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16. Abstract

Dowel Bar Inserters (DBI) are automated mechanical equipment that position dowel bars in Portland Cement Concrete (PCC) after concrete is placed. Compared to the alternative approach, which is using dowel baskets, DBIs offer advantages in cost and speed of construction. However, as dowel bars are not anchored to the subgrade similar to dowel baskets, there is a concern about the quality of dowel placement using this equipment. Improper placement of dowel bars can lead to reduced load transfer between slabs, which results in pavement distresses such as faulting and spalling at joints.

To determine the accuracy of dowel placement by DBI, the Nebraska Department of Roads has used an MIT Scan-2 device to scan the joints in projects where a DBI was used. This device uses a nondestructive magnetic imaging technique to capture the position of dowel bars inside the pavement. The aim of the this project is to analyze the MIT Scan-2 data of the joints constructed using a DBI, and to compare them with the corresponding field performance data. This will allow us to judge if DBI is a reliable alternative for dowel placement, and to improve Nebraska's current specifications for dowel placement tolerances.

To meet the objectives, the MIT Scan-2 data of scanned joints were initially compared with dowel placement specifications suggested by national agencies. It was observed that the longitudinal translation and rotation of dowels in a portion of scanned joints fell outside recommended tolerances. The longitudinal and vertical translation of the dowels were respectively higher and lower than the average values reported by a similar study (Khazanovich et al. 2009). MIT Scan-2 data and field performance data were then compared to find any linkage between pavement distresses and dowel misalignment levels, enabling us to potentially improve Nebraska's current specifications as well as conclude if any of the distresses were caused by low placement accuracy of the DBI. No linkage was found between pavement performance and dowel misalignment levels for over 220 joints that were investigated in this study. No transverse cracking was observed during field investigation, and the spalling at joints was likely to be the result of joint saw-cut operations. However, measured distress from joints with missing or completely shifted dowels show that high severity dowel misalignment has an adverse effect on joint performance.

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Disclaimer

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Abstract

Dowel Bar Inserters (DBI) are automated mechanical equipment that position dowel bars in Portland Cement Concrete (PCC) after concrete is placed. Compared to the alternative approach, which is using dowel baskets, DBIs offer advantages in cost and the speed of construction. However, as dowel bars are not anchored to the subgrade similar to dowel baskets, there is a concern about the quality of dowel placement using this equipment. Improper placement of dowel bars can lead to reduced load transfer between slabs, which results in pavement distresses such as faulting and spalling at joints.

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accuracy of the DBI. No linkage was found between pavement performance and dowel misalignment levels for over 220 joints that were investigated in this study. No transverse cracking was observed during field investigation, and the spalling at joints was likely to be the result of joint saw-cut operations. However, measured distress from joints with missing or completely shifted dowels show that high severity dowel misalignment has an adverse effect on joint performance.

Chapter 1 Introduction

Dowel bars are used in jointed Portland Cement Concrete (PCC) pavements to provide load transfer between slabs and prevent pavement distresses. To ensure effective load transfer of the dowels, they need to be properly aligned and positioned. Improper placement may reduce the effectiveness and result in distresses such as faulting, joint spalling, and transverse cracking. Proper positioning of dowel bars enables free, uninhibited opening and closing of the joints, resulting from expansion or contraction of PCC slabs in response to temperature changes as well as initial shrinkage.

Any deviations from the ideal dowel bar position may be defined as misplacement or misalignment. As shown in figure 1.1, Tayabji (1986) identified the following categories of dowel misalignment:

(a) longitudinal translation (side shift),

(b) vertical translation (depth error),

(c) horizontal skew,

(d) vertical tilt, and

(e) horizontal translation.

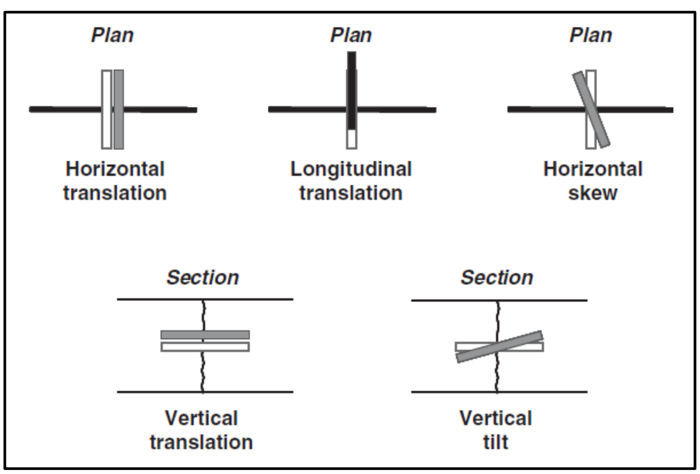


Figure 1.1 Dowel misalingment types

Dowel bars should be centered on the joint to ensure adequate embedment in both approach and leave slabs for proper load transfer. They should also be placed in the mid-depth of the slab to ensure that the bars have adequate concrete cover to resist corrosion and concrete shear cracking, and to prevent them from being cut during sawing operation. Vertical and horizontal rotation of the dowels is believed to cause joint lock-up, preventing free opening and closing of the joints and leading to mid-span transverse cracking (FHWA 2007). Horizontal translation of the dowel bars is considered an issue when dowels are located far enough from their expected position (e.g., wheel path) that the distribution of the load is adversely affected (ACPA 2013).

The conventional method to place dowel bars is by using dowel basket assemblies, which are simple truss structures that hold the bars at the appropriate height before PCC placement. Typically, dowel baskets span an entire lane width and are fabricated from thick gauge wire. They are left in place after the PCC is placed but do not contribute to the pavement structure. Basket assemblies are anchored to the base course in order to prevent movement when the PCC is placed on the dowels.

