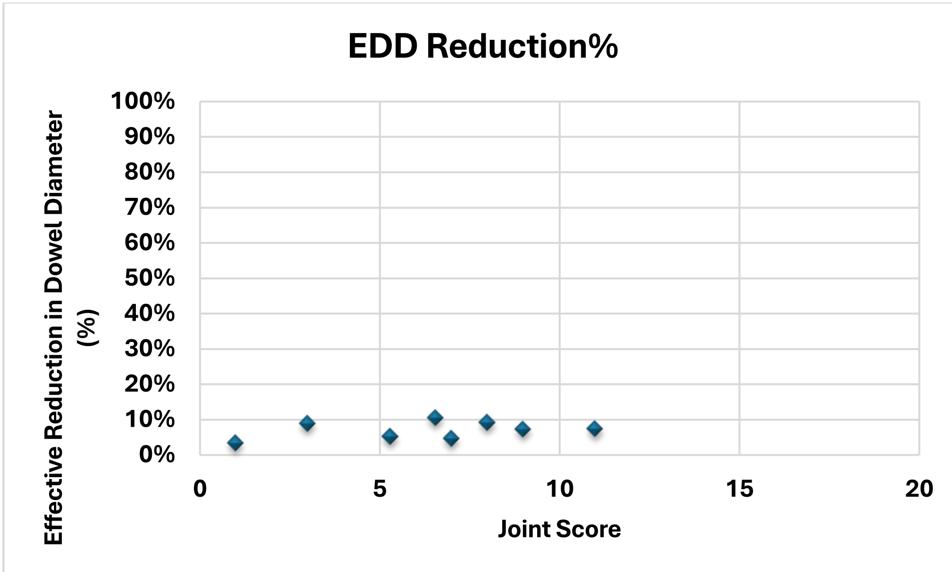

Figure 159. Joint score versus effective reduction in dowel diameter for 139 SB Columbia County

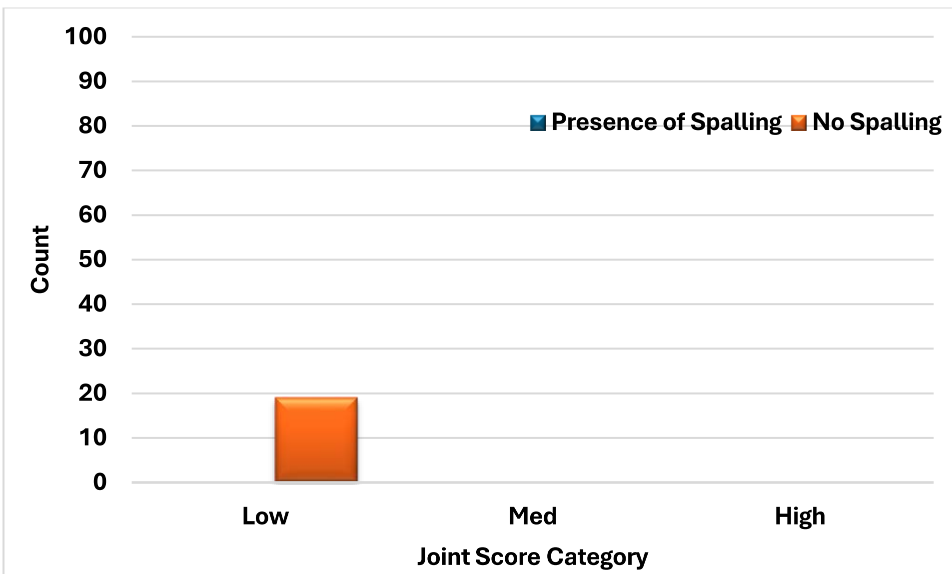

Figure 160. Joint score and presence of spalling for 139 SB Columbia County

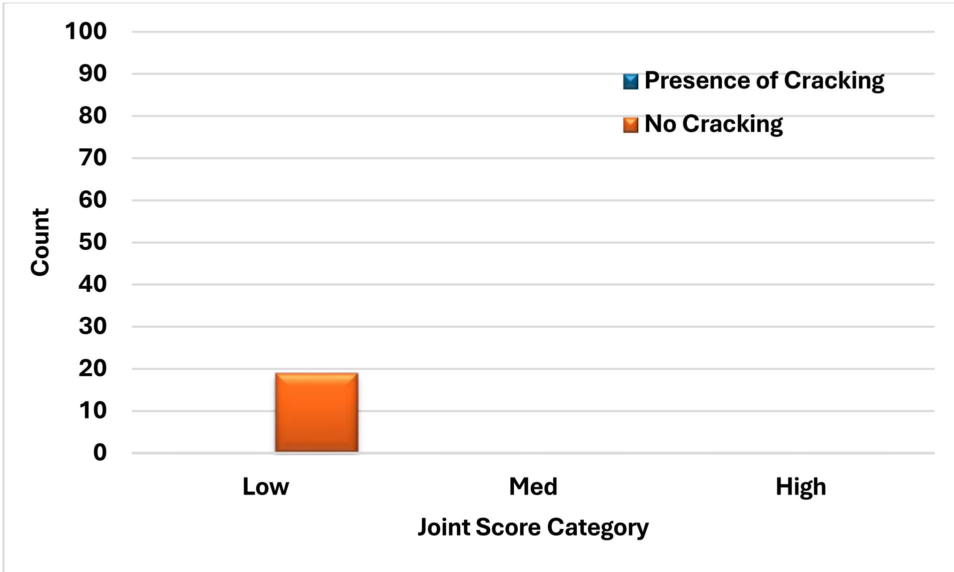

Figure 16160. Joint score and presence of cracking for 139 SB Columbia County

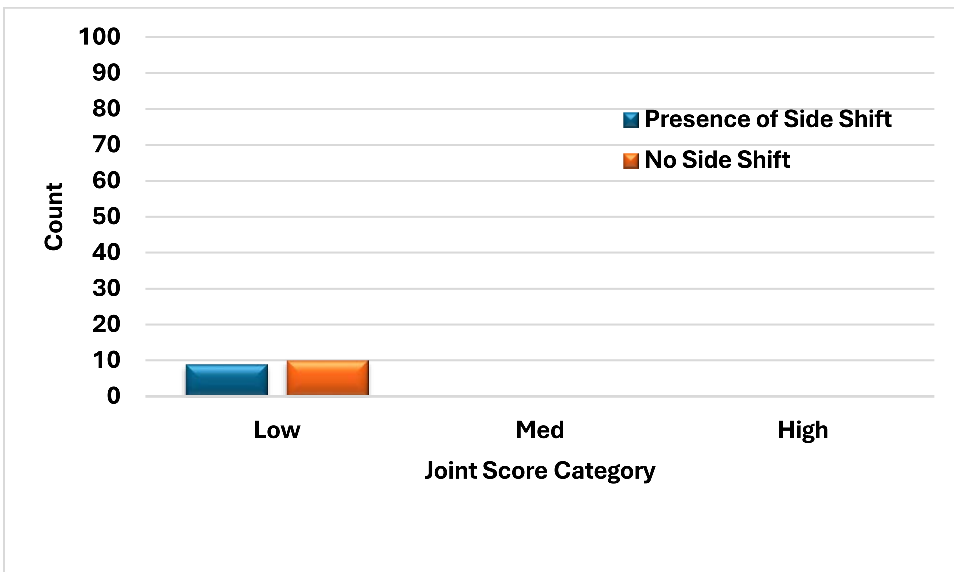

Figure 16261. Joint score and presence of side shift for 139 SB Columbia County

USH 12 SB Section 1 Lane 1

Table 55. Details of test sections in USH 12 SB Section 1 Lane 1

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
USH 12 SB Section 1 Lane 1	9.5	1.25		12

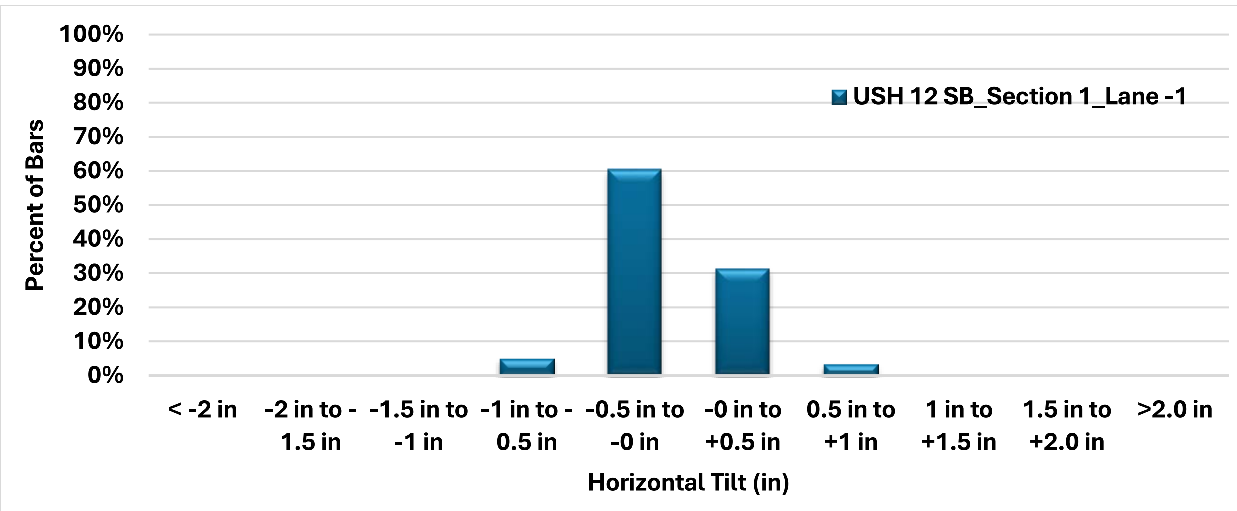

Figure 163. Horizontal Skew distribution for USH 12 SB Section 1 Lane 1

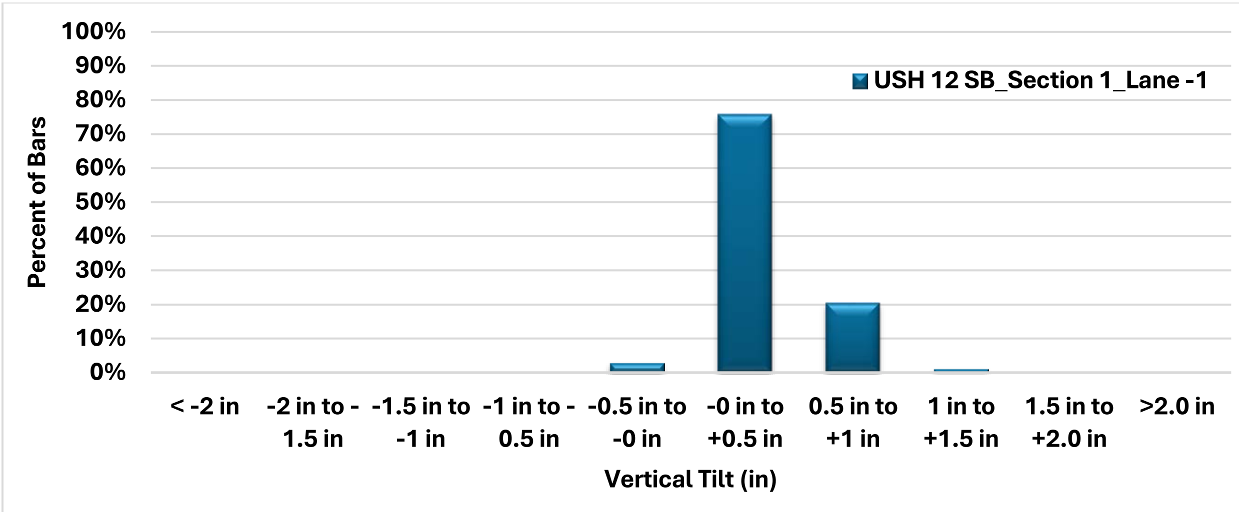

Figure 164. Vertical Tilt distribution for USH 12 SB Section 1 Lane 1

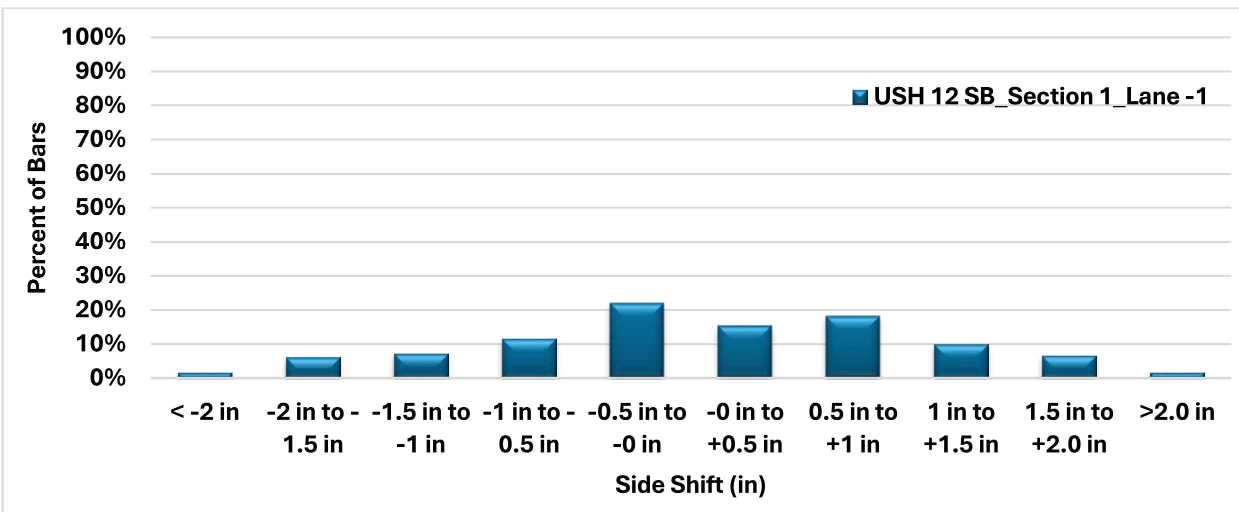

Figure 165. Longitudinal Translation distribution for USH 12 SB Section 1 Lane 1

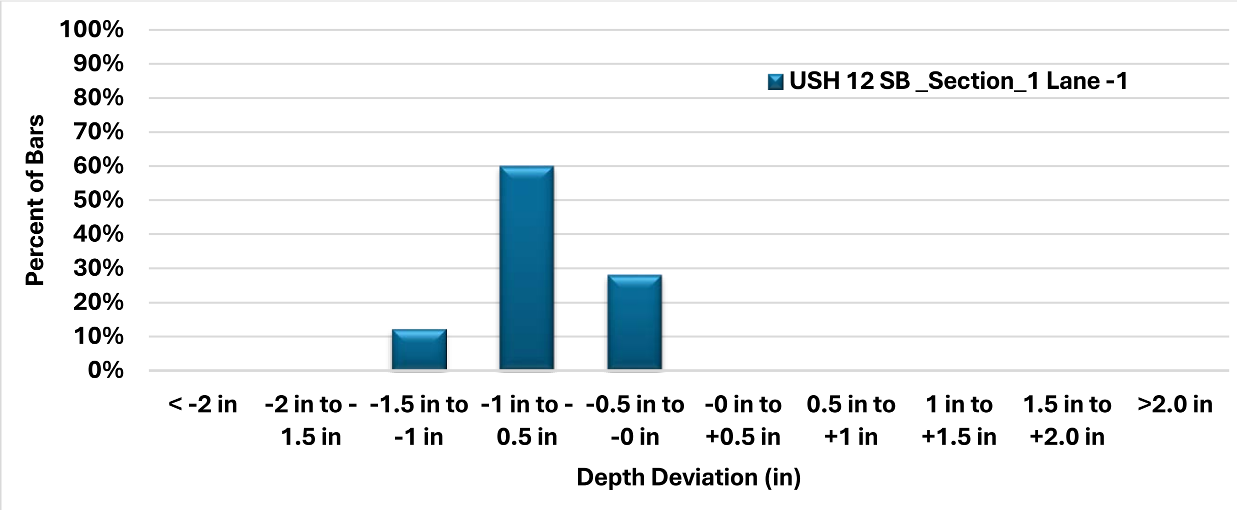

Figure 166. Vertical Translation distribution for USH 12 SB Section 1 Lane 1

Table 56. Dowel misalignment summary for USH 12 SB Section 1 Lane 1

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
USH 12 SB Section 1 Lane 1	-0.09	0.16	0.38	0.18	0.03	0.59	-0.69	0.23

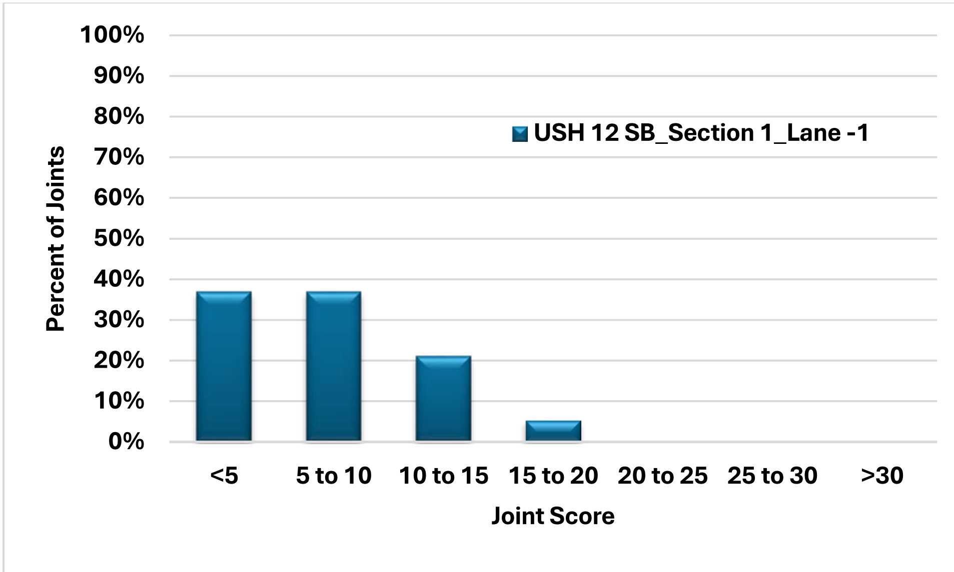

Figure 167. Joint score distribution for USH 12 SB Section 1 Lane 1

Table 57. Joint score and effective dowel diameter for USH 12 SB Section 1 Lane 1

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
USH 12 SB Section 1 Lane 1	6.6	4.6	9.5	1.25	1.210	0.018	3.20

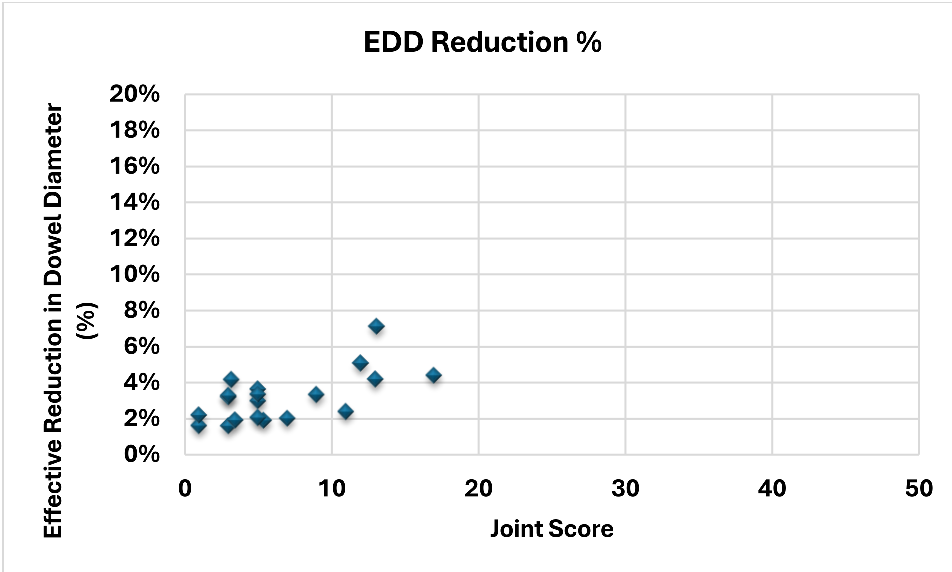

Figure 168. Joint score versus effective reduction in dowel diameter for USH 12 SB Section 1 Lane 1

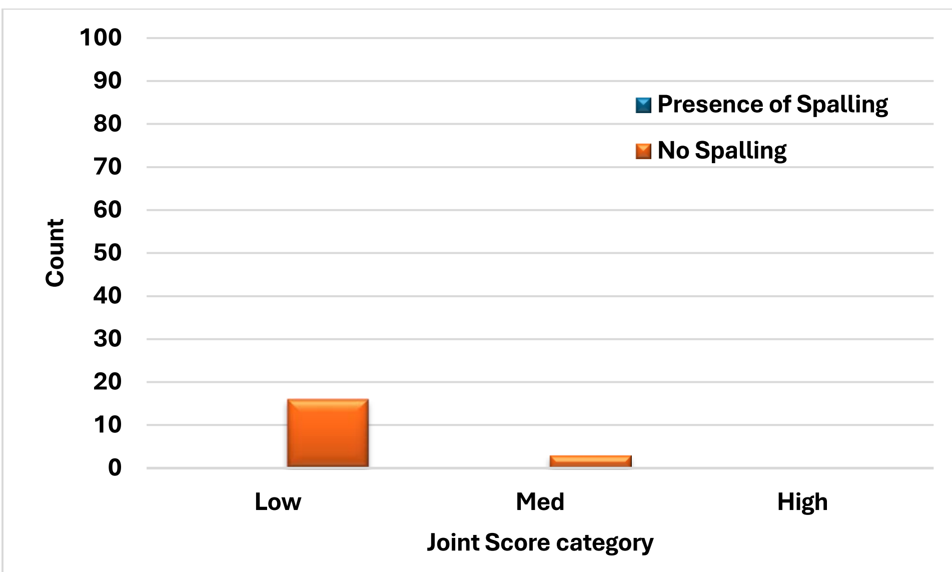

Figure 169. Joint score and presence of spalling for USH 12 SB Section 1 Lane 1

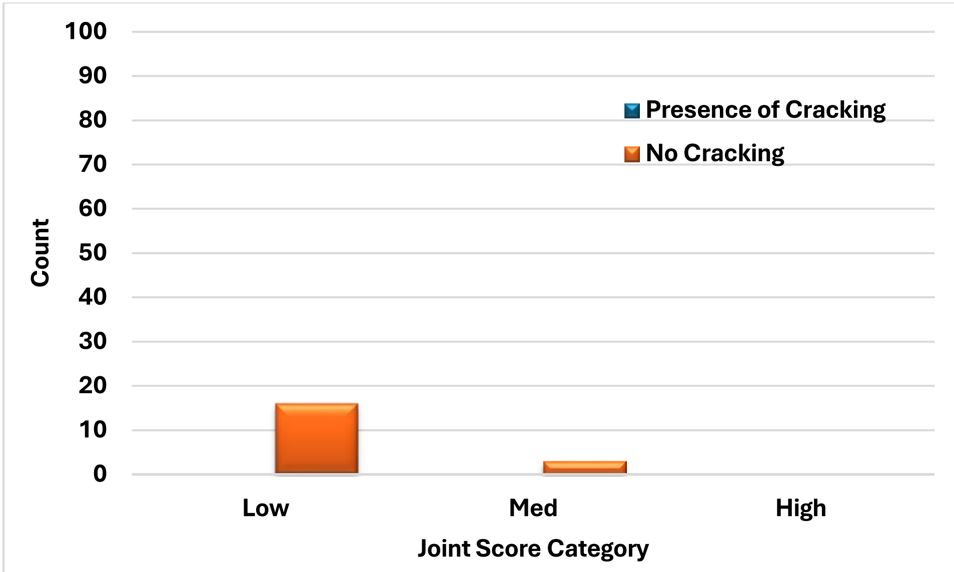

Figure 17062. Joint score and presence of cracking for USH 12 SB Section 1 Lane 1

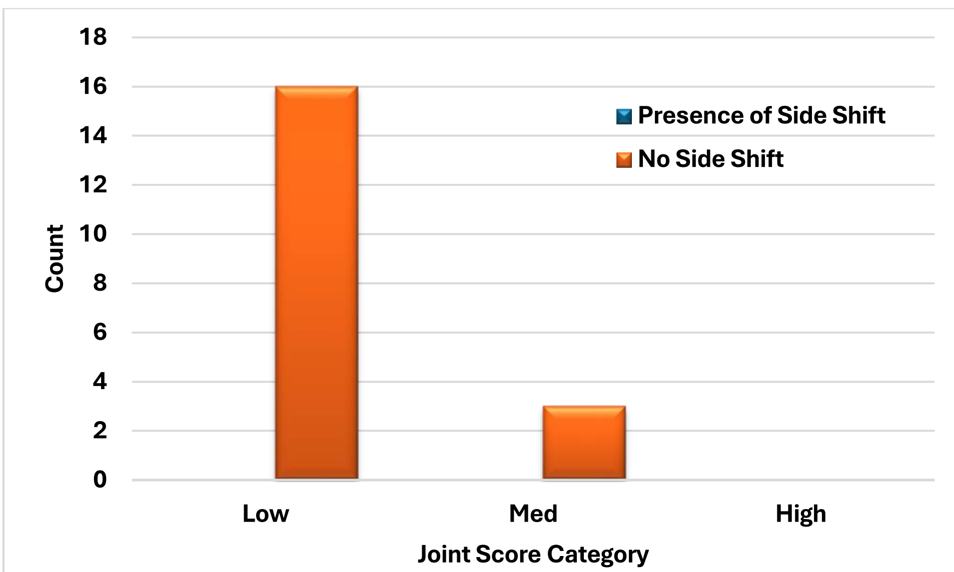

Figure 17163. Joint score and presence of side shift for USH 12 SB Section 1 Lane 1

USH 12 SB Section 1 Lane 2

Table 58. Details of test sections in USH 12 SB Section 1 Lane 2

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
USH 12 SB Section 1 Lane 2	9.5	1.25		12

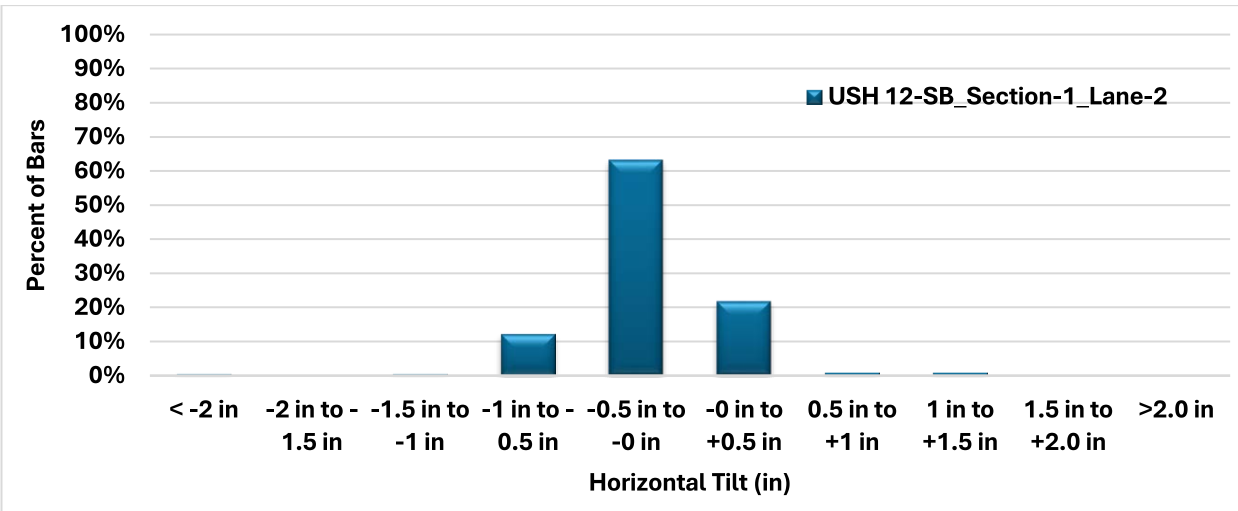

Figure 172. Horizontal Skew distribution for USH 12 SB Section 1 Lane 2

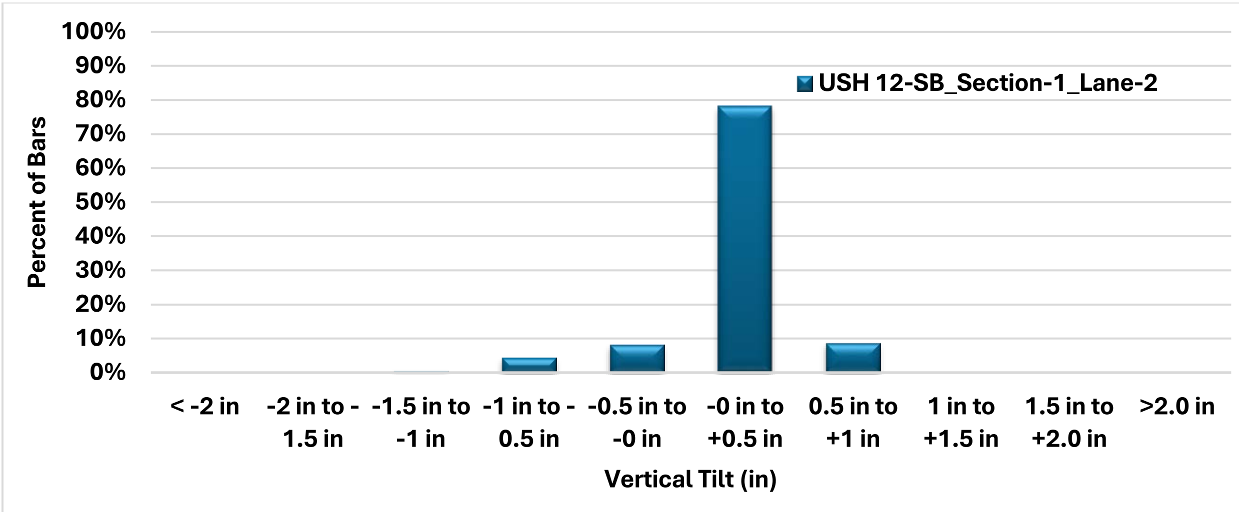

Figure 173. Vertical Tilt distribution for USH 12 SB Section 1 Lane 2

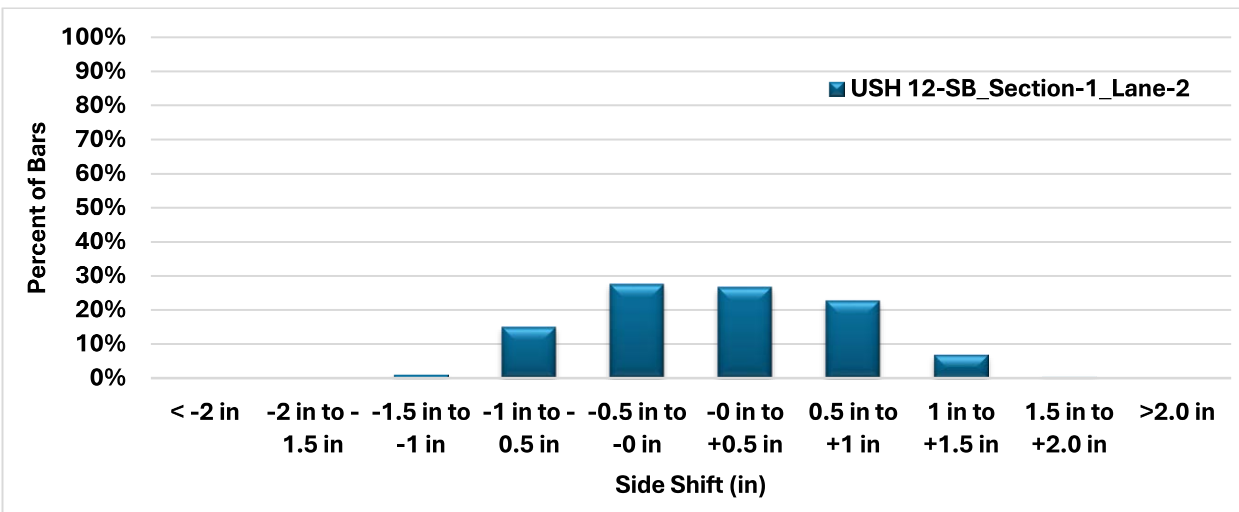

Figure 174. Longitudinal Translation distribution for USH 12 SB Section 1 Lane 2

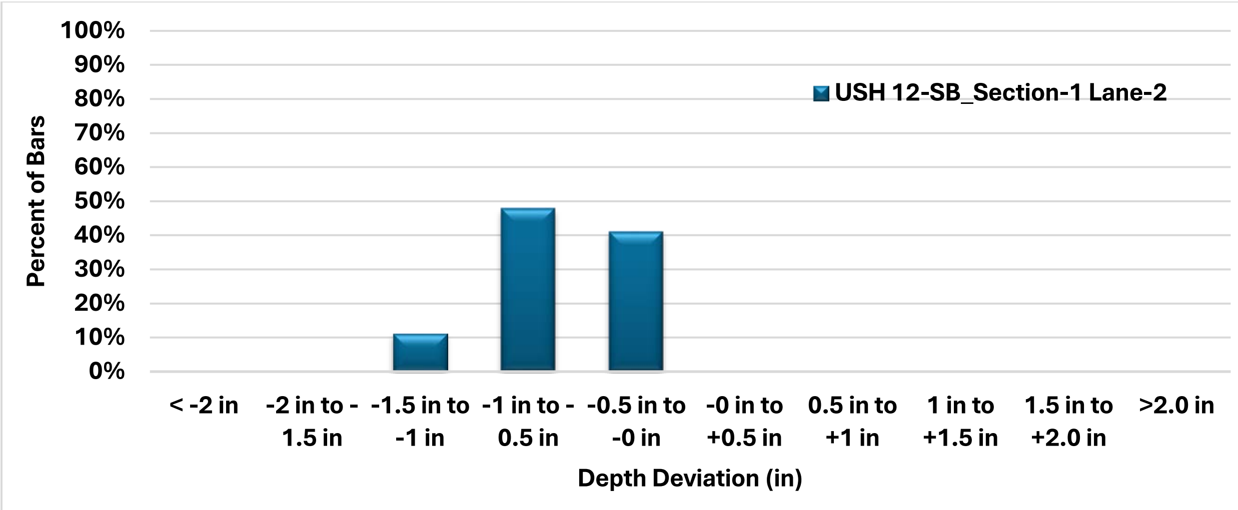

Figure 175. Vertical Translation distribution for USH 12 SB Section 1 Lane 2

Table 59. Dowel misalignment summary for USH 12 SB Section 1 Lane 2

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
USH 12 SB Section 1 Lane 2	-0.19	0.27	0.23	0.18	0.12	0.33	-0.63	0.26

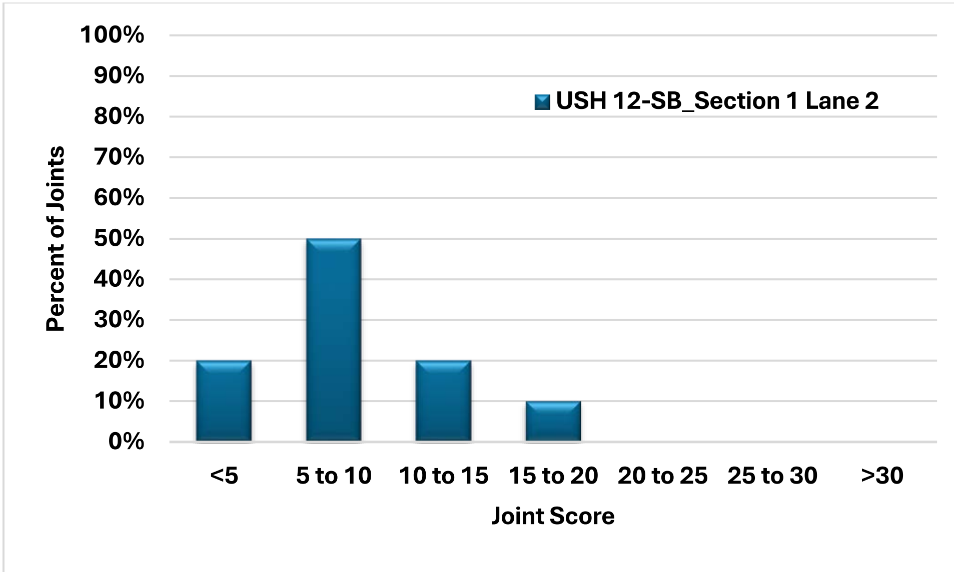

Figure 176. Joint score distribution for USH 12 SB Section 1 Lane 2

Table 60. Joint score and effective dowel diameter for USH 12 SB Section 1 Lane 2

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
USH 12 SB Section 1 Lane 2	8.2	4.5	9.5	1.25	1.226	0.012	1.95

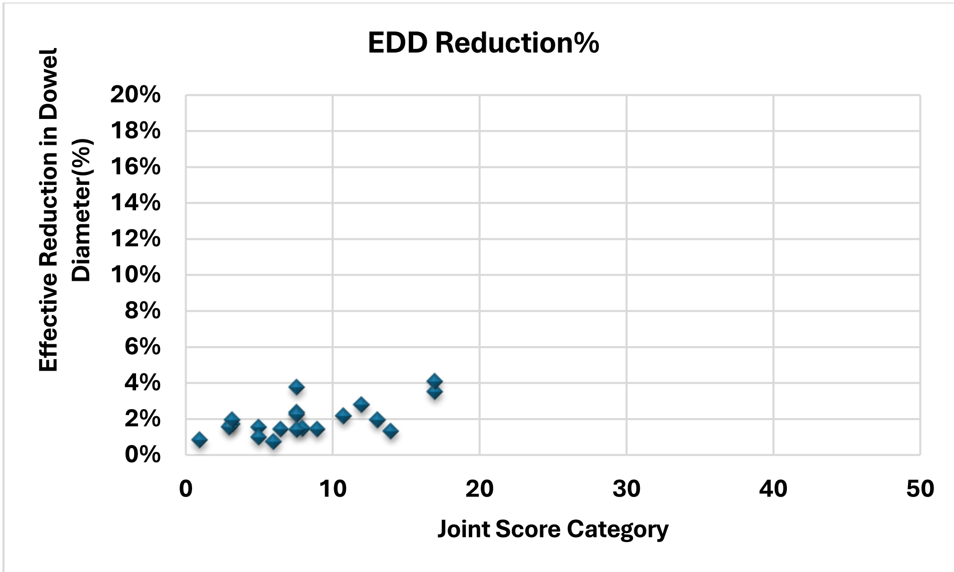

Figure 177. Joint score versus effective reduction in dowel diameter for USH 12 SB Section 1 Lane 2