An alternative method of placing dowel bars is using a Dowel Bar Inserter (DBI), shown in figure 1.2, as an attachment to slipform pavers. This equipment places dowel bars on fresh PCC surface and then pushes them down to the intended elevation by a series of forked rods. The rods are usually vibrated while the dowel bars are inserted in order to facilitate insertion and move the PCC back into the space created by the dowels. This process usually occurs after PCC vibration and before the tamper bar. As DBIs eliminate the need to place and anchor dowel baskets, they offer an advantage in construction cost and speed. However, state agencies have concerns about how reliable DBIs are, and whether the dowels are being placed accurately inside the PCC mix.

Figure 1.2 Dowel Bar Inserter (DBI)

NDOR has used the MIT Scan-2 (figure 1.3), which is a nondestructive testing device operating based on magnetic tomography technology, for measuring the position and alignment of dowel bars in past projects where a DBI was used. The MIT Scan-2 consists of three main components: (a) a sensor unit that emits electromagnetic pulses and detects the induced magnetic field; (b) an onboard computer that runs the test, collects, and stores the test data; and (c) a glass-fiber reinforced plastic rail system that guides the sensor unit along the joint. The device is easy to use and allows the entire joint to be scanned in one pass, providing results for all dowel bars in the joint. The dowel alignment can be checked within a few hours of concrete placement, and the results can be printed using the onboard printer immediately after scanning.

Figure 1.3 A joint being scanned by MIT Scan-2

1.1 Research Objectives and Scopes

The primary objective of this research is to analyze the MIT Scan-2 data that monitored dowel alignment at the joints of projects where DBI was used. Pavement performance data of the sections (in particular at the joints) will also be investigated and subsequently compared with the MIT Scan-2 data to find any linkage between dowel misalignments and pavement distresses. More specifically, this research will allow to:

- Identify the MIT Scan-2 device and assess its capability as a potential nondestructive quality control (QC) – quality assurance (QA) approach,
- Determine if the DBI method is a proper alternative for dowel placement,
- And improve Nebraska's current specifications and guidelines for dowel placement.

1.2 Organization of the Report

This report is organized into five chapters. Following this introduction, chapter 2 provides a brief literature review of national and regional studies about dowel placement specifications, the MIT Scan-2 device, and Dowel Bar Inserters. Chapter 3 reviews the results of the MIT Scan-2 data investigation, and provides a comparison between the levels of misalignment observed in the field, and other projects from different parts of the U.S., as well as specifications of national transportation agencies. Chapter 4 reviews the results of the data analysis task, which is aimed at finding a linkage between field performance and dowel misalignment levels. Finally, chapter 5 provides a summary of the findings and conclusions of this study.

Chapter 2 Literature Review

This chapter describes the results of the literature review conducted regarding different types of dowel misalignment and their effect on pavement performance, as well as national agency and state specifications for dowel placement tolerances. Studies and reports concerning the use of the MIT Scan-2 and Dowel Bar Inserters are also summarized.

2.1 Types of Dowel Misalignment

This section reviews the information present in the literature about each type of dowel misalignment.

2.1.1 Longitudinal Translation

When using dowel bars, sufficient dowel embedment is needed in both approach and leave slabs in order to provide effective load transfer between slabs. Longitudinal translation of dowel bars (figure 2.1) will result in reduction of embedment length in one slab, leading to loss of load transfer effectiveness and possibly pavement distresses such as faulting.

Longitudinal translation can occur due to a missed saw cut when using both DBIs and dowel baskets. Improper anchoring of dowel baskets to the subgrade or a faulty DBI can also contribute to this type of misalignment. A study of more than 2,300 joints using the MIT Scan-2 showed that longitudinal translation of most dowels fall within the range of ±2 inch. This level of misalignment is not considered to have an adverse effect on joint performance (Khazanovich et al. 2009).

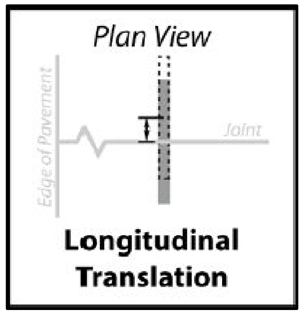


Figure 2.1 Longitudinal translation

Khazanovich et al. (2009) conducted a series of shear-pull tests on dowels with varying amounts of concrete embedment, in which dowels were subjected to shear force after they underwent the pull-out test. This was done in order to simulate the effect of vehicle load after the joint was opened due to slab shrinkage or contraction. Figure 2.2 shows the result of the lab test.

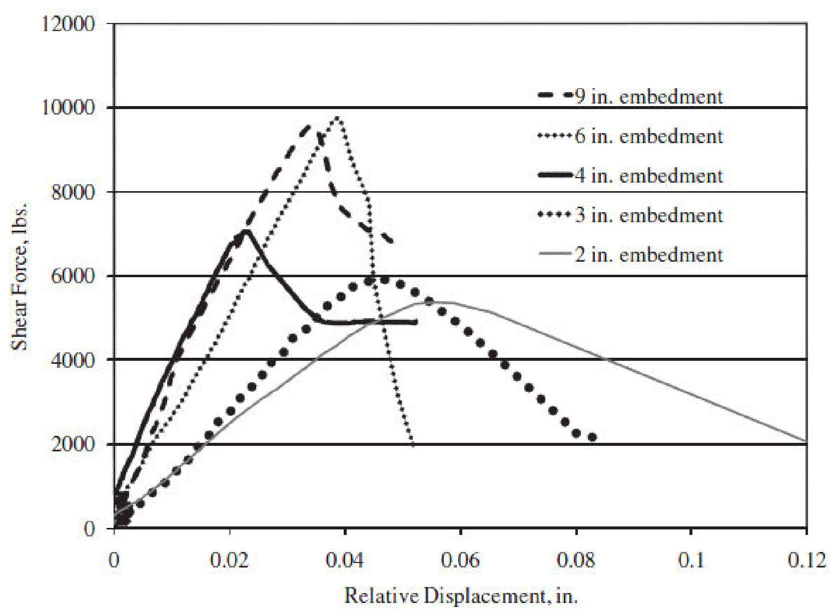


Figure 2.2 Shear-pull test results

It can be observed that reduction of embedment length from 9 in. to 6 in. did not result in any significant loss of shear capacity and stiffness, while further reduction of embedment to 4 in.

lead to an approximately 25% reduction in shear capacity of the dowel. According to the NCPTC (2011), the maximum load transferred by a dowel in a typical highway pavement is generally less than 3,000 lb., which means that dowels with as low as 2 in. of embedment have more than sufficient shear capacity for the typical traffic. However, the reduction of shear stiffness which is visible in 2 in. and 3 in. cases will result in increased differential deflection and higher potential for faulting and pumping.

Khazanovich et al. (2009) compared faulting and load transfer effectiveness (LTE) values for joints with dowels that were centered within ±0.5 in. of the joint versus those that had more than 2 in. of longitudinal translation. They found no statistically significant differences in faulting and LTE between the two groups. However, Burnham (1999) reported that significant early faulting was observed when embedment lengths fell below 2.5 in. on I-35 in Minnesota.

Federal Highway Administration (FHWA) Technical Brief (2007) suggests using an acceptance criteria of ±2 in. for longitudinal translation of dowels during dowel placement. Furthermore, any joints with fewer than three bars with 6 in. or more embedment should be rejected. For the dowels that fall between the acceptance and rejection limits, a Percent Within Limits provision or warranty program is suggested. Khazanovich et al. (2009) and the guideline proposed by the American Concrete Pavement Association (2013) suggest an acceptance criteria of ±2.1 in. and ±2 in., respectively. The ACPA recommends corrective action proposal for longitudinal translations higher than 5 in.

2.1.2 Vertical Translation

Dowels should be placed in the mid-depth of pavement to ensure adequate concrete cover and prevent shear cracking of concrete as well as corrosion of dowel bars. Vertical translation (figure 2.3) leads to reduced concrete cover and shear capacity, which will have an adverse effect on the LTE of dowels. Moreover, if concrete cover is less than the saw cut depth, the sawing operation will cut through the dowel and eliminate its load transfer capability.

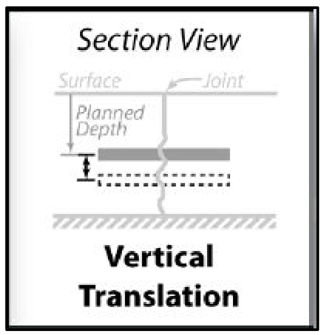


Figure 2.3 Vertical translation

Vertical translation can happen due to improperly sized dowel baskets, or settlement of dowels in concrete when using a DBI, among other reasons. Khazanovich et al. (2009) reported that vertical translation of most dowels fall within the range of ±0.5 in. for pavements with a thickness of 12 in. or less.

A study by Odden et al. (2003) showed that dowels with 2 in. of concrete cover perform as good as dowels with 3 in. of cover for up to 10 million load cycles. The lab tests also showed that a dowel with 1.25 in. of concrete cover has a shear capacity of 4.5 kips, which is greater than the maximum shear force subjected to dowels in typical highway pavements, although the joint with less cover had slightly lower LTE values.

Khazanovich et al. (2009) reported that a vertical translation of 2 in. that reduced concrete cover from 3.25 in. to 1.25 in., lead to a decrease of shear capacity from 9.3 kips to 4.3 kips during shear-pull test. However, when comparing joint performance and dowel vertical translation for in-service projects, they reported no difference in terms of faulting and LTE between dowels at mid-depth of pavement and those with average vertical translation higher than 1 in.

The acceptance criteria suggested by Khazanovich et al. (2009) is ±0.5 in. for pavements with 12 in. thickness or less, and ±1.0 in. for pavements with more than 12 in. thickness. FHWA Technical Brief (2007) allows for 1 in. of vertical translation similar to ACPA, while ACPA also requires the concrete cover between dowel bars and saw cut to be higher than 0.5 in.

The rejection criteria of all agencies concerns thickness of dowel concrete cover. Khazanovich et al. (2009) and ACPA (2013) propose a minimum of 2.0 in. and 2.5 in. concrete cover above or below dowel bars, respectively, while FHWA proposes 3.0 in. concrete cover above the dowel bars, and a minimum of 3 dowels in wheel path with concrete covers more than 3.0 in.. ACPA (2013) also requires a minimum of 0.25 in. cover between dowel bars and saw cut.

2.1.3 Horizontal Translation

Horizontal translation (figure 2.4) is the dislocation of dowel bars relative to the planned location from the pavement edge, longitudinal joint, or other dowel bars. This misalignment is generally not considered to have an adverse effect on pavement performance, except for very high values, in which case the distribution of forces among the dowels are affected. The ACPA guide (2013) reports that current doweling practice with the uniform dowel bar spacing of 12 in. is overly conservative, and horizontal translation will generally not be of concern unless alternative dowel arrangements are used.

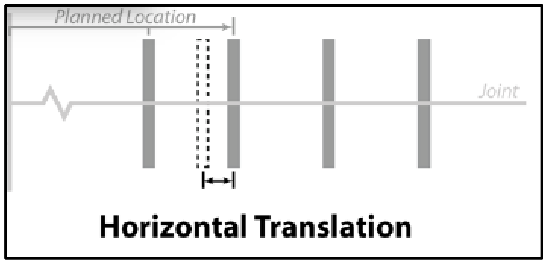


Figure 2.4 Horizontal translation

The acceptance criteria proposed by ACPA (2013) and Khazanovich et al. (2009) for horizontal translation is 2 and 1 in., respectively. Dowels with horizontal translation higher than 3 in. fall outside the ACPA rejection criteria while other reports do not have a rejection criteria for this type of misalignment.

2.1.4 Vertical and Horizontal Rotation

Vertical and horizontal rotation, also known as vertical tilt and horizontal skew (figure 2.5), are deviations of the dowel bar from parallel alignment with respect to the surface and edge of pavement, respectively. While longitudinal and vertical translation affect the load transfer capability of dowels, vertical and horizontal rotation of the dowels are considered to hinder the movement of joints. Excessive rotation of dowels might prevent free opening and closing of joints, resulting in mid-span stresses and transverse cracking of the slabs.