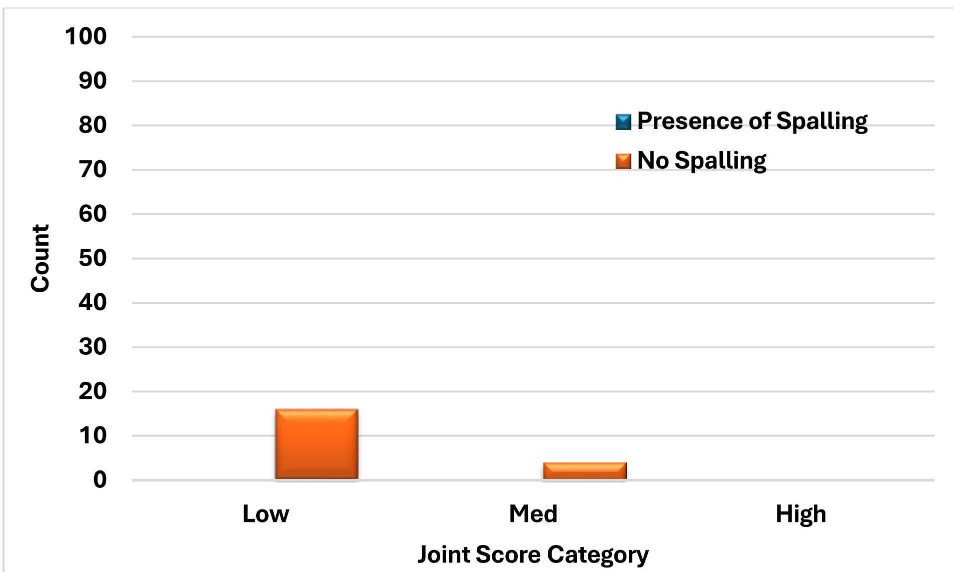

Figure 178. Joint score and presence of spalling for USH 12 SB Section 1 Lane 2

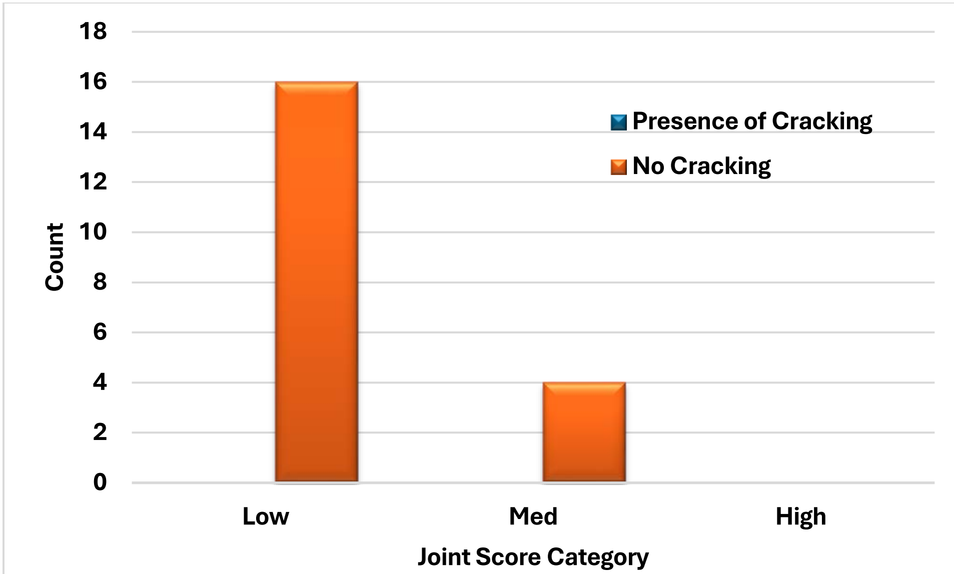

Figure 17964. Joint score and presence of cracking for USH 12 SB Section 1 Lane 2

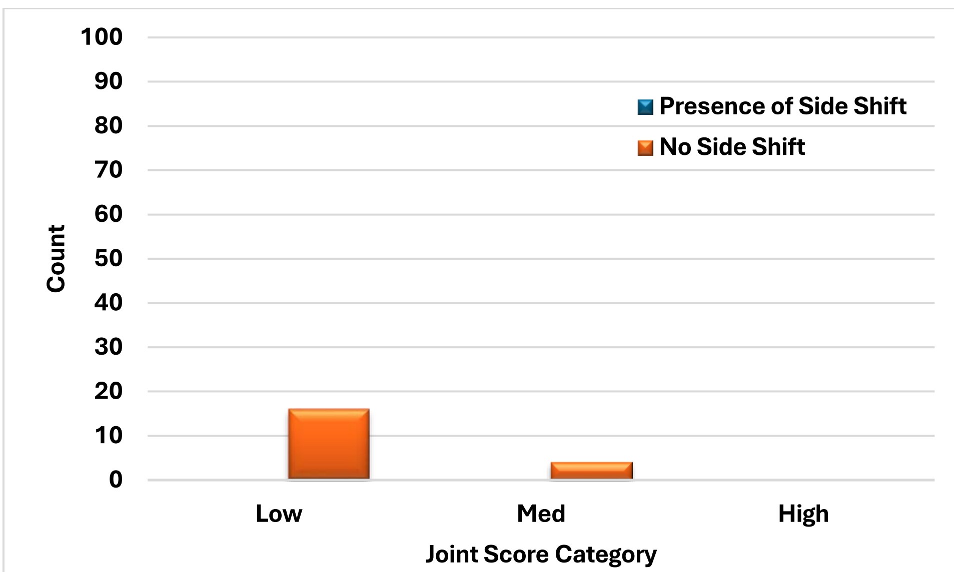

Figure 18065. Joint score and presence of side shift for USH 12 SB Section 1 Lane 2

USH 12 SB Section 2 Lane 1

Table 61. Details of test sections in USH 12 SB Section 2 Lane 1

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
USH 12 SB Section 2 Lane 1	9.5	1.25		12

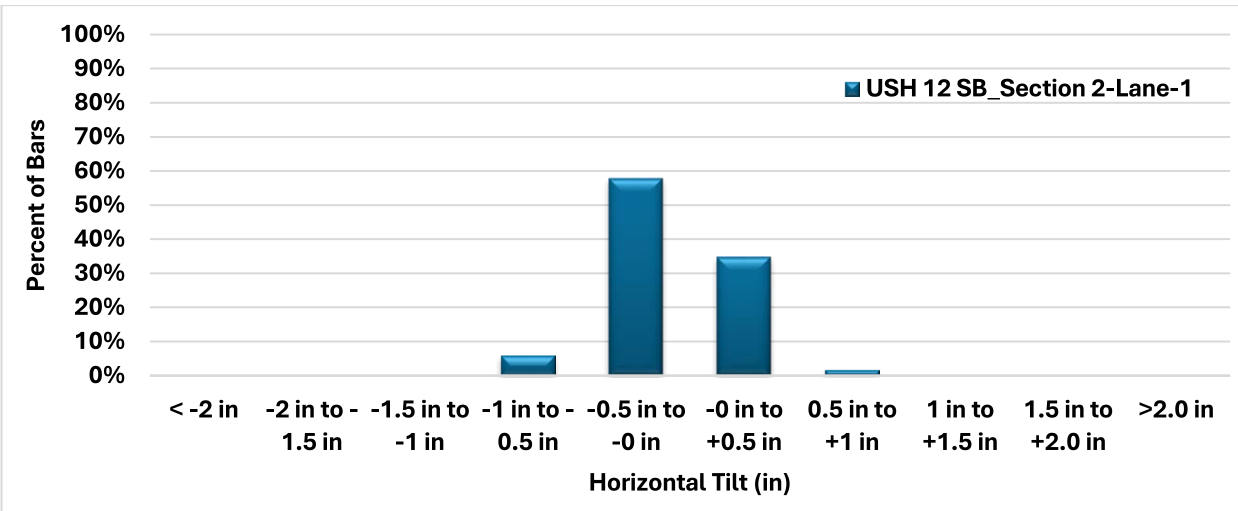

Figure 181. Horizontal Skew distribution for USH 12 SB Section 2 Lane 1

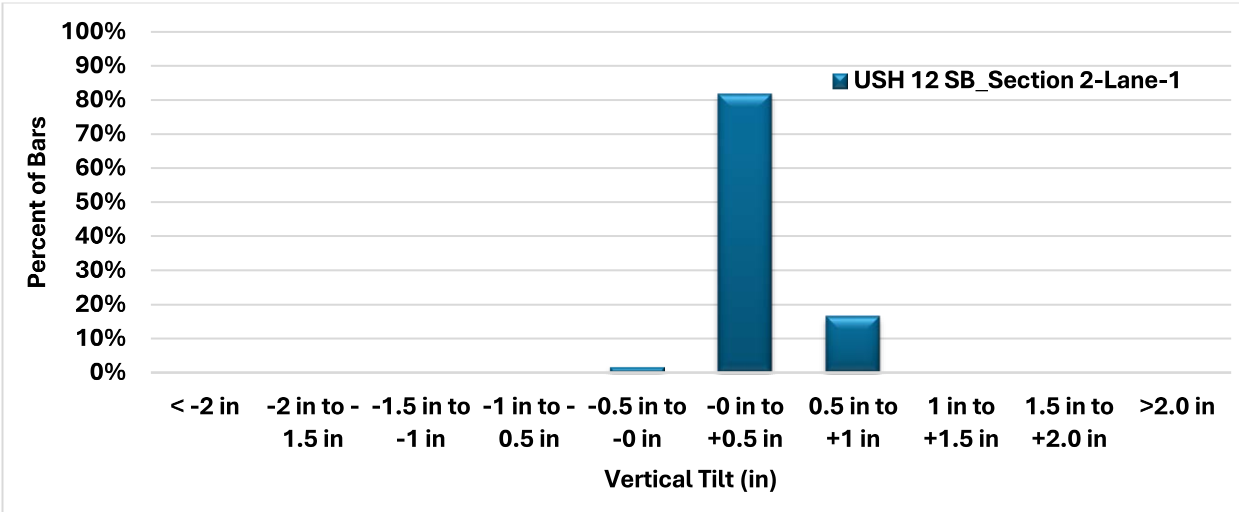

Figure 182. Vertical Tilt distribution for USH 12 SB Section 2 Lane 1

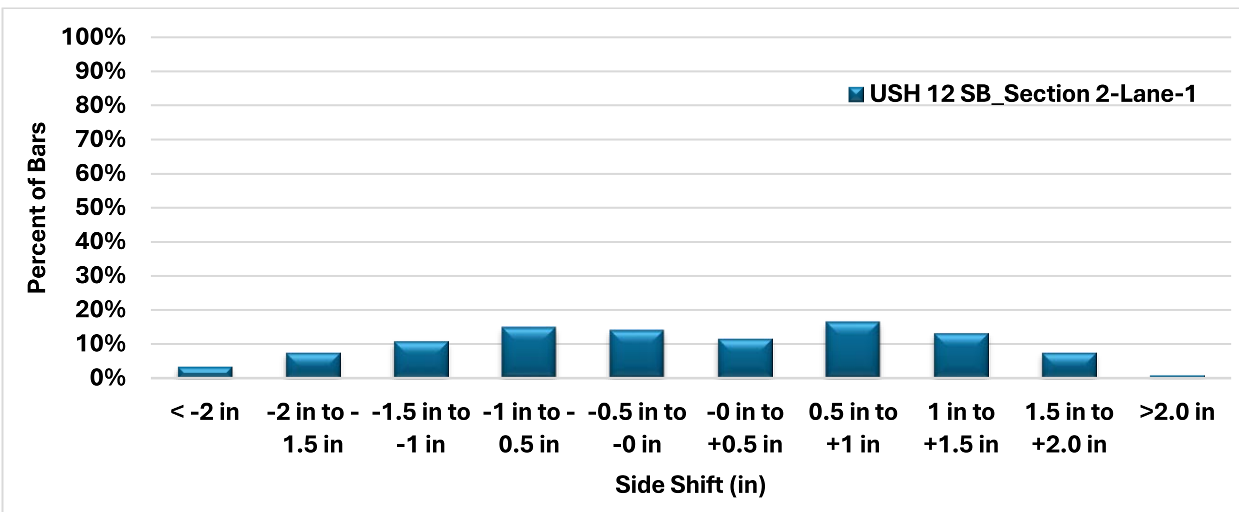

Figure 183. Longitudinal Translation distribution for USH 12 SB Section 2 Lane 1

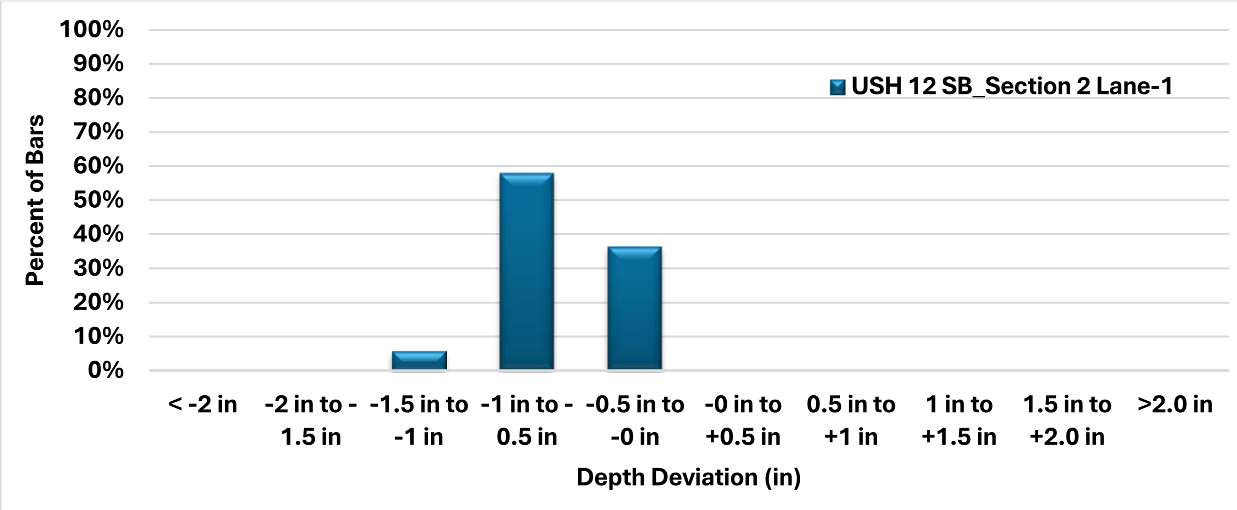

Figure 184. Vertical Translation distribution for USH 12 SB Section 2 Lane 1

Table 62. Dowel misalignment summary for USH 12 SB Section 2 Lane 1

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
USH 12 SB Section 2 Lane 1	-0.12	0.17	0.35	0.15	-0.03	0.58	-0.63	0.21

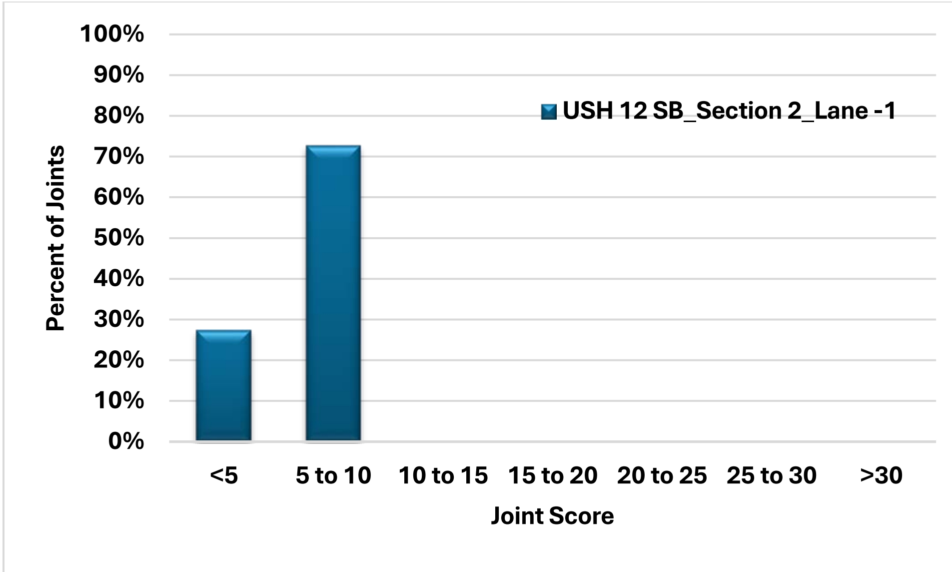

Figure 185. Joint score distribution for USH 12 SB Section 2 Lane 1

Table 63. Joint score and effective dowel diameter for USH 12 SB Section 2 Lane 1

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
USH 12 SB Section 2 Lane 1	5.0	1.8	9.59	1.25	1.226	0.011	1.92

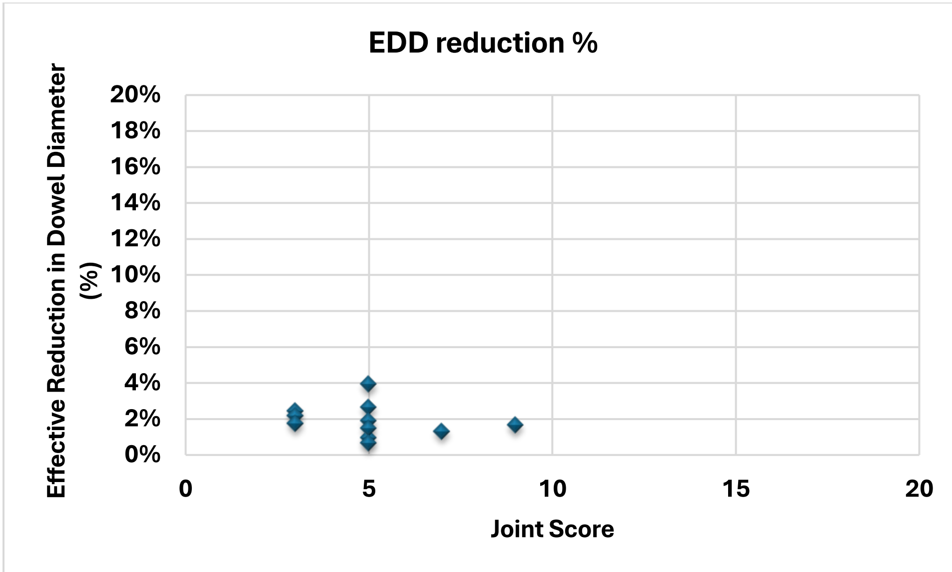

Figure 186. Joint score versus effective reduction in dowel diameter for USH 12 SB Section 2 Lane 1