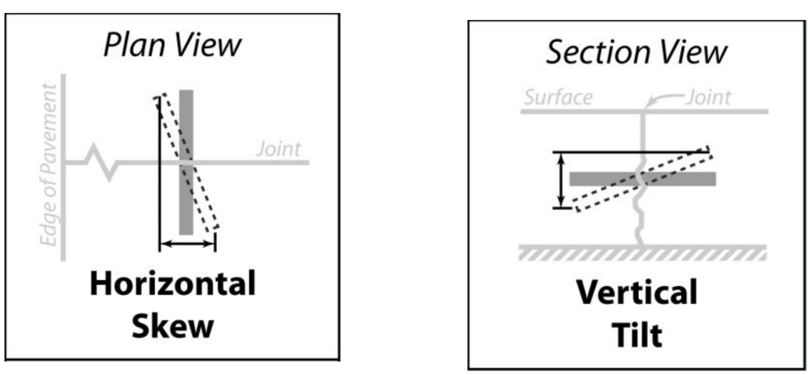


Figure 2.5 Vertical and horizontal rotation

Most dowels observed in the field fall inside the rotation range of ±0.5 in. over 18 in. of dowel length, as reported by Khazanovich et al. (2009). All rotational values used in this report are expressed as a deviation from alignment over 18 in., which is the typical length of dowels used in practice. Prabhu et al. (2006) conducted slab pull out tests to determine the effect of rotationally misaligned dowels on joint opening. It was observed that joints with high misalignment levels (over ¾ in.) developed cracking, but only at excessive levels of joint opening (0.4 in. and above). The cracking was observed only when the dowel misalignment was non-uniform, which is the case when dowels are misaligned in the opposite direction, as opposed to uniform alignment when dowels are misaligned in the same direction.

Dowel pull out tests performed by Khazanovich et al. (2009) showed that there is no significant difference between the means of pull out forces for dowels with 2 in. of rotation and aligned dowels. However, 4 in. rotated dowels required significantly higher pull out forces. They also observed that during the shear-pull test, a vertical tilt of up to 2 in. did not have a significant effect on shear stiffness or the capacity of the dowels, while 4 in. of vertical tilt greatly reduced shear capacity and stiffness. Furthermore, a comparison of faulting values for joints with higher average vertical tilt (greater than ±0.75 in.) and joints with lower average vertical tilt (less than ±0.25 in.) showed that joints with higher average vertical tilt had higher values of faulting (Khazanovich et al. 2009).

The ACPA guide (2013) and FHWA tech brief (2007) suggest the use of the joint score method proposed by Yu (2005) to assess the effect of dowel rotation on free joint movement. In this method, each dowel in a joint is given a weighting factor based on the Single Dowel Misalignment (SDM) value. The sum of all the weighting factors for the dowels determines the joint's score, which is a measure of the likelihood that a joint is locked. Single Dowel Misalignment and the joint's score are defined as:

$$Single\ Dowel\ Misalignment = \sqrt{Vertical\ rotation^2 + Horizontal\ rotation^2}$$

$$Joint\ Score = \sum_{i=1}^{n} W_i$$

where,

n = number of dowels in a single joint

W_i = Weighting factor for dowel *i* (see table 2.1)

Table 2.1 Joint score weighting factors

Single Dowel Misalignment (SDM)	W, Weighting Factor
SDM ≤ 0.6 in. (15mm)	0
0.6 in. (15mm) < SDM ≤ 0.8 in. (20 mm)	2
0.8 in. (20 mm) < SDM ≤ 1 in. (25 mm)	4
1 in. (25 mm) < SDM ≤ 1.5 in. (38 mm)	5
1.5 in. (38 mm) < SDM	10

A joint with a score above 10 is considered to have a moderate risk of being locked. Field studies have shown that occasional locked joints have no negative impact on pavement performance (Yu 2005). However, consecutive locked joints may lead to build up of stress in slabs and excessive joint movement in neighboring free joints. Thus, maximum allowable consecutive locked joints should be established, and groups of locked joints that fall outside the criteria should be rejected. The ACPA guide (2013) proposes an allowable length of 60 ft., while FHWA suggests that it should be based on maximum joint movement, which should not exceed 0.2 in.

Khazanovich et al. (2009) used a finite element model to compute the longitudinal stresses in slabs between joints containing aligned and misaligned dowels. The results of longitudinal stress versus deflection is showed in figure 2.6.

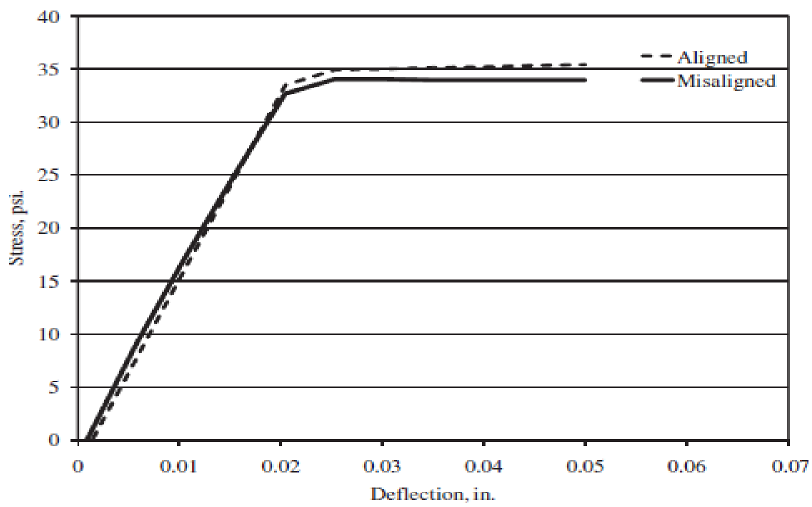


Figure 2.6 Stress-deflection curve for aligned and misaligned dowels

It can be seen that there is no significant stress difference between the aligned and misaligned cases. Based on this result, Khazanovich et al. (2009) argued that dowel misalignment alone is not a sufficient cause for joint lock up. The acceptance and rejection criteria of national agencies for rotational misalignment is presented in table 2.2.