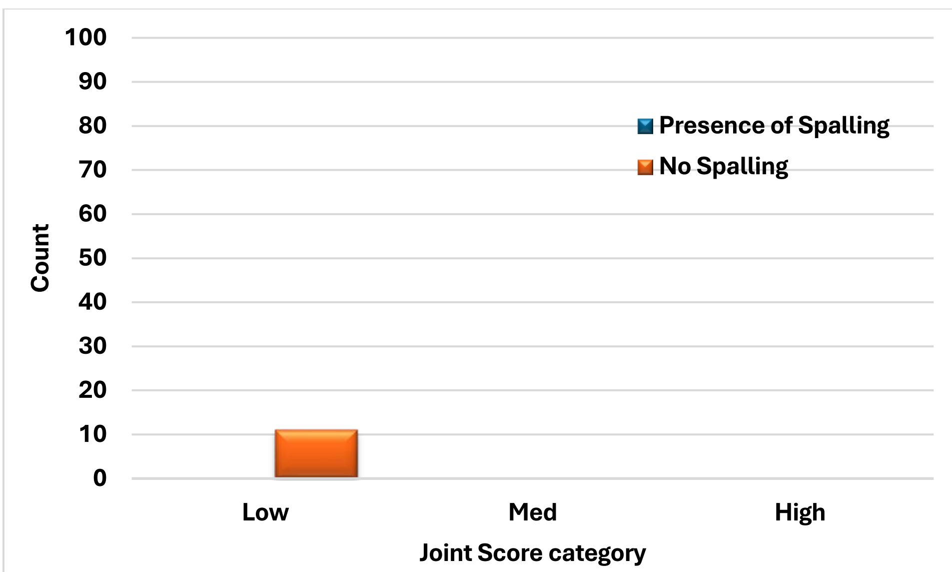

Figure 187. Joint score and presence of spalling for USH 12 SB Section 2 Lane 1

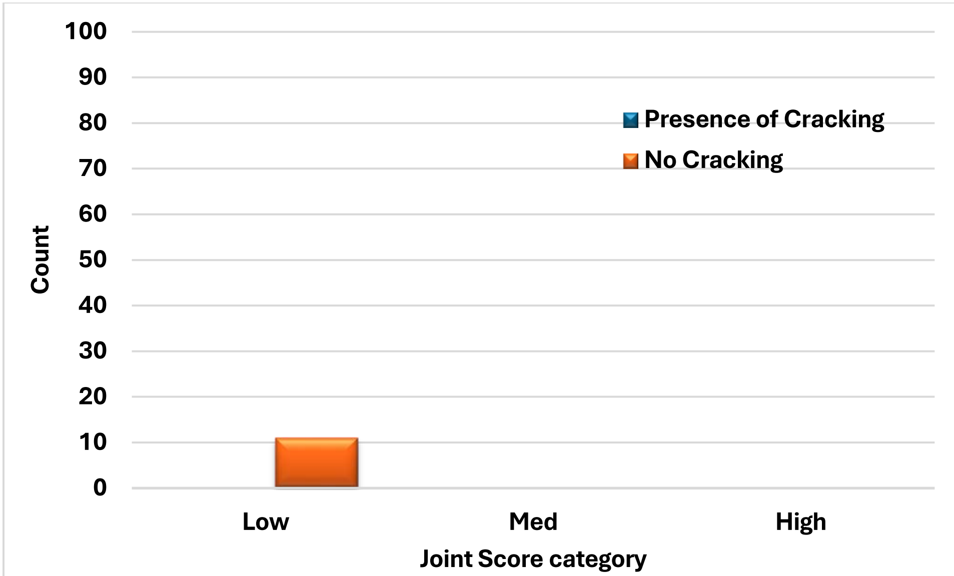

Figure 18866. Joint score and presence of cracking for USH 12 SB Section 2 Lane 1

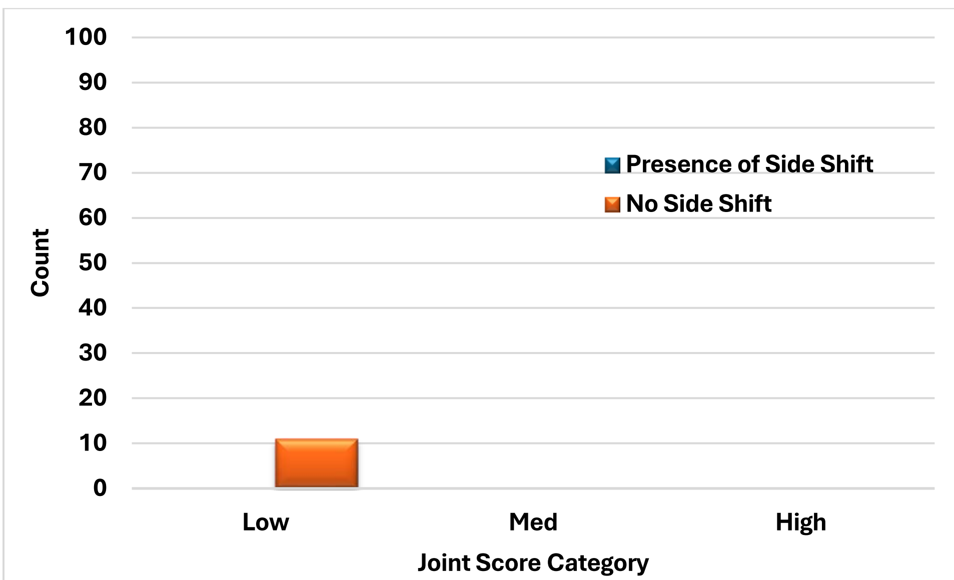

Figure 18967. Joint score and presence of side shift for USH 12 SB Section 2 Lane 1

USH 12 SB Section 2 Lane 2

Table 64. Details of test sections in USH 12 SB Section 2 Lane 2

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
USH 12 SB Section 2 Lane 2	9.5	1.25		12

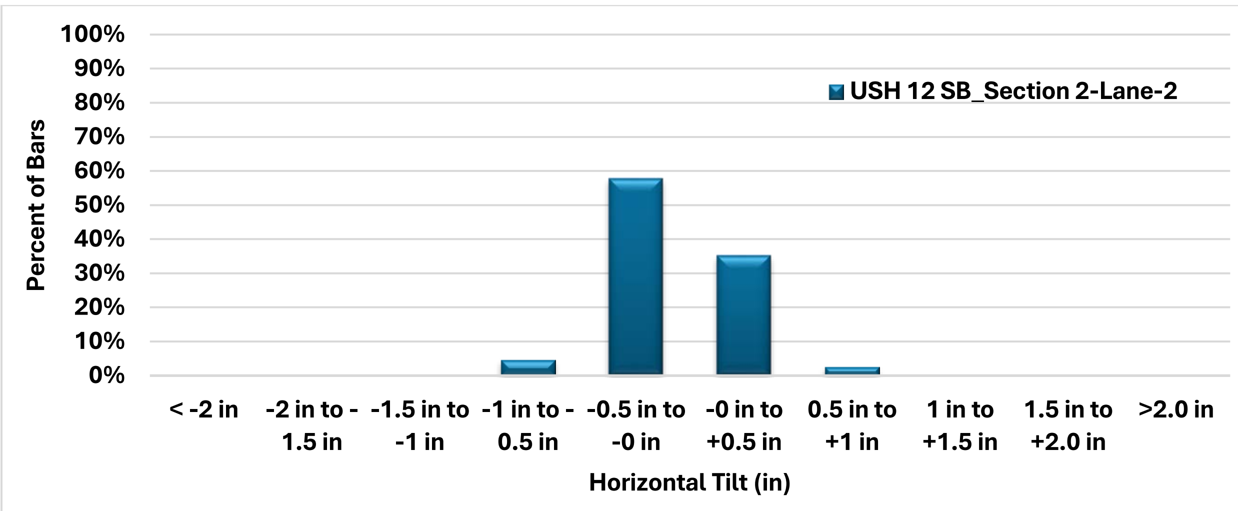

Figure 190. Horizontal Skew distribution for USH 12 SB Section 2 Lane 2

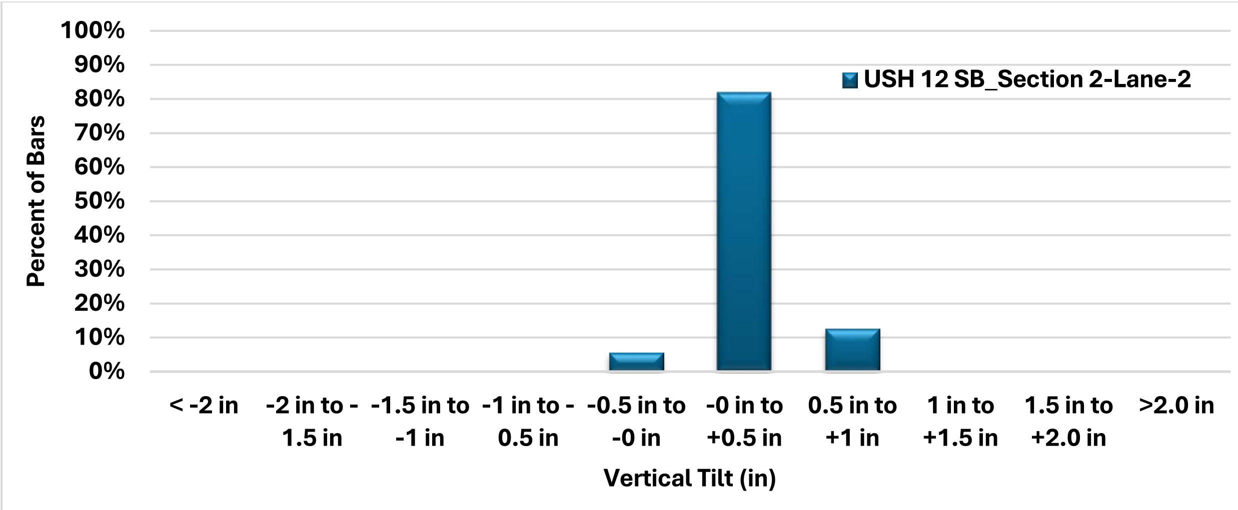

Figure 191. Vertical Tilt distribution for USH 12 SB Section 2 Lane 2

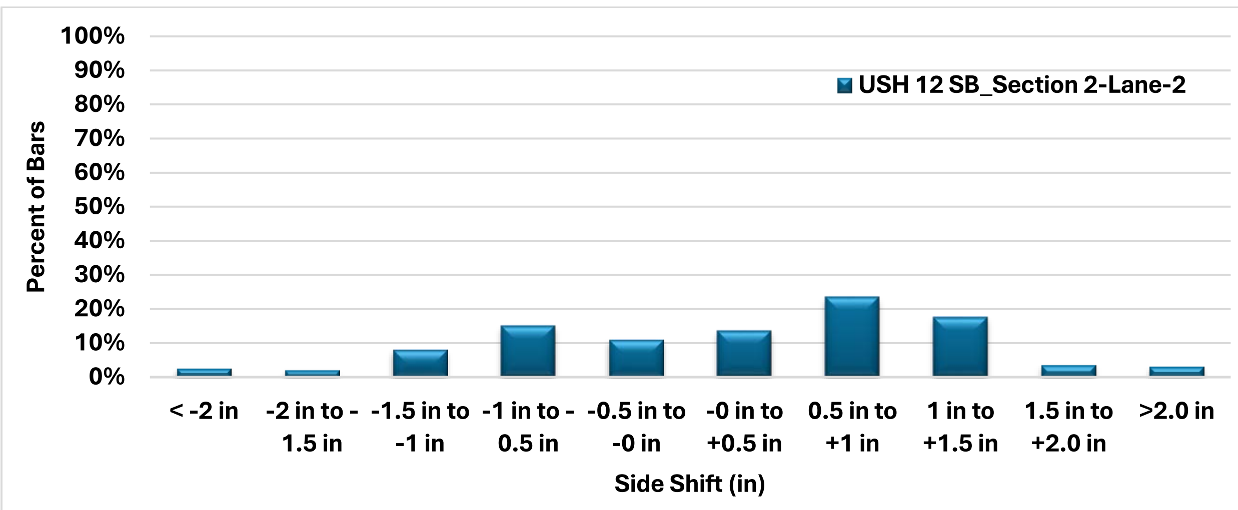

Figure 192. Longitudinal Translation distribution for USH 12 SB Section 2 Lane 2

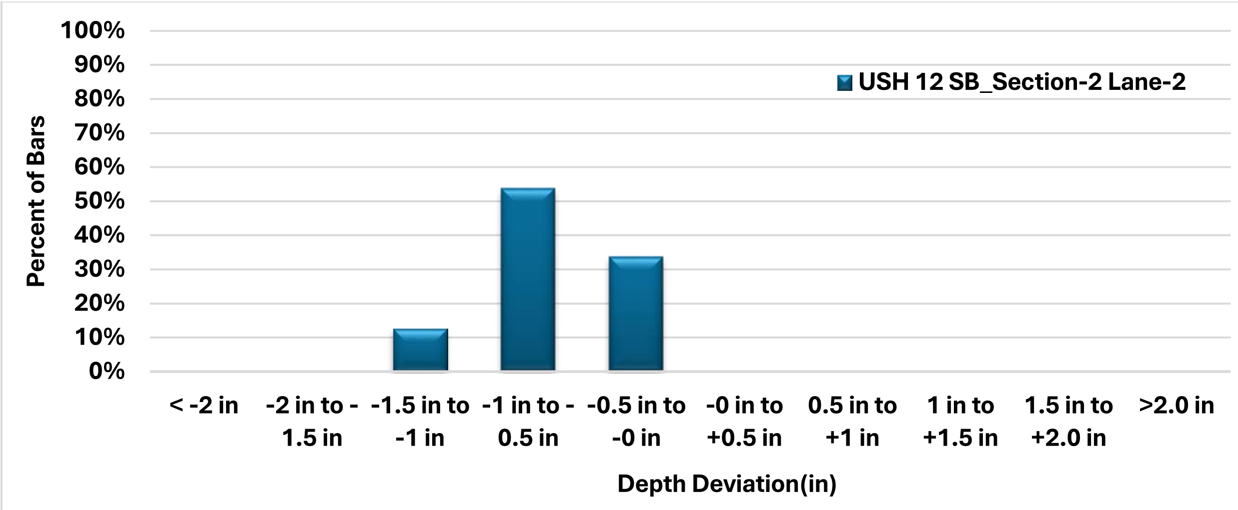

Figure 193. Vertical Translation distribution for USH 12 SB Section 2 Lane 2

Table 65. Dowel misalignment summary for USH 12 SB Section 2 Lane 2

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
USH 12 SB Section 2 Lane 2	-0.09	0.17	0.31	0.16	0.23	0.56	-0.67	0.26

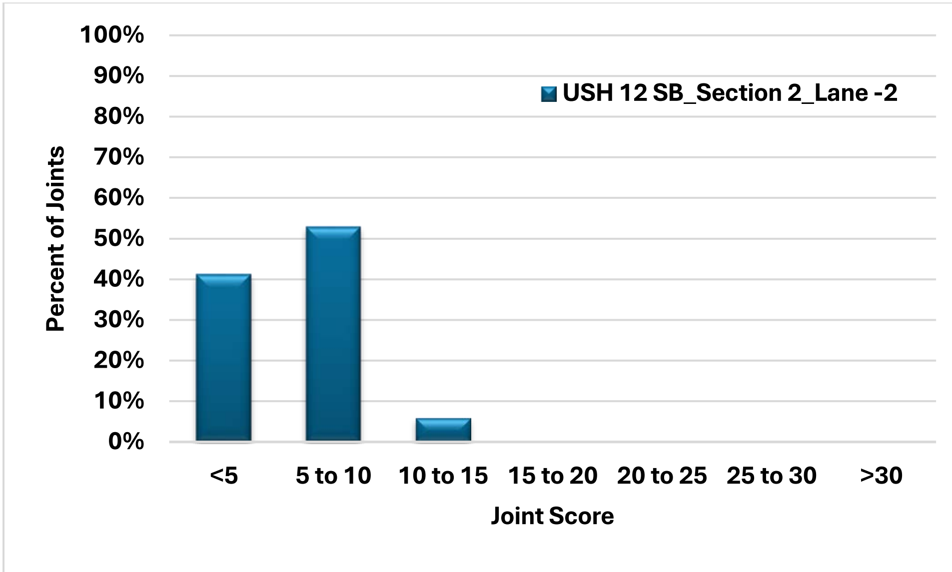

Figure 194. Joint score distribution for USH 12 SB Section 2 Lane 2

Table 66. Joint score and effective dowel diameter for USH 12 SB Section 2 Lane 2

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
USH 12 SB Section 2 Lane 2	5.1	3.0	9.5	1.25	1.223	0.012	2.16

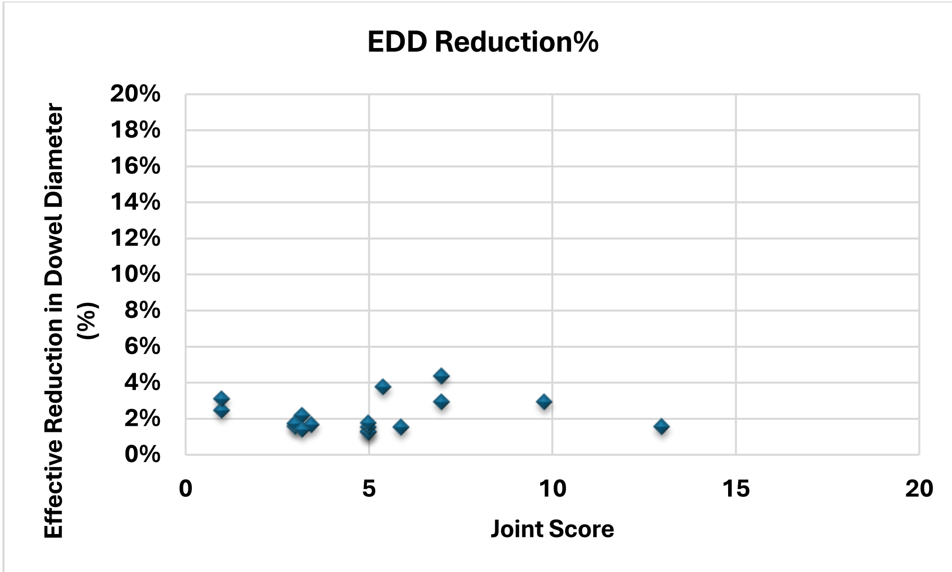

Figure 195. Joint score versus effective reduction in dowel diameter for USH 12 SB Section 2 Lane 2

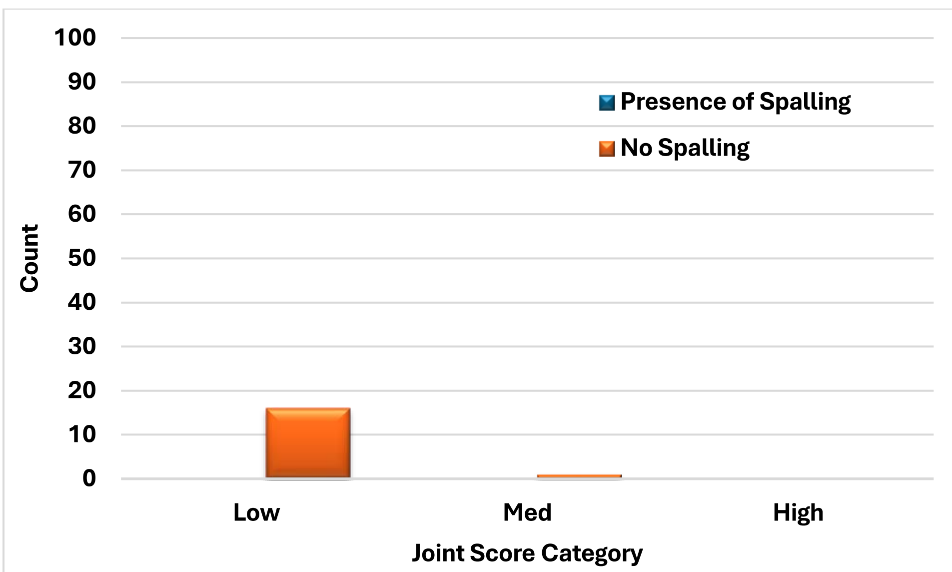

Figure 196. Joint score and presence of spalling for USH 12 SB Section 2 Lane 2

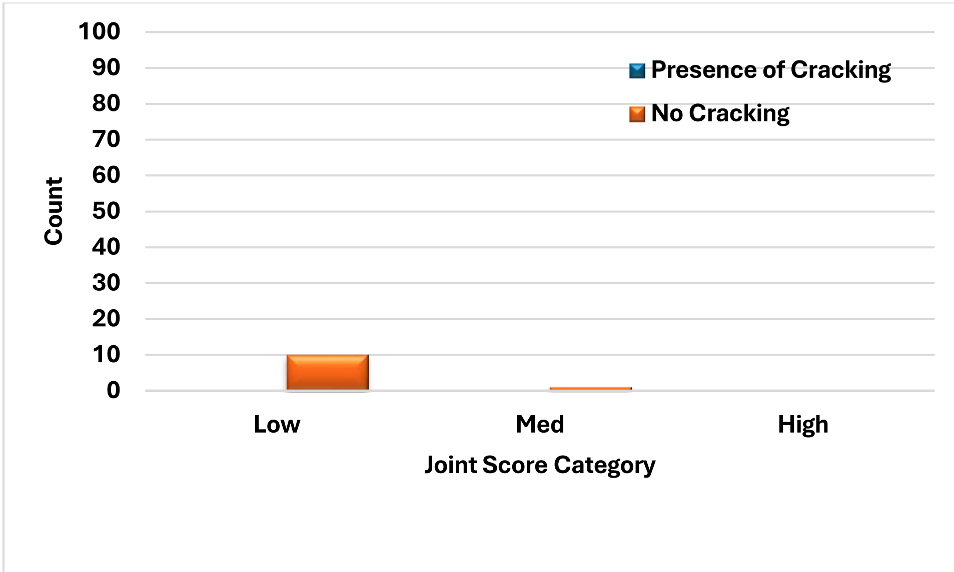

Figure 19768. Joint score and presence of cracking for USH 12 SB Section 2 Lane 2

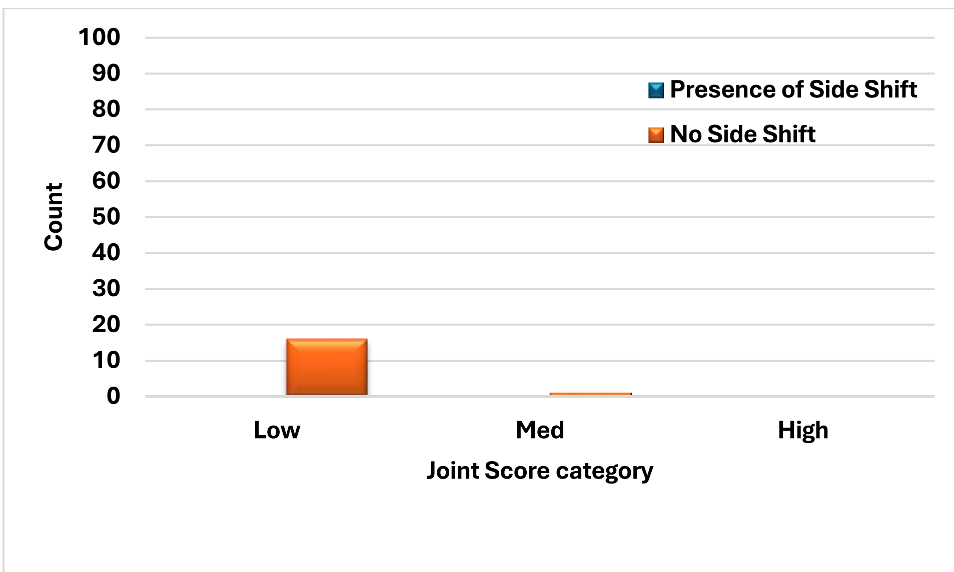

Figure 19869. Joint score and presence of side shift for USH 12 SB Section 2 Lane 2

USH 12 SB

Table 67. Details of test sections in USH 12 SB

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
USH 12 SB	9.5	1.25		12

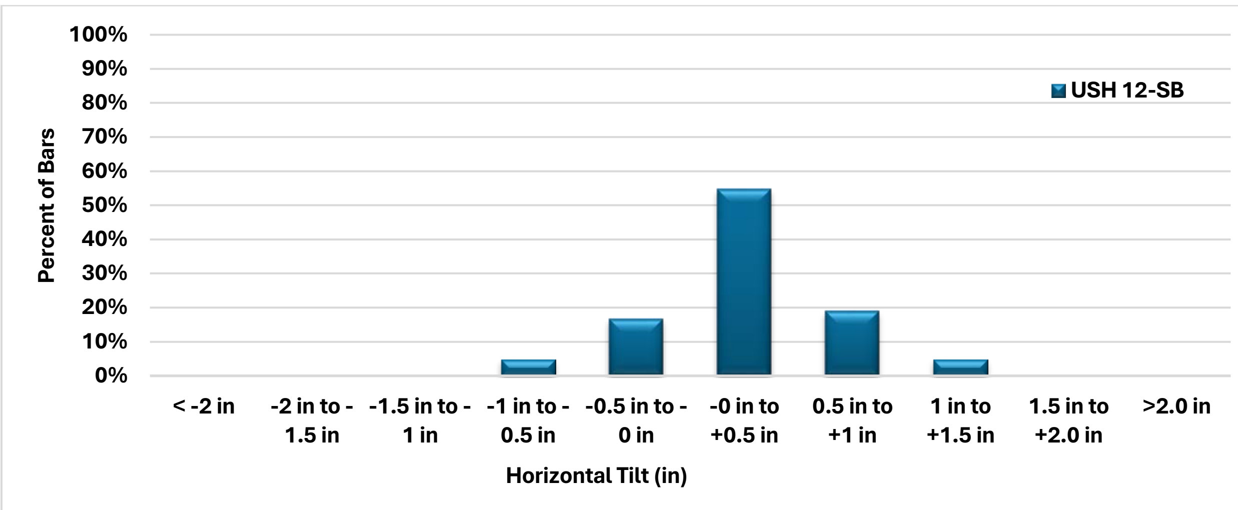

Figure 199. Horizontal Skew distribution for USH 12 SB

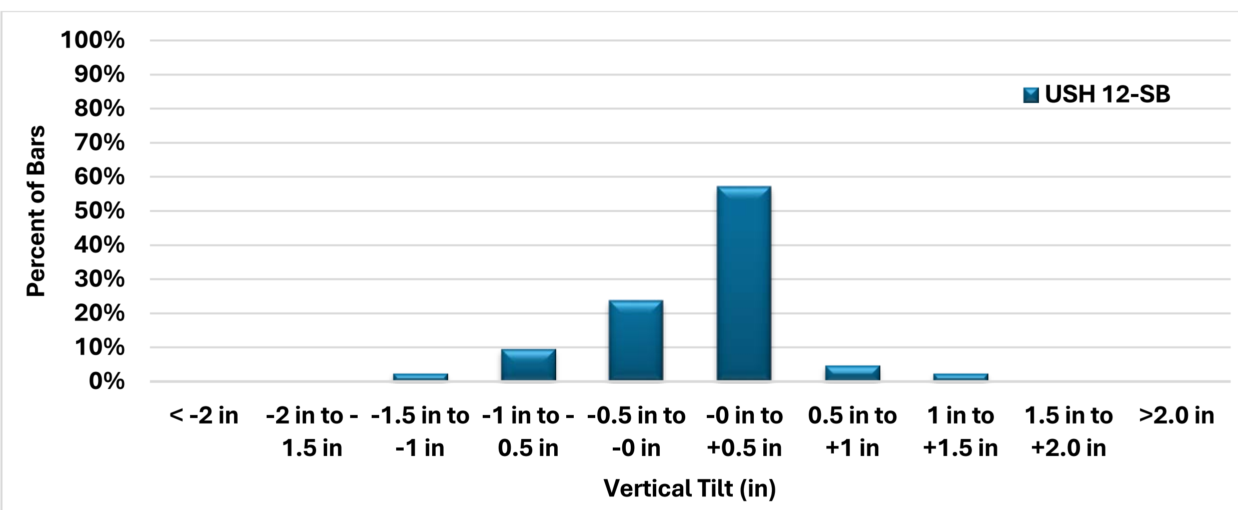

Figure 200. Vertical Tilt distribution for USH 12 SB

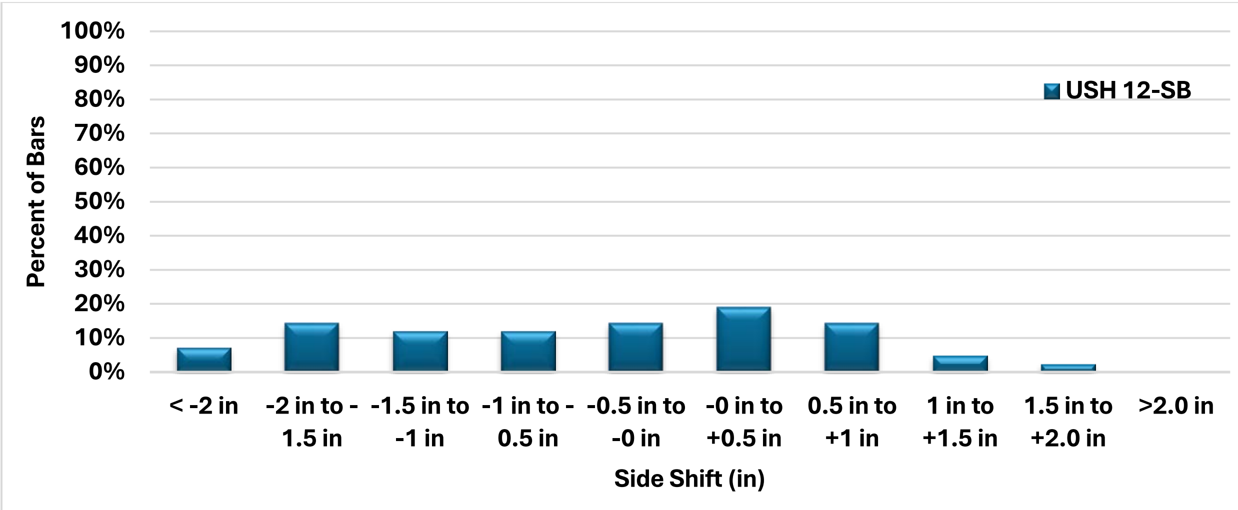

Figure 201. Longitudinal Translation distribution for USH 12 SB

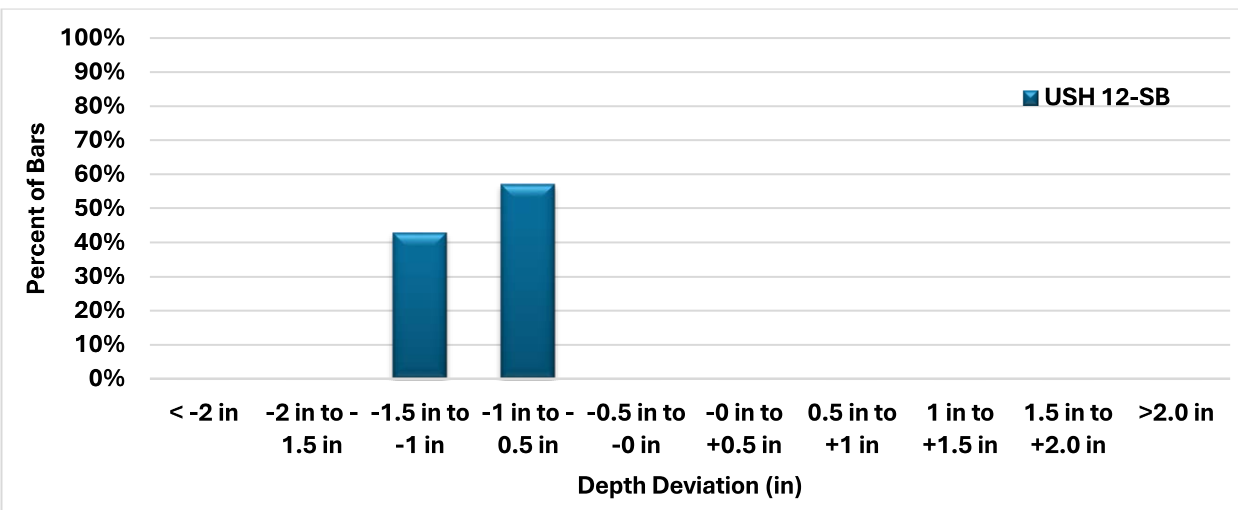

Figure 202. Vertical Translation distribution for USH 12 SB

Table 68. Dowel misalignment summary for USH 12 SB

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
USH 12 SB	0.22	0.33	0.03	0.30	-0.52	0.98	-0.96	0.18

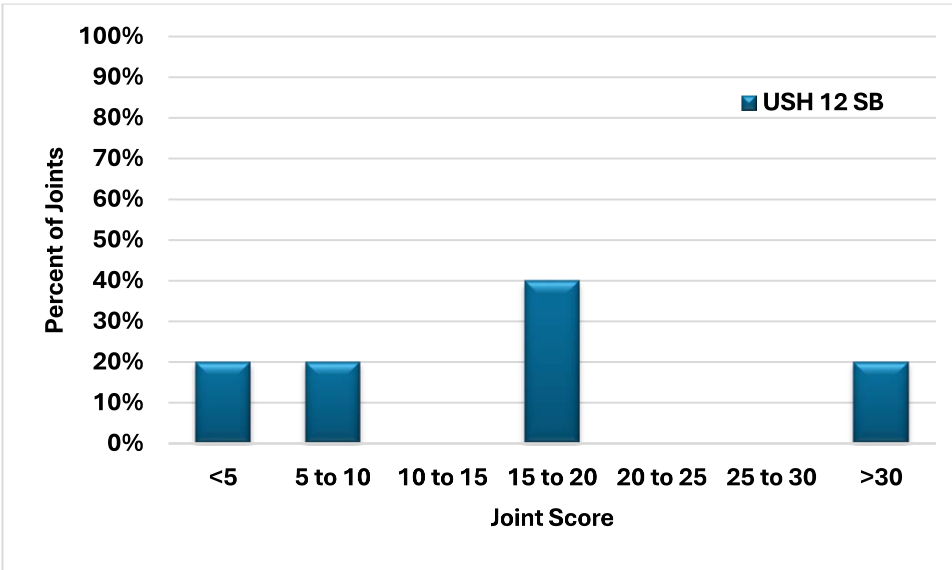

Figure 203. Joint score distribution for USH 12 SB

Table 69. Joint score and effective dowel diameter for USH 12 SB

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
USH 12 SB	19.8	22.4	9.5	1.25	1.125	0.05	10.00

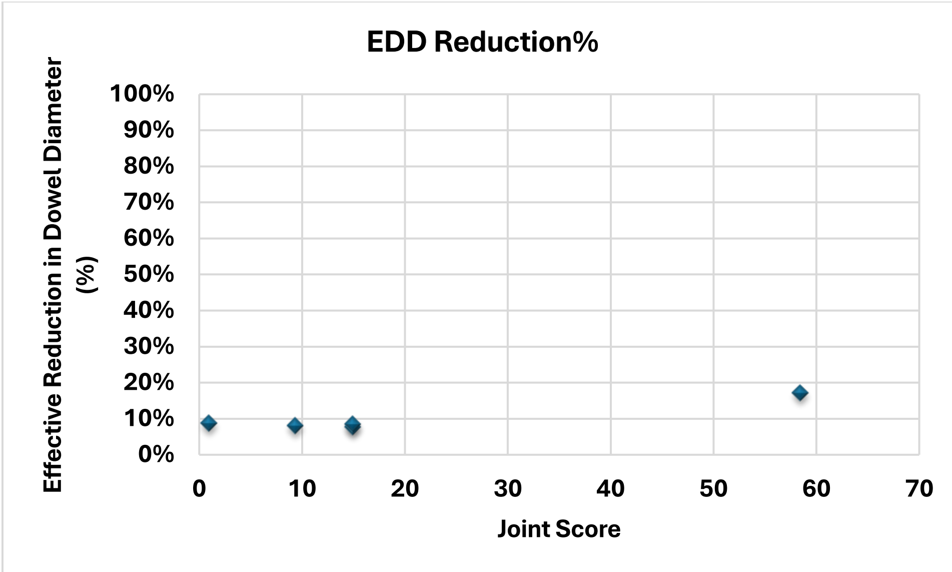

Figure 204. Joint score versus effective reduction in dowel diameter for USH 12 SB

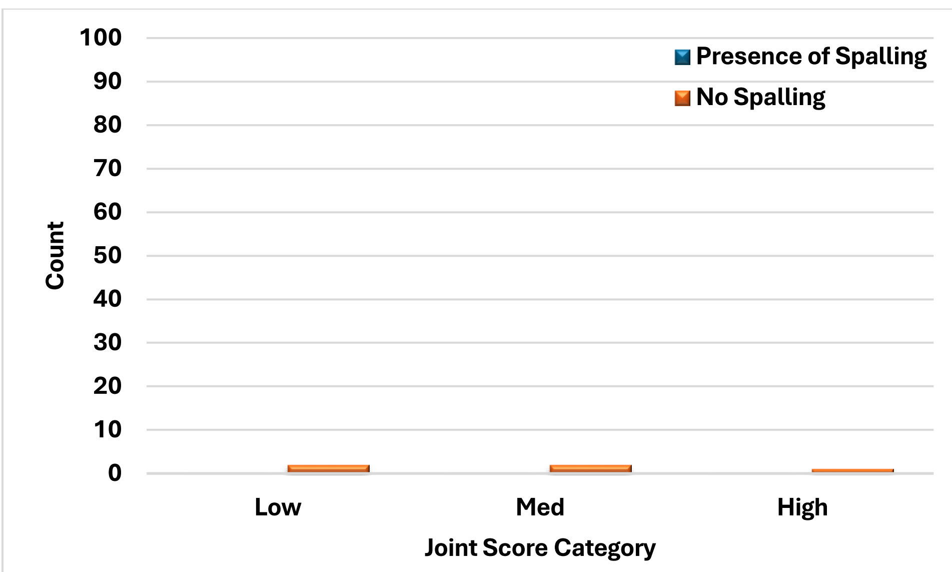

Figure 205. Joint score and presence of spalling for USH 12 SB

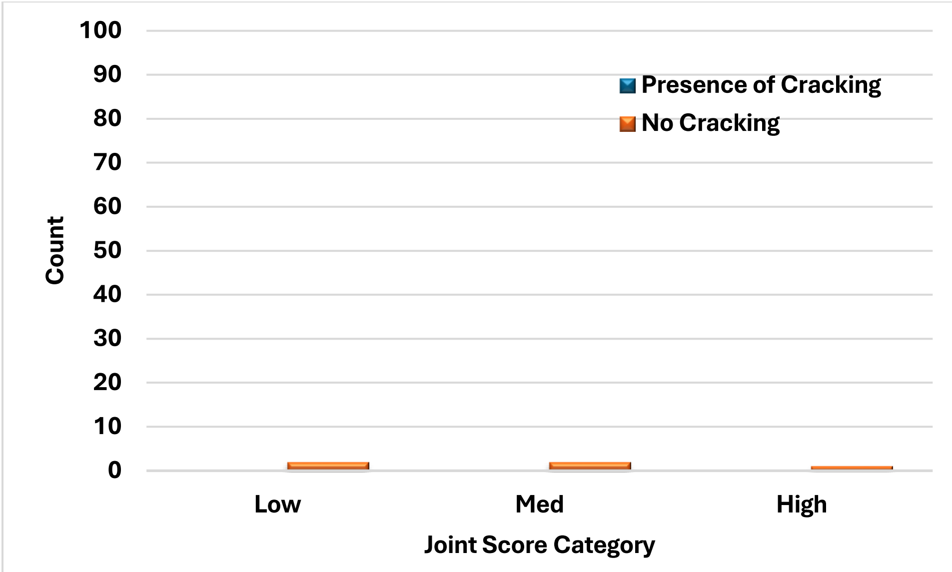

Figure 20670. Joint score and presence of cracking for USH 12 SB

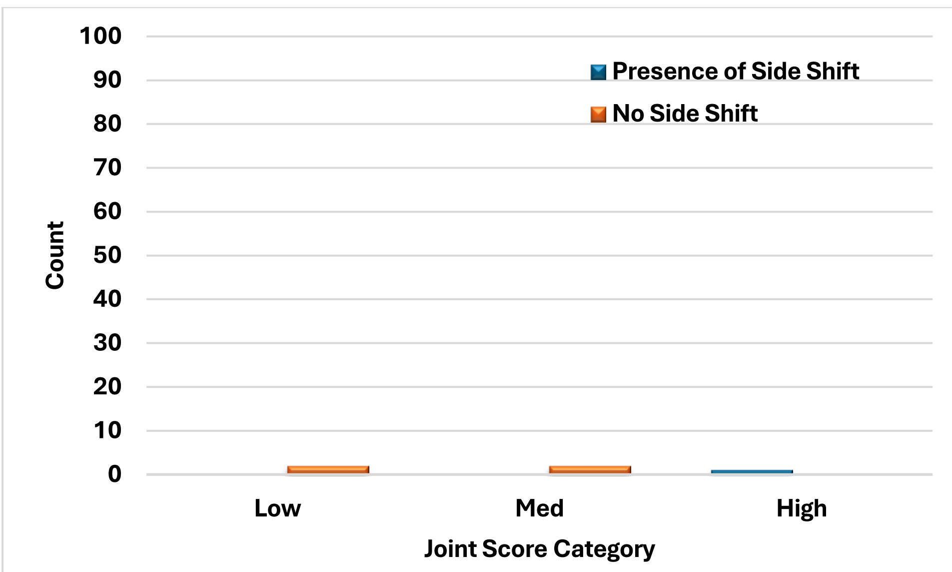

Figure 20771. Joint score and presence of side shift for USH 12 SB

HW 151 SB Fond du Lac

Table 70. Details of test sections in HW 151 SB Fond du Lac

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
HW 151 SB Fond du Lac	10	1.5		12