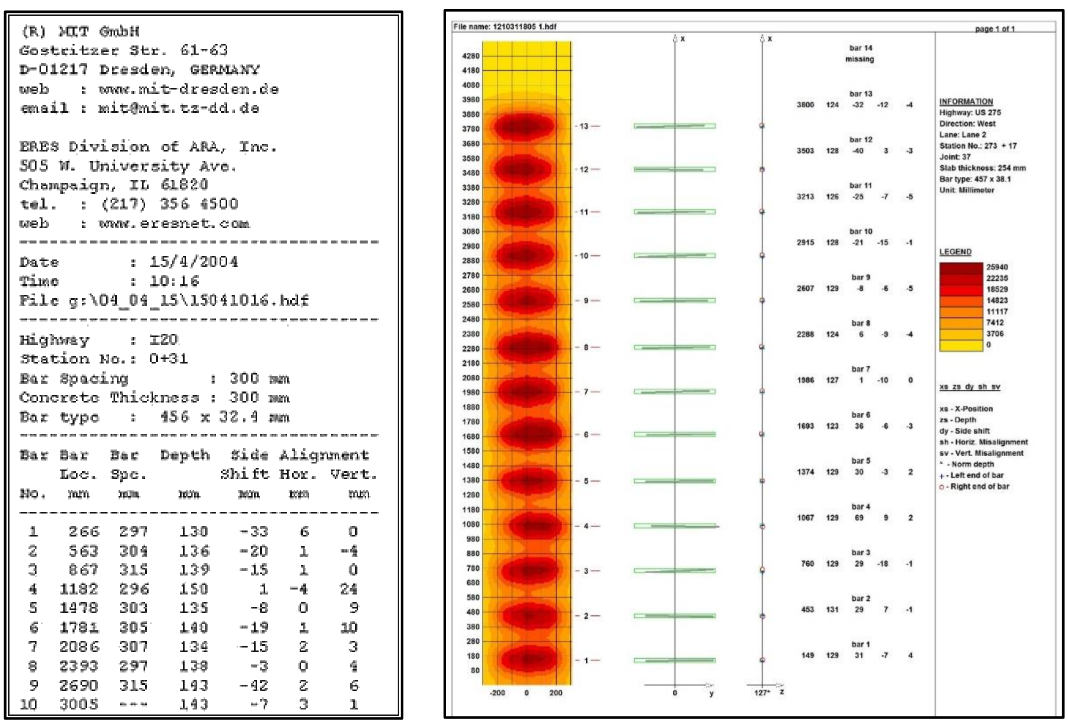
Table 2.2 Acceptance and rejection criteria for rotational misalignment

Agency	Acceptance Criteria	Rejection Criteria
ACPA	Each component less than 0.6 in.	SDM more than 1.5 in.
NCHRP	Each component less than 0.5 in.	SDM more than 3.0 in.
FHWA	Each component less than 0.6 in.	SDM more than 1.5 in.

2.2 MIT Scan-2 Device

The MIT Scan-2 was developed by MIT GmbH of Dresden, Germany, and was specifically aimed at locating dowel and tie bars inside concrete pavements. It can determine the location of dowels in an entire joint (up to 3 lanes) in one scan. The device was designed to work continuously for at least 8 hours with one battery charge, during which time a 2-person crew can scan 200 or more joints.

Preliminary results of the scan can be printed on the on-board computer, and more comprehensive analysis of the data can be done later using MagnoProof software. The results provided by the on-board computer are accurate for a smaller range of misalignment values. Typical results of the on-board computer and MagnoProof are displayed in figure 2.7.



Bar No.	Bar Loc. mm	Bar Spc. mm	Depth mm	Side Shift mm	Alignment Hor. mm	Alignment Vert. mm
1	266	297	130	-33	6	0
2	563	304	136	-20	1	-4
3	867	315	139	-15	1	0
4	1182	296	150	1	-4	24
5	1478	303	135	-8	0	9
6	1781	305	140	-19	1	10
7	2086	307	134	-15	2	3
8	2393	297	138	-3	0	4
9	2690	315	143	-42	2	6
10	3005	---	143	-7	3	1

Figure 2.7 Typical results of MIT Scan-2

A study by FHWA (2005) investigated the accuracy and operating range of the MIT Scan-2 as well as the effect of cover materials on the device. Manual measurements of exposed joints and repeatability tests were conducted, and the device was proven to be accurate within the following limits:

- depth: 3.9 in. to 7.5 in.;
- side shift (longitudinal translation): ±4 in.;
- horizontal misalignment: ±1.6 in.; and
- vertical misalignment: ±1.6 in.

The overall standard deviation of the measurement error was calculated to be 3.0 mm (0.12 in.), which means that measurement accuracy of +5 mm (0.20 in.) will have a 95% reliability.

Dowel bar cover materials and water does not have an effect on the measurements of the MIT Scan-2 device. However, since the device detects the magnetic field induced by metallic objects, the presence of foreign metal objects such as tie bars will affect the measurement results. In order to obtain good measurement results with dowel baskets and prevent interference from basket wires, dowels should be insulated using paint or epoxy coating, and the transport ties should be cut. Furthermore, the device should be calibrated to account for dowel baskets. With proper calibration, the device can provide a similar level of accuracy to dowels placed using a DBI (FHWA 2005).

2.3 State Dowel Placement Specifications

Table 2.3 shows the specifications for dowel placement of several states which have been surveyed via direct inquiries or through a review of state specification manuals. Generally, states are moving towards less strict acceptance ranges than in the past (Khazanovich et al. 2009) as research has shown that small amounts of misalignment do not have an adverse effect on pavement performance. Except Ohio, other states in the table have either an acceptance criteria or a rejection criteria. However, having both criteria would prove useful because a tight acceptance criteria will promote accurate placement of the dowels, while a rejection criteria will distinguish between the values of misalignment that do and do not have a negative effect on joint performance.