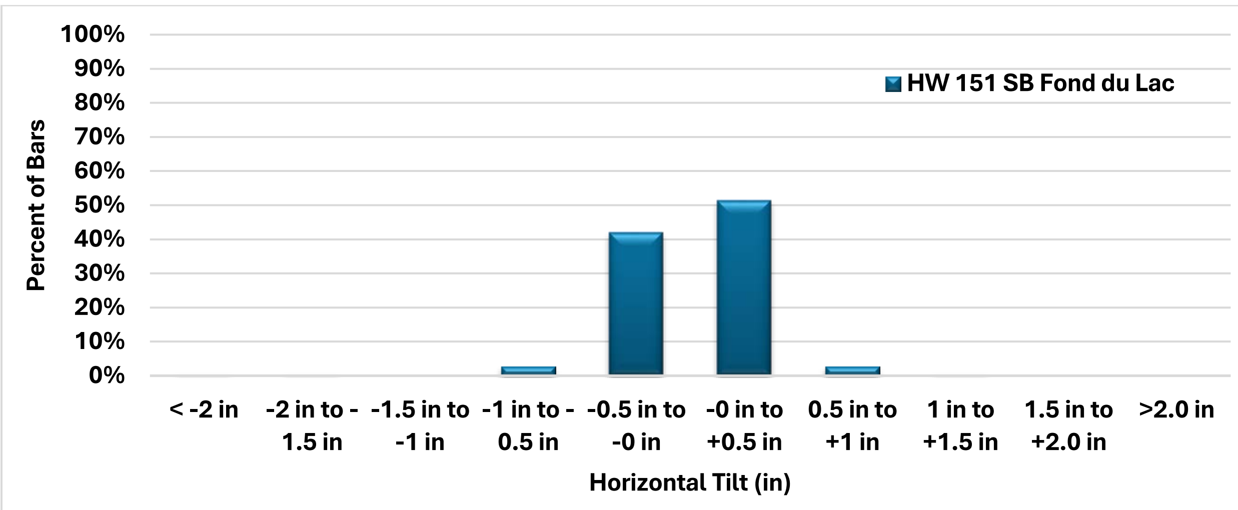

Figure 208. Horizontal Skew distribution for HW 151 SB Fond du Lac

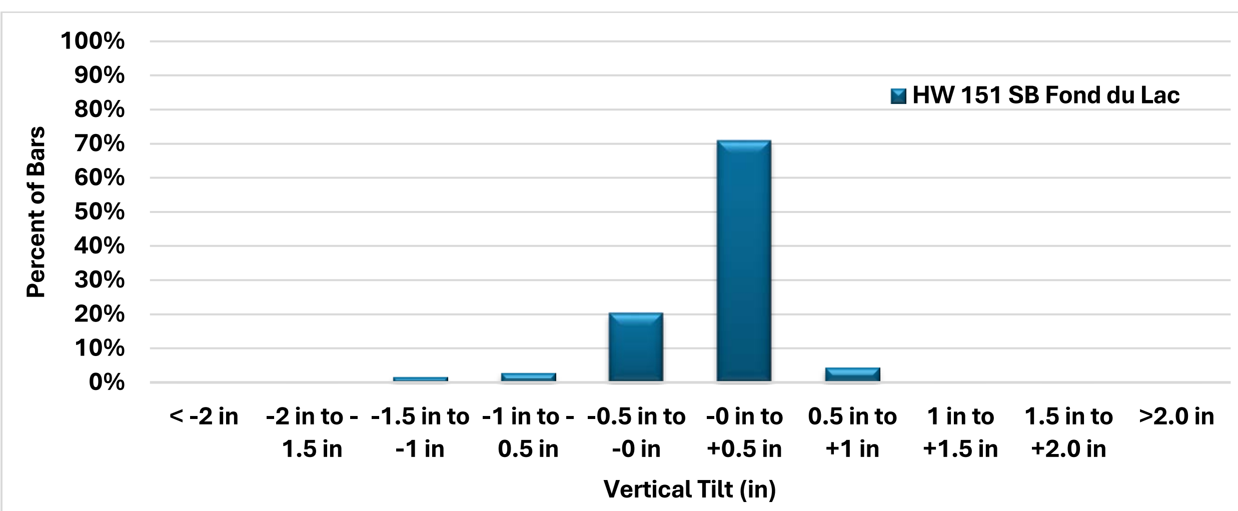

Figure 209. Vertical Tilt distribution for HW 151 SB Fond du Lac

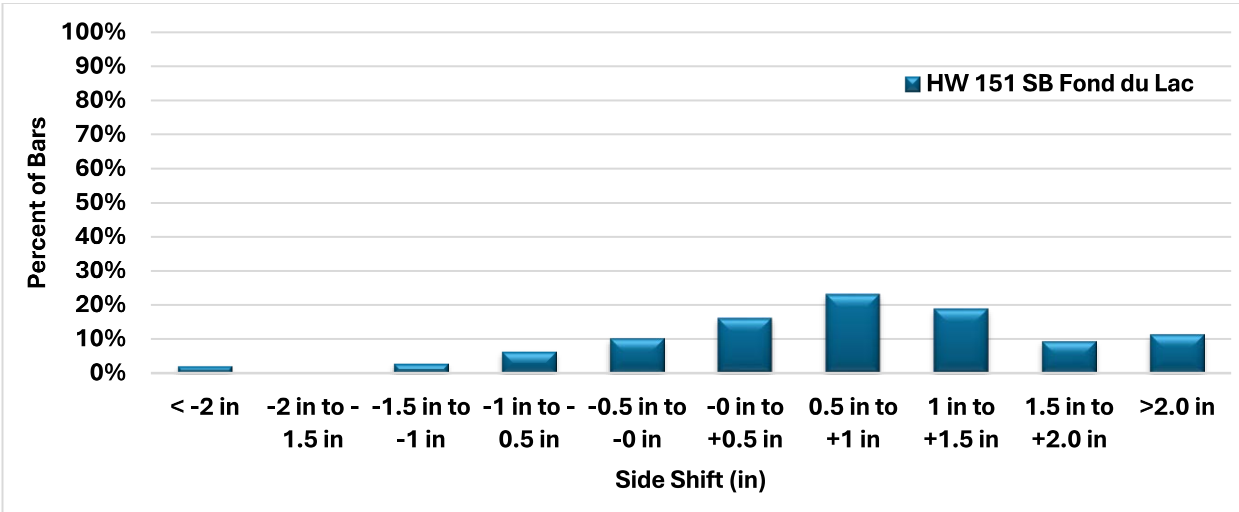

Figure 210. Longitudinal Translation distribution for HW 151 SB Fond du Lac

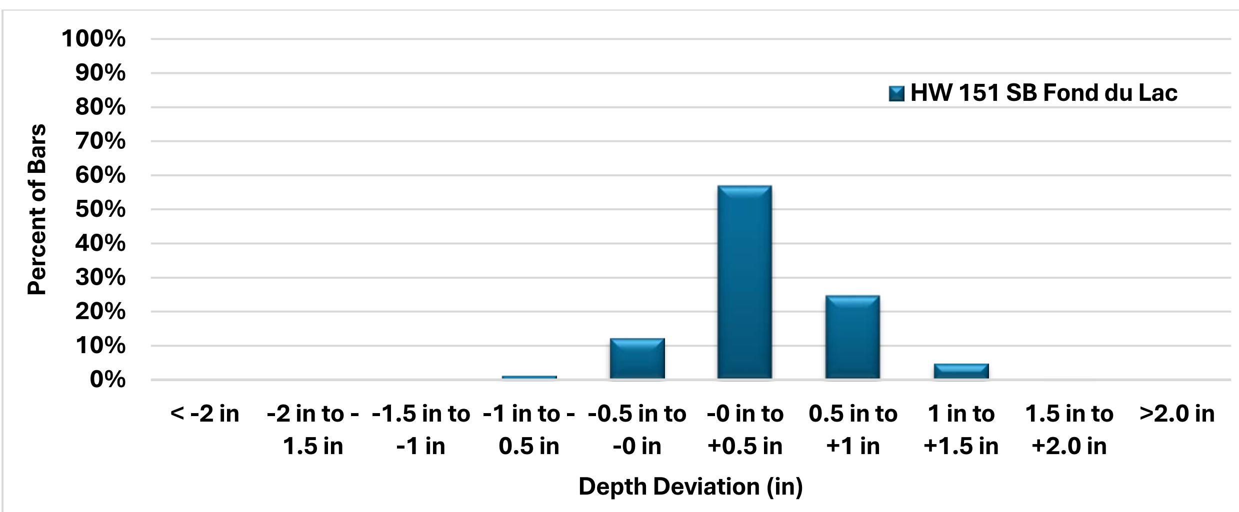

Figure 211. Vertical Translation distribution for HW 151 SB Fond du Lac

Table 71. Dowel misalignment summary for HW 151 SB Fond du Lac

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
HW 151 SB Fond du Lac	0.00	0.24	0.12	0.22	0.74	0.84	0.37	0.36

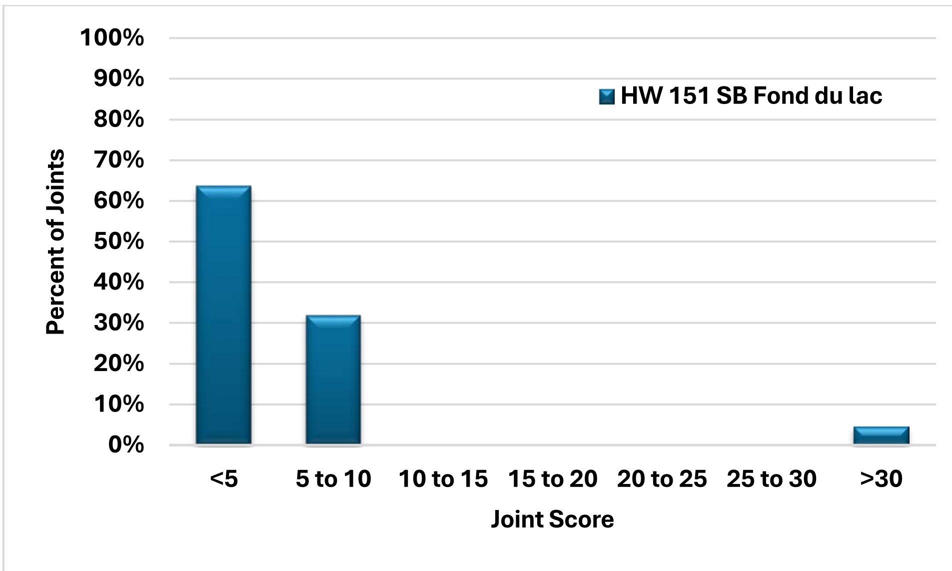

Figure 212. Joint score distribution for HW 151 SB Fond du Lac

Table 72. Joint score and effective dowel diameter for HW 151 SB Fond du Lac

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
HW 151 SB Fond du Lac	5.5	10.9	10	1.5	1.476	0.018	1.60

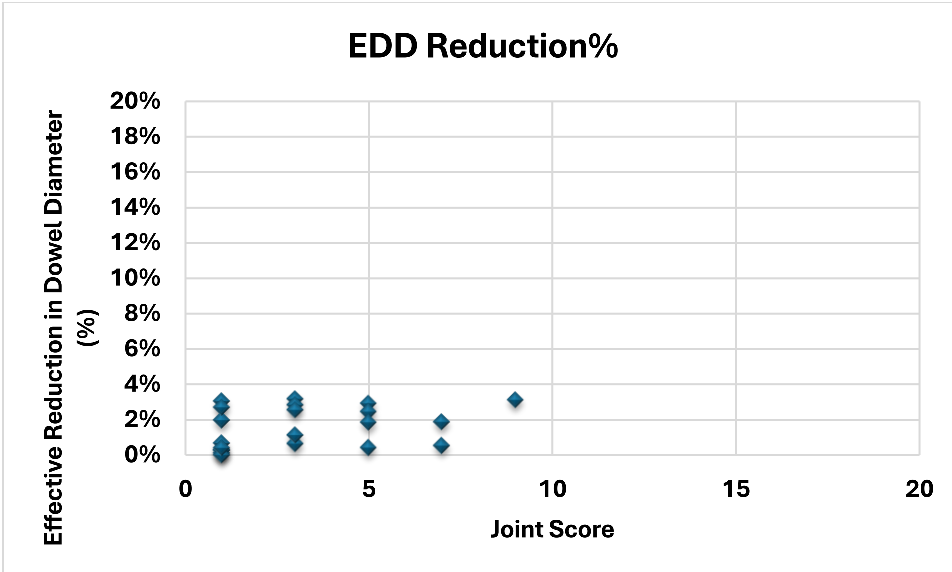

Figure 213. Joint score versus effective reduction in dowel diameter for HW 151 SB Fond du Lac

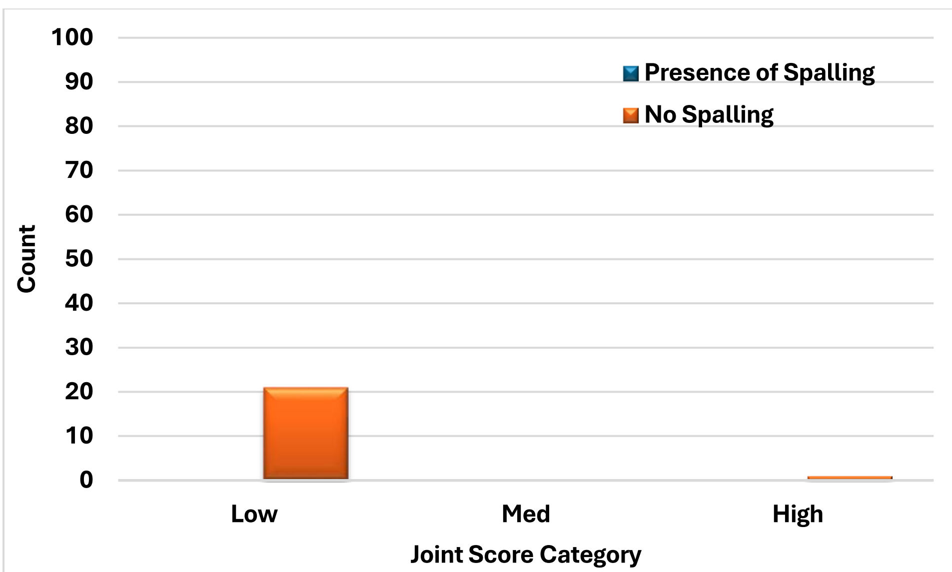

Figure 214. Joint score and presence of spalling for HW 151 SB Fond du Lac

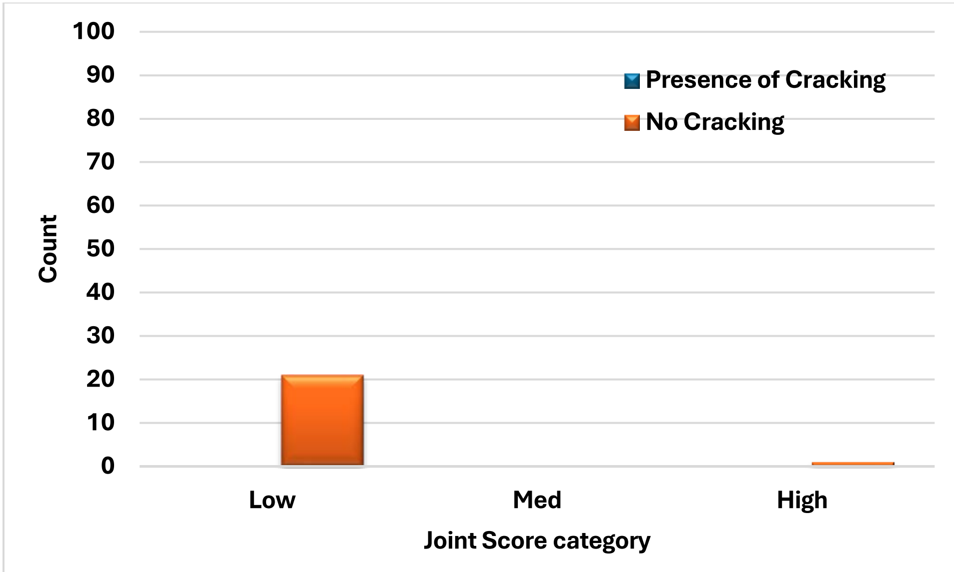

Figure 21572. Joint score and presence of cracking for HW 151 SB Fond du Lac

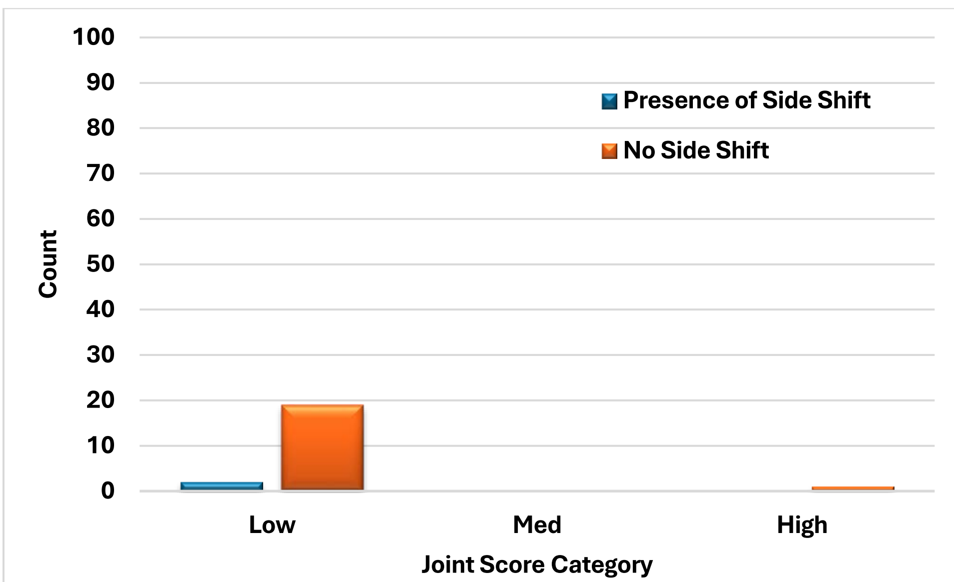

Figure 21673. Joint score and presence of side shift for HW 151 SB Fond du Lac

HW 151 SB Fond du Lac County 2

Table 73. Details of test sections in HW 151 SB Fond du Lac County 2

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
HW 151 SB Fond du Lac	10	1.25		12