Table 2.3 State specifications

State	Vertical tilt	Horizontal Skew	Longitudinal Translation	Vertical Translation	Horizontal Translation
Missouri	0.25	0.25	0.5	0.5	N/A
Wyoming	0.4	0.4	3	1	1
Colorado	SDM 1.5	SDM 1.5	Embed. < 6 in.	Cover < 3	N/A
N Dakota	3/8	3/8	2	1	2
Wisconsin	0.5	0.5	2	1	1
Ohio	0.6-1	0.6-1	2-4	T[1]/6	2-3
N Carolina	JS	JS	2	0.5	2
Oregon	SDM 3/16	SDM 3/16	N/A	3/8	N/A
Washington	0.5	0.5	1	1	N/A
Kansas	SDM 0.5	SDM 0.5	2	T/10	1
California	5/8	5/8	2	Saw Cut+ 0.5[2]	1

2.4 Dowel Bar Inserters

Although FHWA officially encouraged the use of Dowel Bar Inserters (DBIs) as an alternative to dowel baskets in 1996 (Missouri Department of Transportation, 2003), many states

[1] Pavement thickness
[2] A minimum of 0.5 in. cover between dowel and saw cut

do not allow the contractor to use them due to concerns about dowel placement accuracy. A study by the Missouri Department of Transportation using Ground Penetrating Radar (GPR), concluded that DBIs offer the same placement accuracy as dowel baskets. The study also reports that Texas and Wisconsin DOTs came to the same conclusions in separate investigations. However, not all states have had good experience with DBIs. Colorado DOT used the MIT Scan-2 to evaluate dowel bar placement by DBI in an I-25 project. They discovered that 34% of the joints fell outside NCHRP recommended rejection tolerances. Sturges et al. (2014) used the MIT Scan-2 to measure dowel bar misalignment on a project where a 2-step DBI was used. They discovered that 73% of the joints had a high potential for locking using the joint score method. As a result, Ohio has banned the use of 2-step DBIs on all ODOT-related projects. In two step DBIs, the forks do not vibrate when the dowels are placed, and the vibration is carried out using a second paver.

States have different experiences with DBIs as their performance depends on many factors such as DBI design and calibration, concrete mix properties, and the paving operations. The mix has to be sufficiently stable to hold the bars in place when the DBI places the dowels, and it should have sufficient fluidity to fill the voids caused by insertion of the dowel bars. Table 2.4 shows the policies of several states regarding the use of DBIs. Some states require the contractor to demonstrate the performance of DBI in a test section prior to using it for the project. The dowel bar positions of the test section are checked using the MIT Scan-2 or other methods, and if the DBI shows acceptable performance, the contractor may use it for the rest of the project.

Table 2.3 State policies regarding the use of DBI

State	DBI Allowed	Dowel Alignment Measurement Method	Remarks
Wyoming	Yes	Pachometer and Coring	Use of test sections
Wisconsin	Yes	N/A	N/A
Ohio	Yes	MIT Scan 2	Use of test sections + scans everyday
Kansas	No	N/A	N/A
South Dakota	No	N/A	N/A
California	Yes	Coring	Use of test sections
Illinois	Yes	MIT Scan 2	N/A
Minnesota	Yes	MIT Scan 2	MIT Scan-2 necessary for all large projects
North Dakota	No	No methods	N/A
North Carolina	Yes	MIT Scan 2	Performance evaluation using joint score method

Chapter 3 Investigation of MIT Scan-2 Data

MIT Scan-2 results of approximately 500 joints that were previously scanned by NDOR were analyzed and the dowel misalignment values were investigated. The joints belonged to 4 different projects across the state of Nebraska: Hooper, Kimball, Roscoe, and Norfolk. The number of years the projects were in service varied, but all projects were constructed using a DBI for dowel bar placement.

3.1 Project Level Data Investigation

Figure 3.1 shows the dowel positions for the 110 joints scanned in the US 275 “Hooper” project, which was completed in 2009. It can be seen that vertical and horizontal translation of the dowels is not a concern, while high longitudinal translation and rotation of the dowels is present. Approximately 20% of the dowels fall outside acceptance criteria for longitudinal translation (2.0-2.1 inches), and 1 joint has to be rejected based on ACPA and FHWA rejection criteria due to average longitudinal translation of 5.1 inches. However, it should be noted that no distress was observed during the field performance measurement of this joint.

As for dowel rotation, 6% of the dowels fall outside acceptance criteria and 3% of the bars should be rejected based on ACPA and FHWA criteria. Many of the dowels with high values of rotation were in the same joint that should be rejected due to longitudinal translation. Three missing dowels were also identified on separate joints in the Hooper project. All of the missing dowels lay in the vehicle wheel-path and thus the load distribution among dowels is expected to be adversely affected.

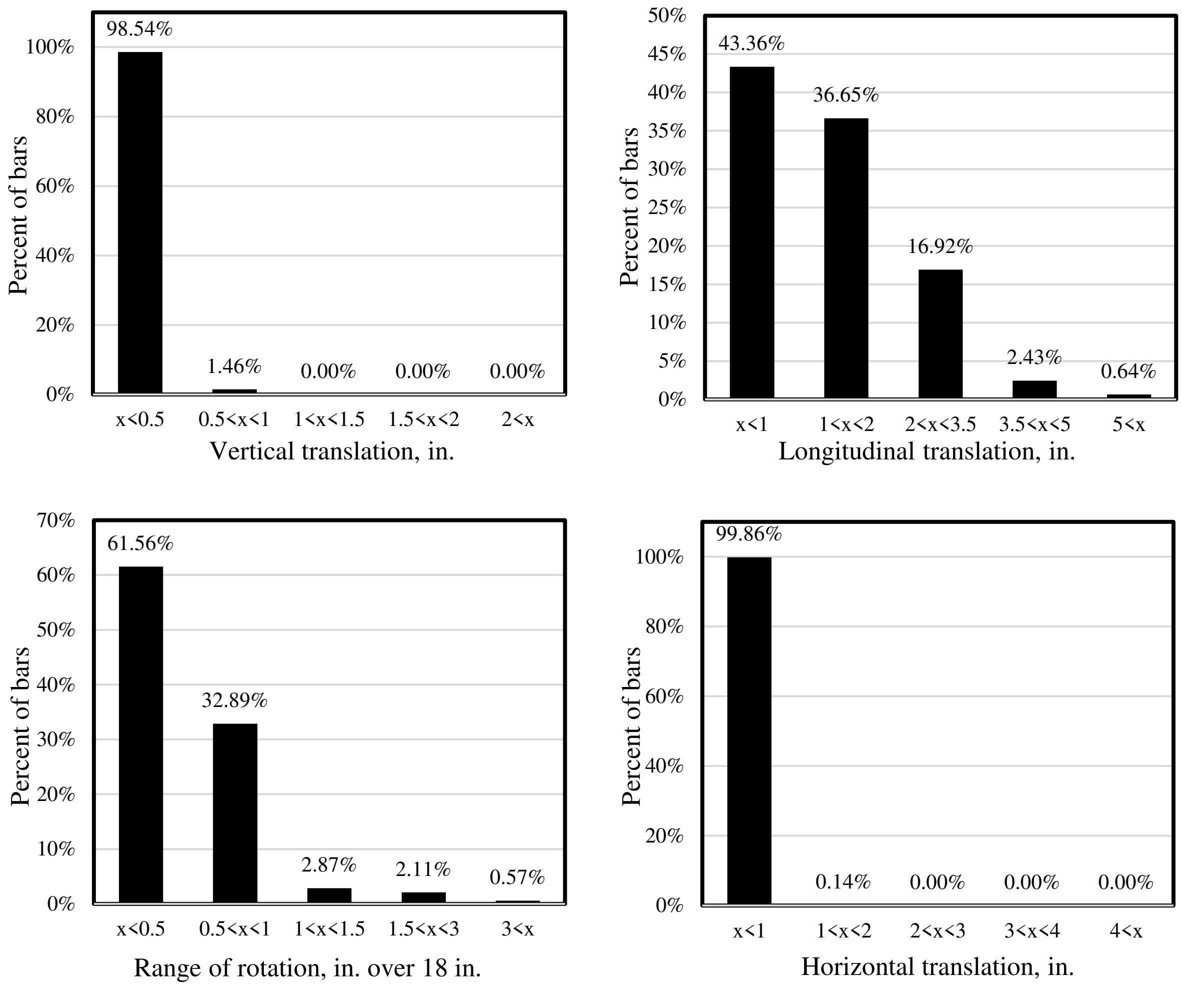


Figure 3.1 Dowel misalignment values of Hooper project

The dowel misalignment values of the 55 joints in SR 71 "Kimball" project can be seen in figure 3.2. Compared to the previous project, higher longitudinal and vertical translation of the dowels can be seen. Only 60% of the dowels showed acceptable longitudinal translation values, and 3 joints should be rejected based on ACPA and FHWA criteria. However, 97% of dowels presented acceptable vertical translations, and the other 3% still have sufficient concrete cover based on all criteria. Regarding rotational misalignment, four joints will be rejected based on the criteria of all agencies, two of which also had excessive longitudinal translations.