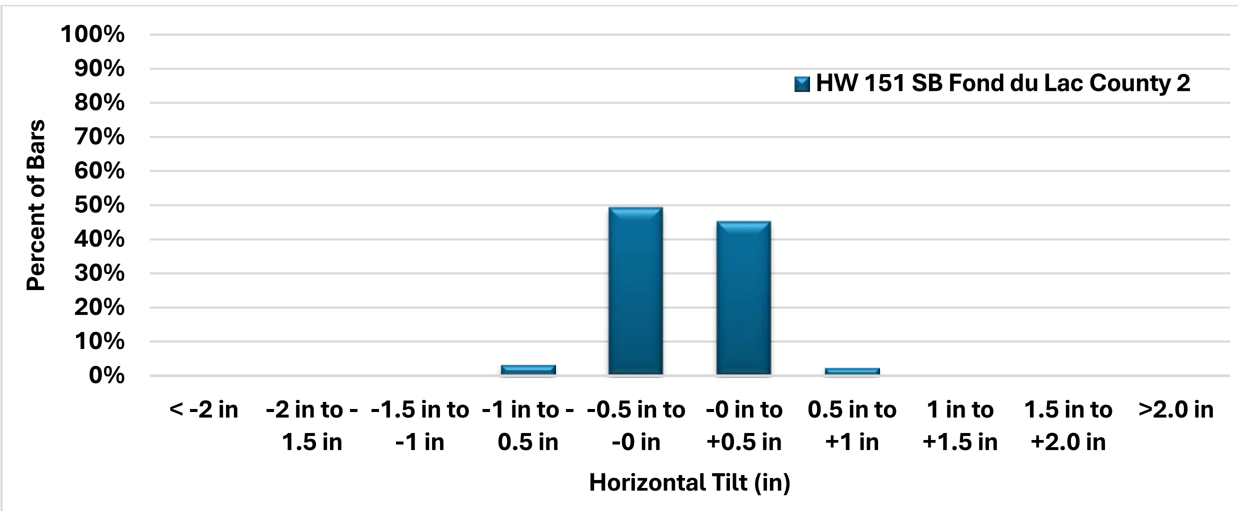

Figure 217. Horizontal Skew distribution for HW 151 SB Fond du Lac County 2

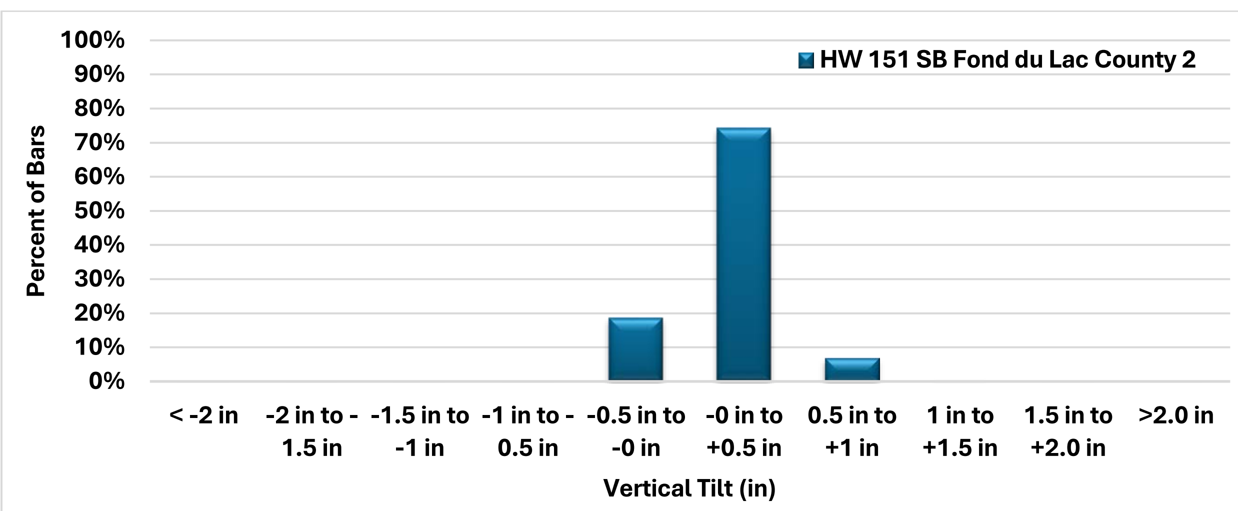

Figure 218. Vertical Tilt distribution for HW 151 SB Fond du Lac County 2

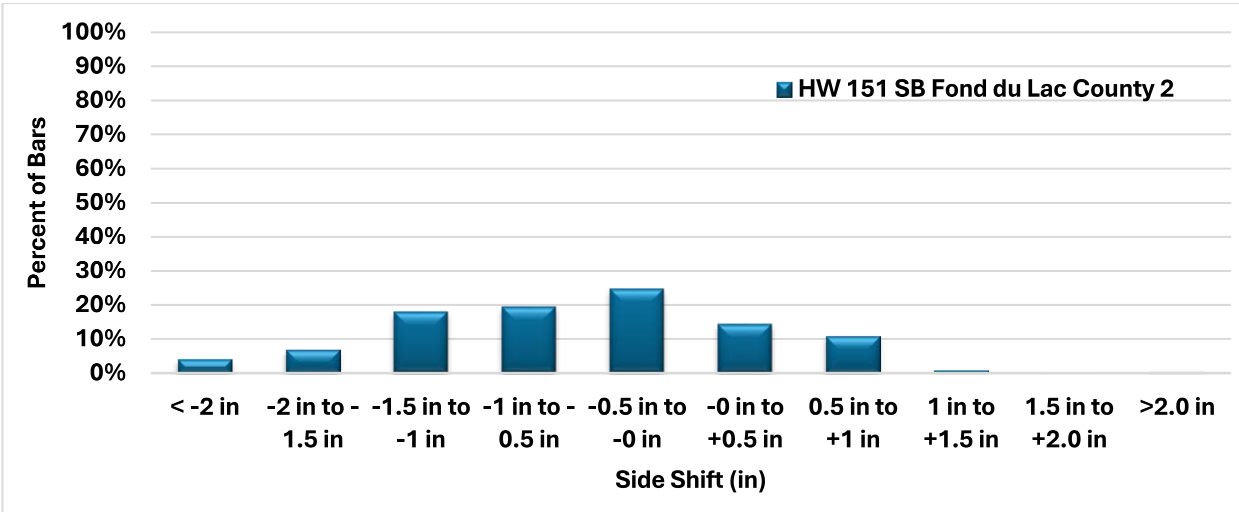

Figure 219. Longitudinal Translation distribution for HW 151 SB Fond du Lac County 2

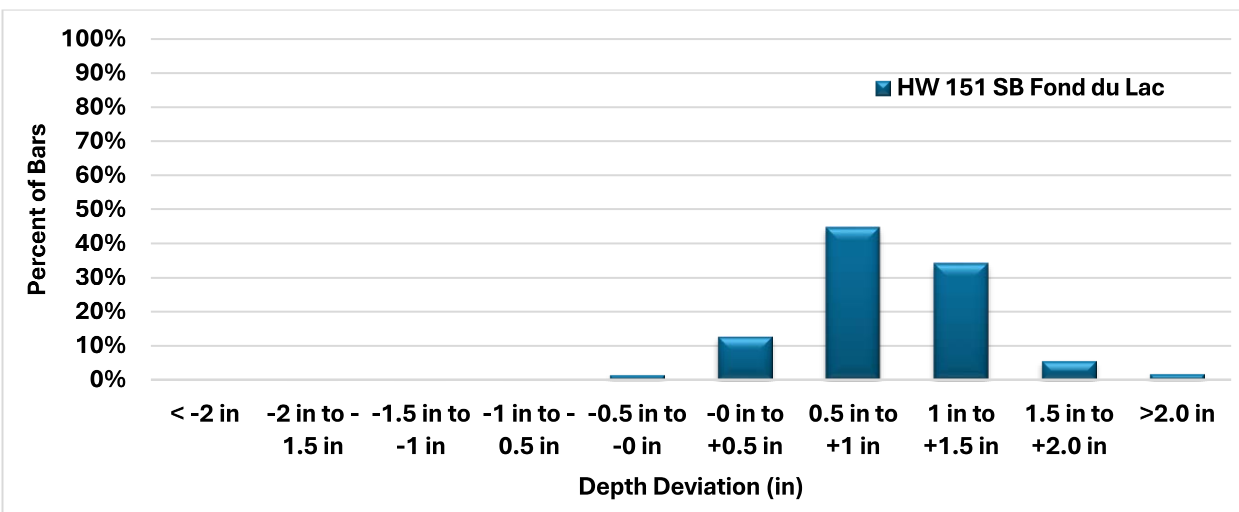

Figure 220. Vertical Translation distribution for HW 151 SB Fond du Lac County 2

Table 74. Dowel misalignment summary for HW 151 SB Fond du Lac County 2

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
HW 151 SB Fond du Lac	-0.05	0.16	0.19	0.17	-0.52	0.62	0.93	0.43

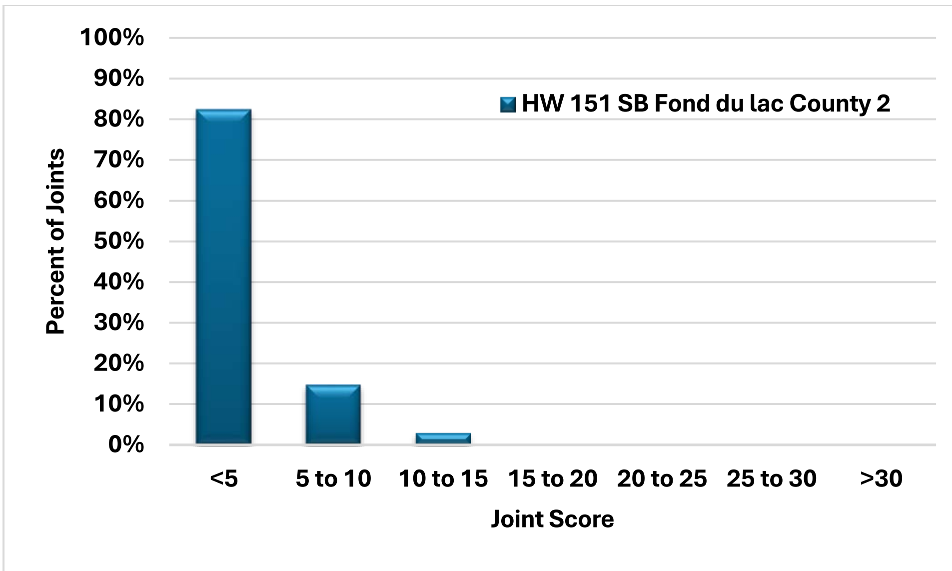

Figure 221. Joint score distribution for HW 151 SB Fond du Lac County 2

Table 75. Joint score and effective dowel diameter for HW 151 SB Fond du Lac County 2

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
HW 151 SB Fond du Lac	3.0	2.7	10	1.5	1.329	0.224	11.40

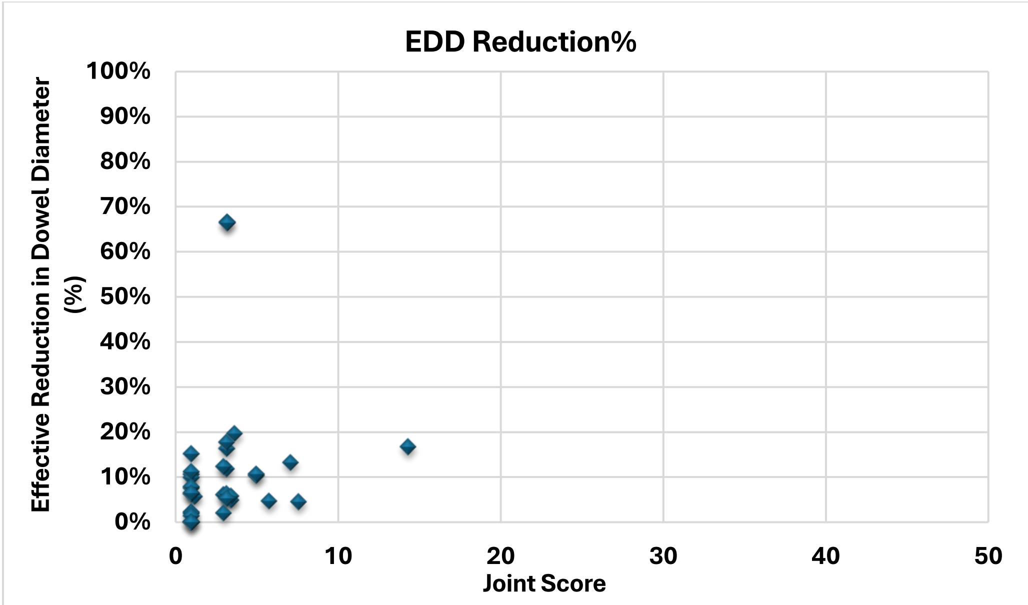

Figure 222. Joint score versus effective reduction in dowel diameter for HW 151 SB Fond du Lac County 2

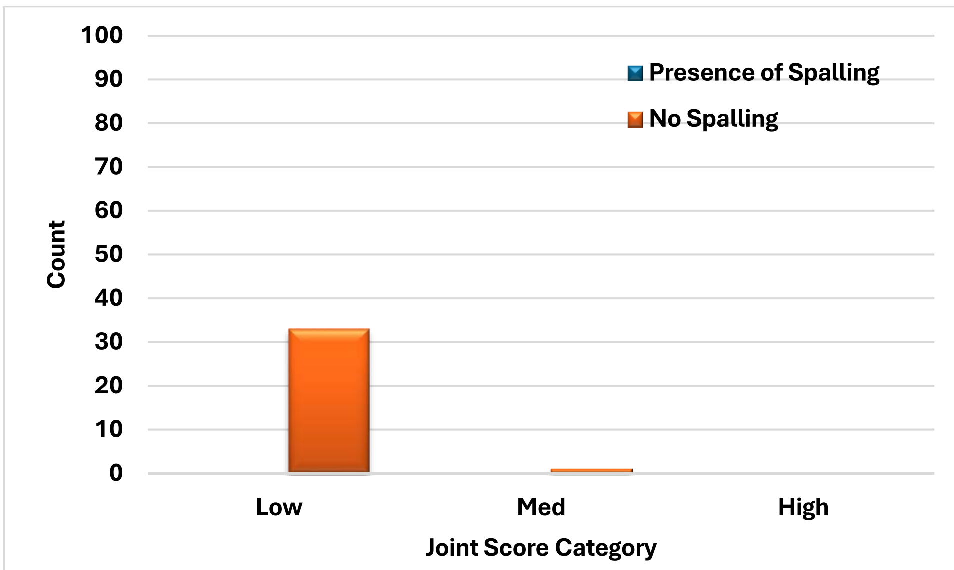

Figure 223. Joint score and presence of spalling for HW 151 SB Fond du Lac County 2

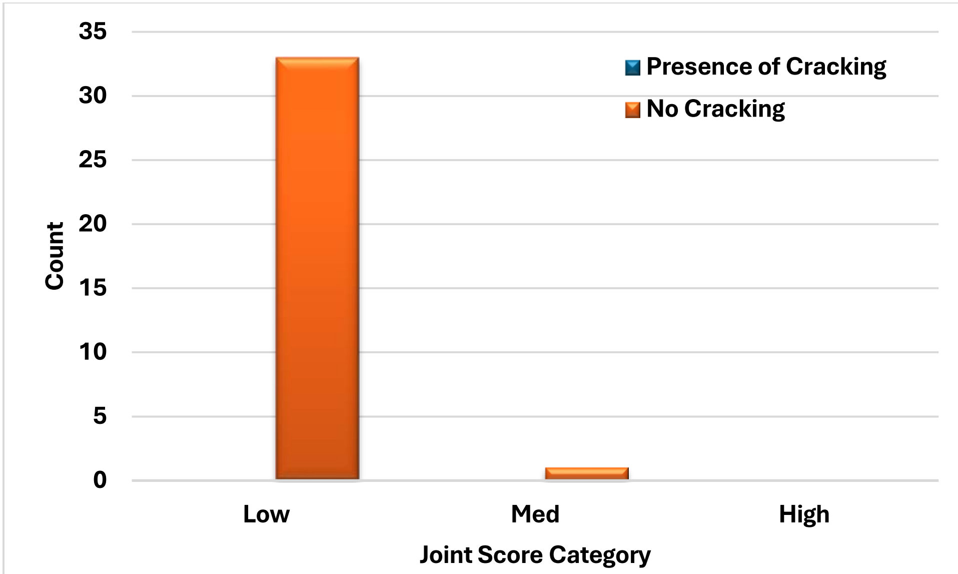

Figure 22474. Joint score and presence of cracking for HW 151 SB Fond du Lac County 2

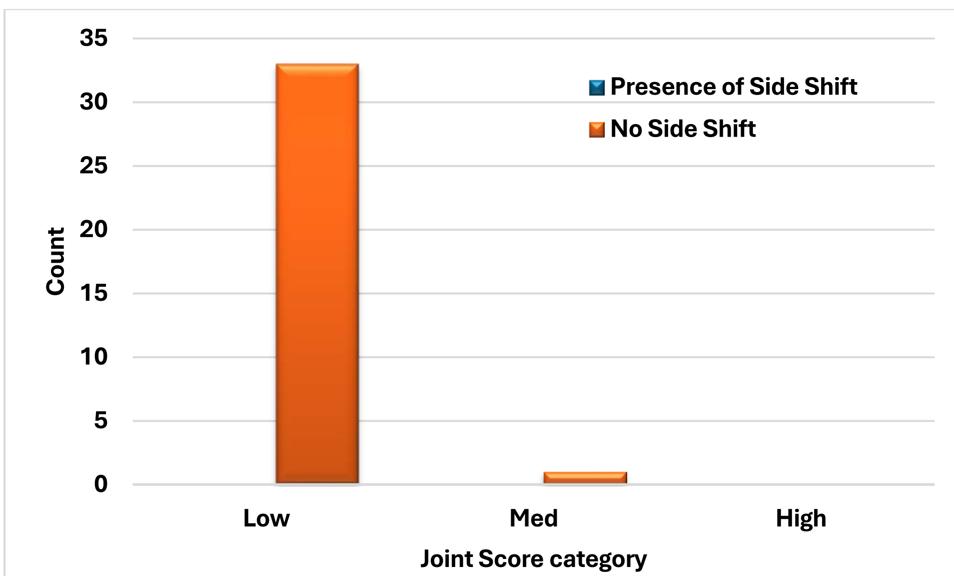

Figure 22575. Joint score and presence of side shift for HW 151 SB Fond du Lac County 2

CTG G to I-94 on Ramp

Table 76. Details of test sections in CTG G to I-94 on Ramp

Test Section	PCC Thickness (in)	Dowel Diameter (in)	Scan Date	Lane Width (ft)
CTG G to I-94 on Ramp	7	1. 5		15

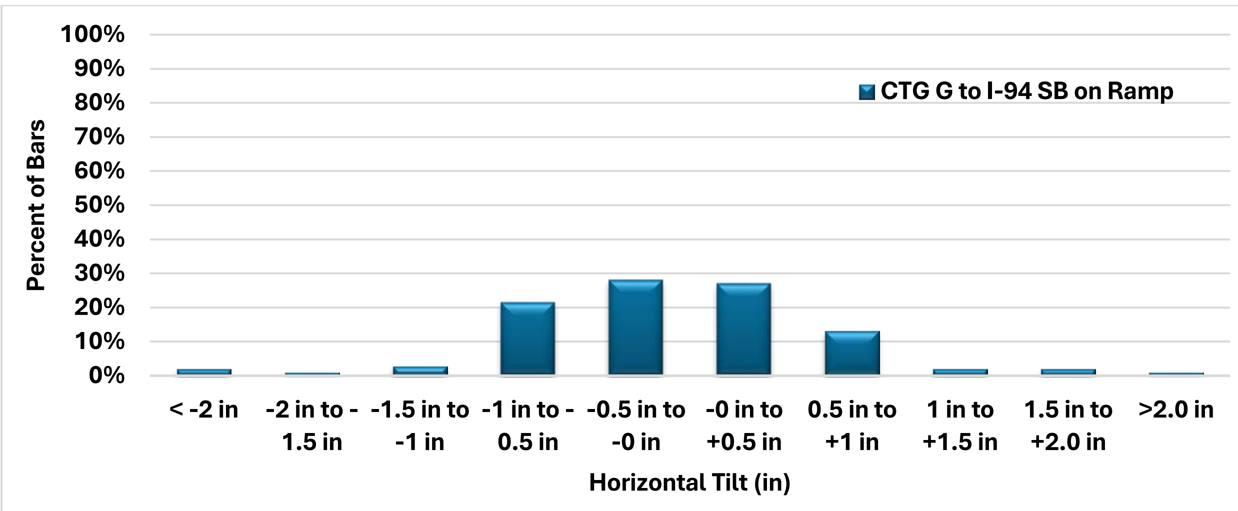

Figure 226. Horizontal Skew distribution for CTG G to I-94 on Ramp

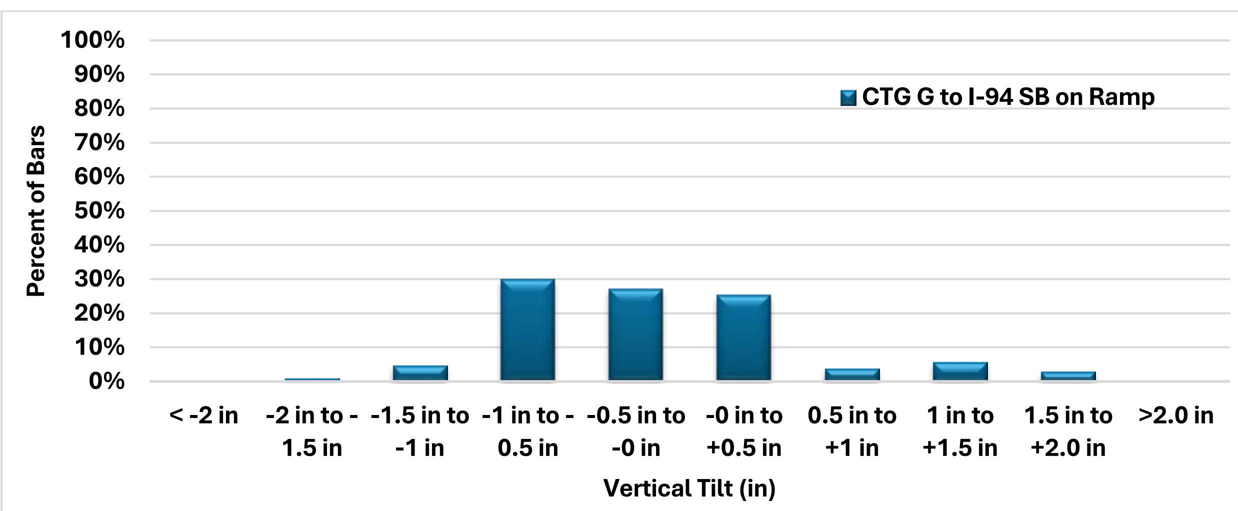

Figure 227. Vertical Tilt distribution for CTG G to I-94 on Ramp

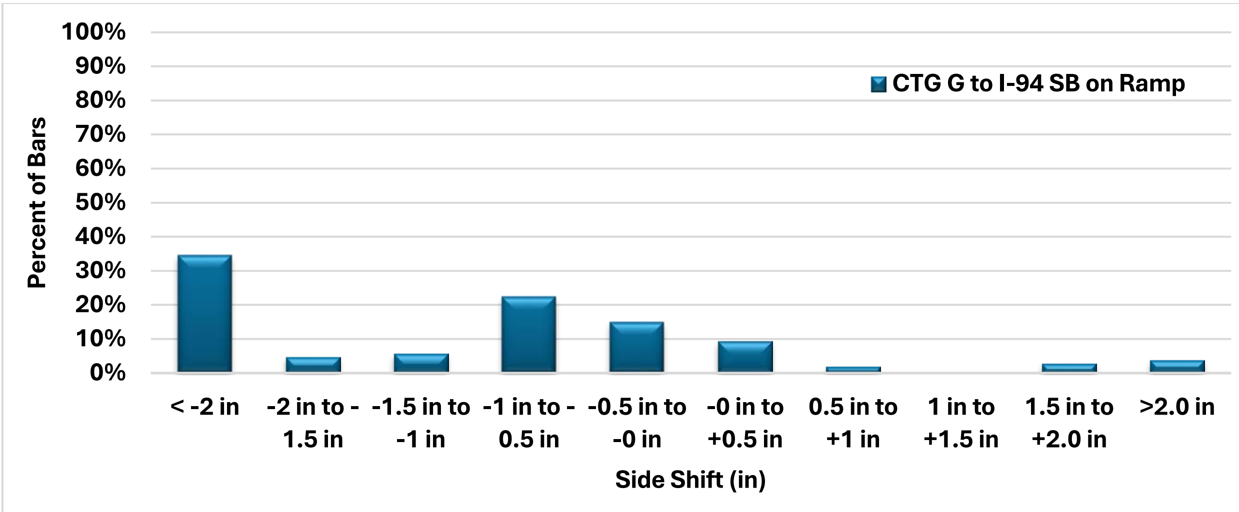

Figure 228. Longitudinal Translation distribution for CTG G to I-94 on Ramp

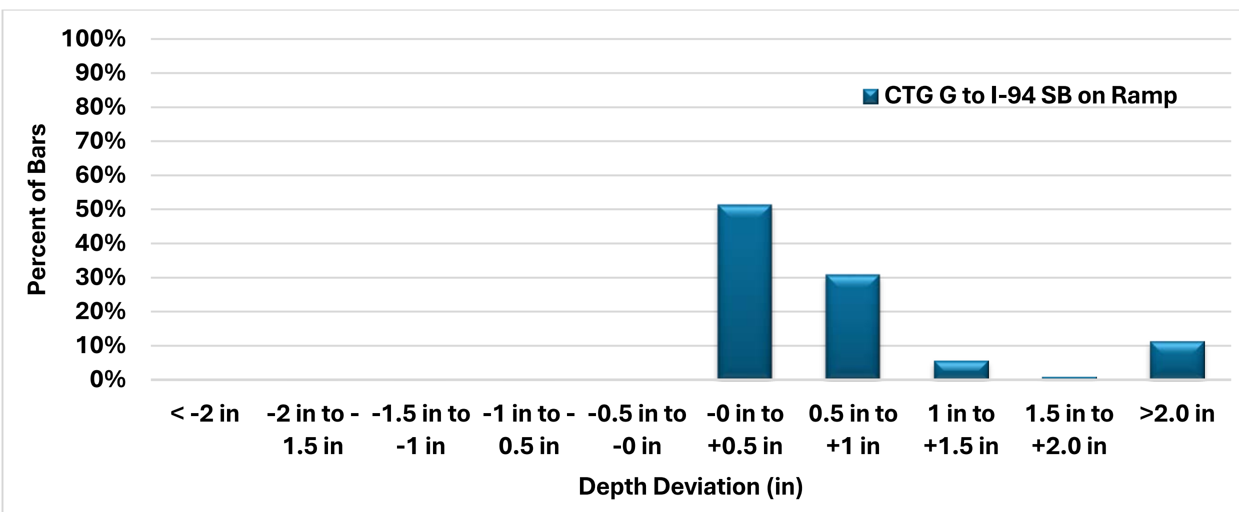

Figure 229. Vertical Translation distribution for CTG G to I-94 on Ramp

Table 77. Dowel misalignment summary for CTG G to I-94 on Ramp

ID	Horizontal Skew Average (in)	Horizontal Skew Standard Deviation (in)	Vertical Tilt Average (in)	Vertical Tilt Standard Deviation (in)	Longitudinal Translation Average (in)	Longitudinal Translation Standard Deviation (in)	Vertical Translation Average (in)	Vertical Translation Standard Deviation (in)
CTG G to I-94 on Ramp	-0.10	0.49	-0.17	0.39	-1.23	1.46	0.80	1.04

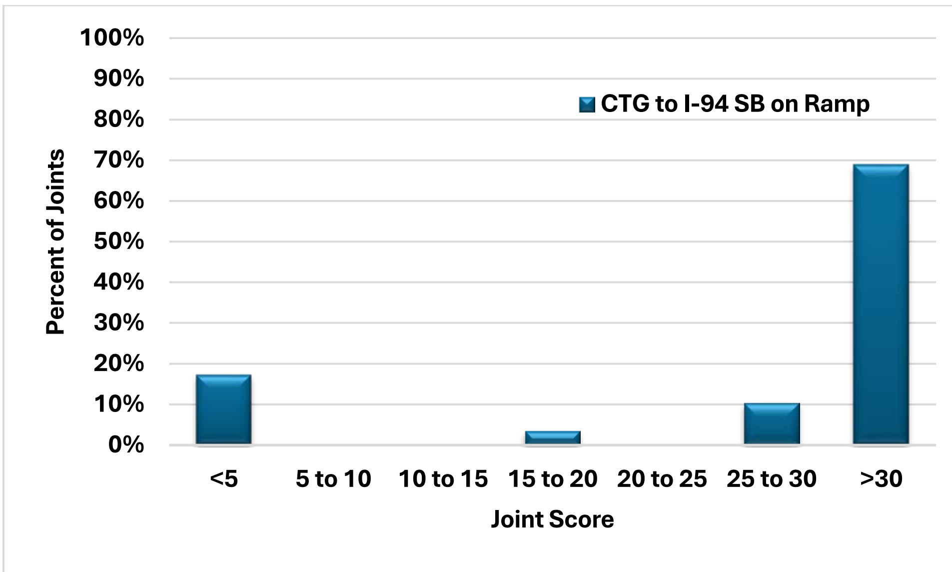

Figure 230. Joint score distribution for CTG G to I-94 on Ramp

Table 78. Joint score and effective dowel diameter for CTG G to I-94 on Ramp

Section	Joint Score Average	Joint Score Standard Deviation	Average PCC Thickness (in)	Actual Dowel Diameter (in)	Effective Dowel Diameter Average (in)	Effective Dowel Diameter Standard Deviation (in)	Effective Reduction in Dowel Diameter, %
CTG G to I-94 on Ramp	53.7	46.5	7	1.5	0.994	0.31	20.48

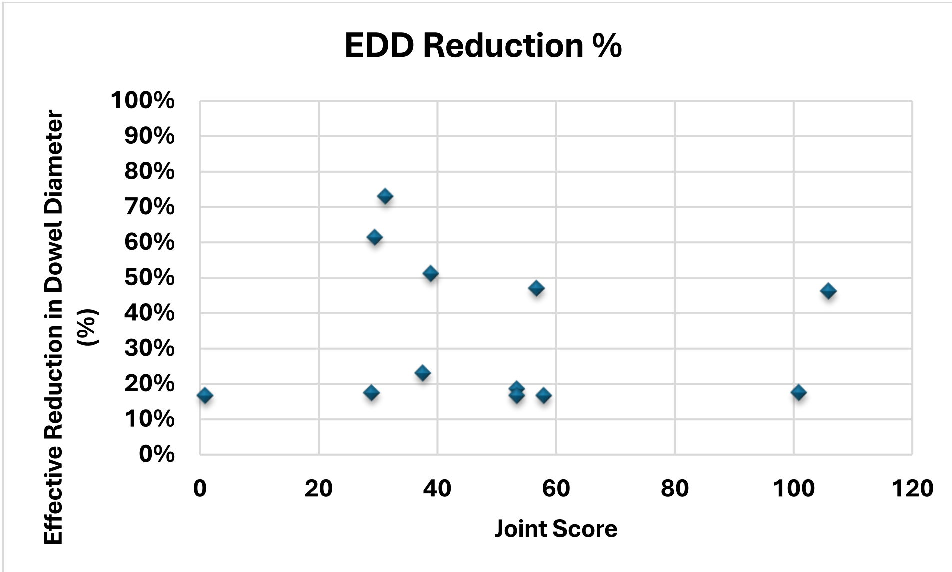

Figure 231. Joint score versus effective reduction in dowel diameter for CTG G to I-94 on Ramp

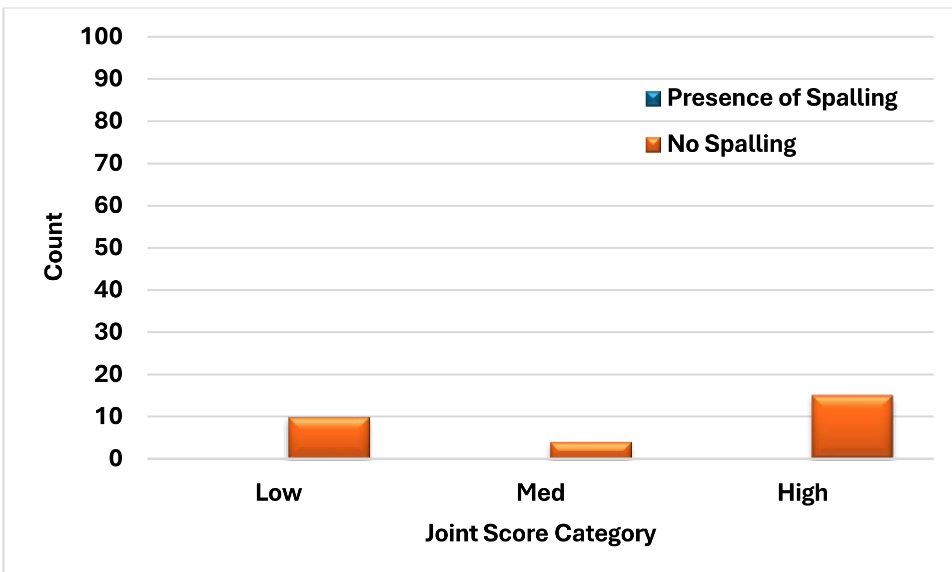

Figure 232. Joint score and presence of spalling for CTG G to I-94 on Ramp

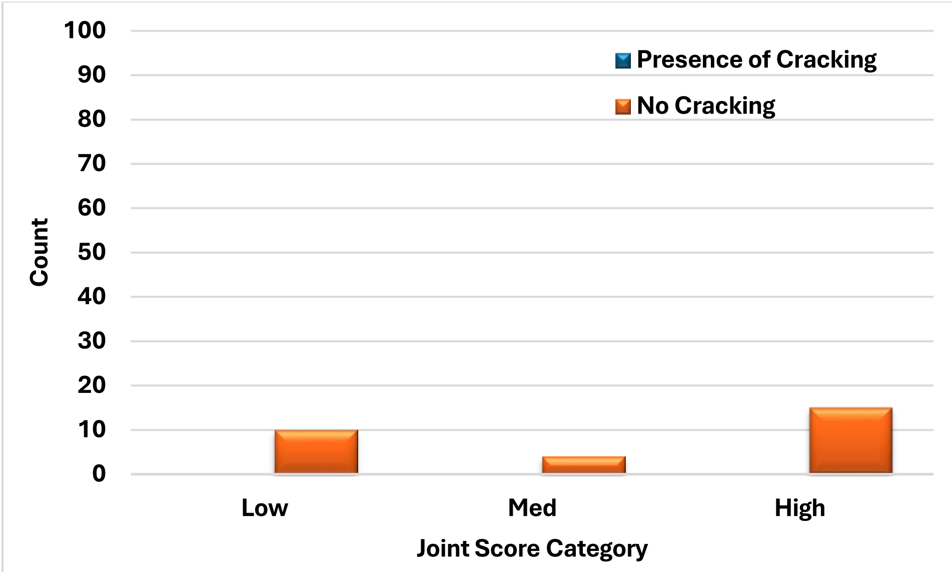

Figure 23376. Joint score and presence of cracking for CTG G to I-94 on Ramp

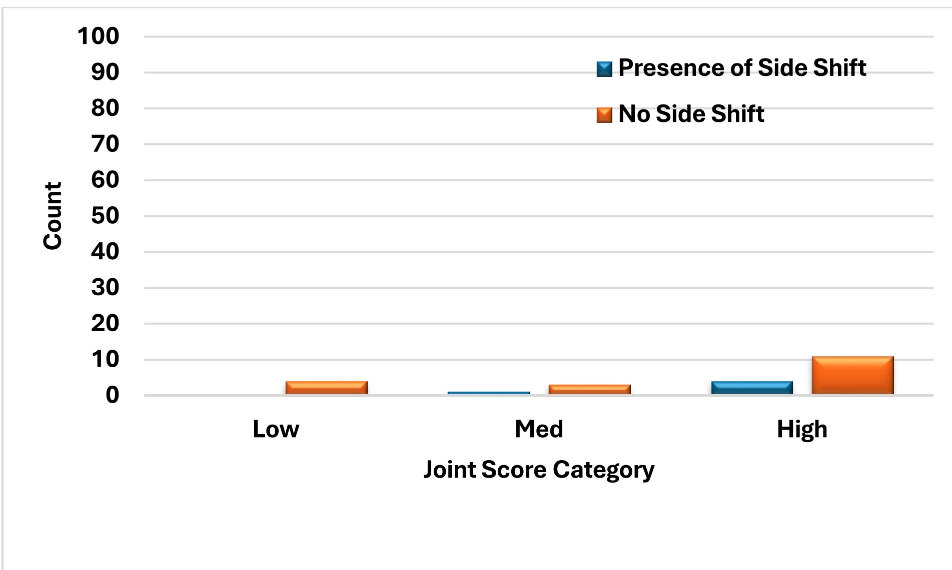

Figure 23477. Joint score and presence of side shift for CTG G to I-94 on Ramp