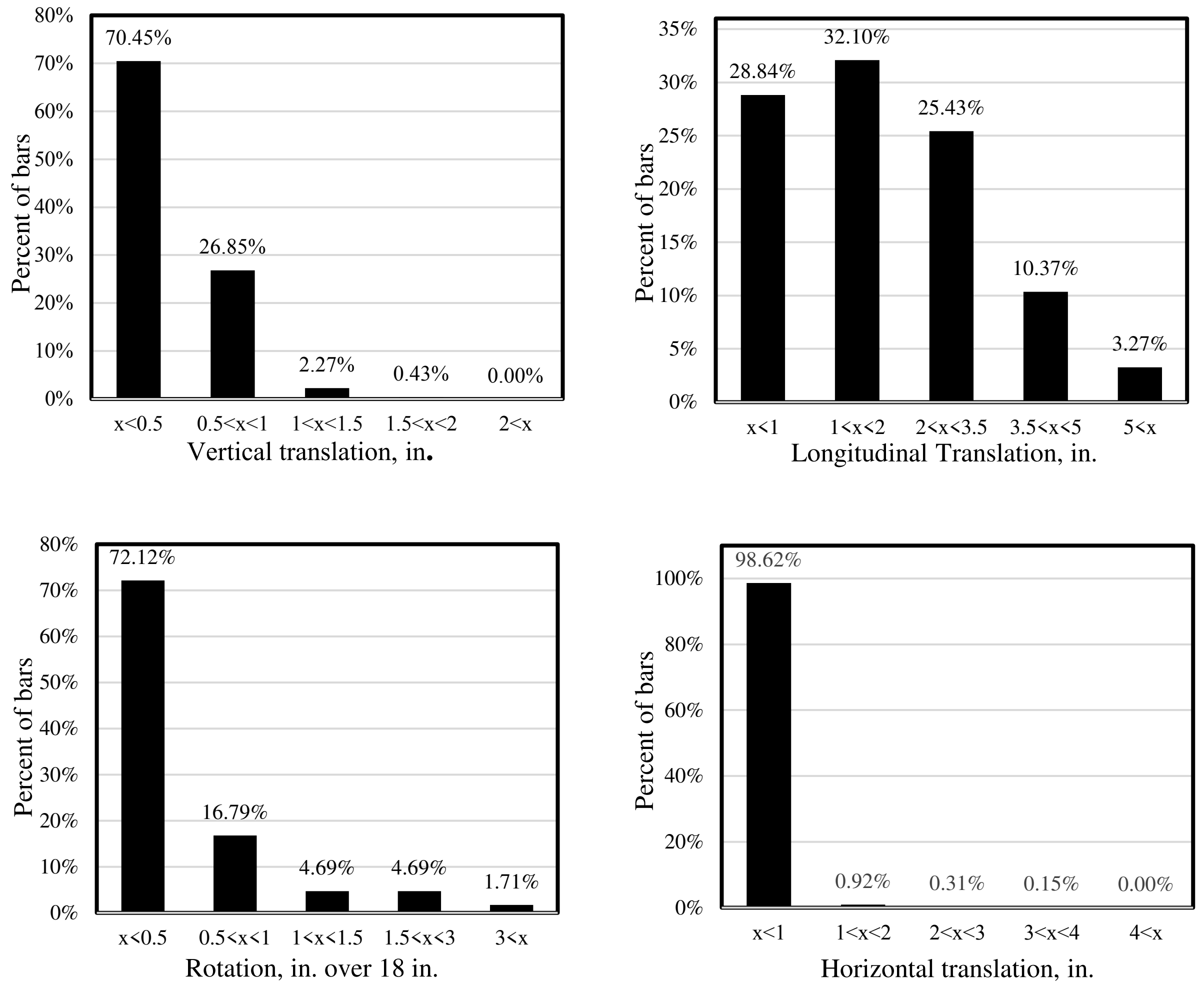


Figure 3.2 Dowel misalignment values of Kimball project

The dowel misalignment values of the I-80 project "Roscoe", and the US 275 project "Norfolk" can be seen in figures 3.3 and 3.4. The number of joints scanned for the projects were 155 and 175, respectively. The east and west directions of Norfolk were completed in 2005 and 2009 respectively, while Roscoe was completed in 2012. Similar to previous projects, both Norfolk and Roscoe showed acceptable vertical and horizontal translations. The dowels in Roscoe project have higher longitudinal translation with 35% of dowels falling outside acceptance criteria of national agencies , and 3 joints that have to be rejected, while Norfolk has 12% of dowels outside acceptance criteria and 3 joints that need corrective action. It can be noted that field investigation showed zero to 1 mm. faulting for those three joints.

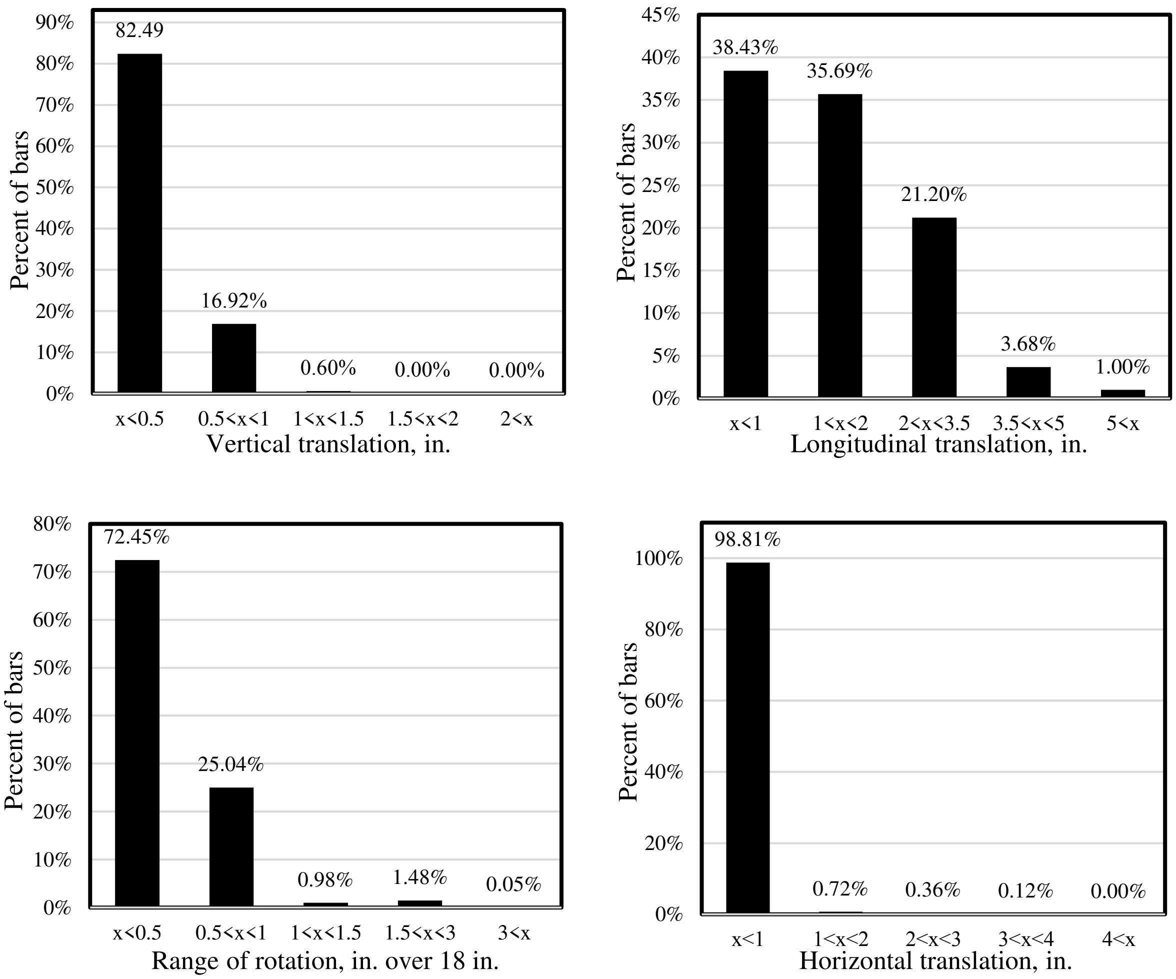


Figure 3.3 Dowel misalgnment values of Roscore project

The Norfolk project has higher rotational misalignment compared to Roscoe, with 12% outside acceptable tolerances compared to less than 3% for Roscoe. Seven percent of Norfolk joints fall outside the rejection criteria of FHWA and ACPA, compared to less than 2% for Roscoe.

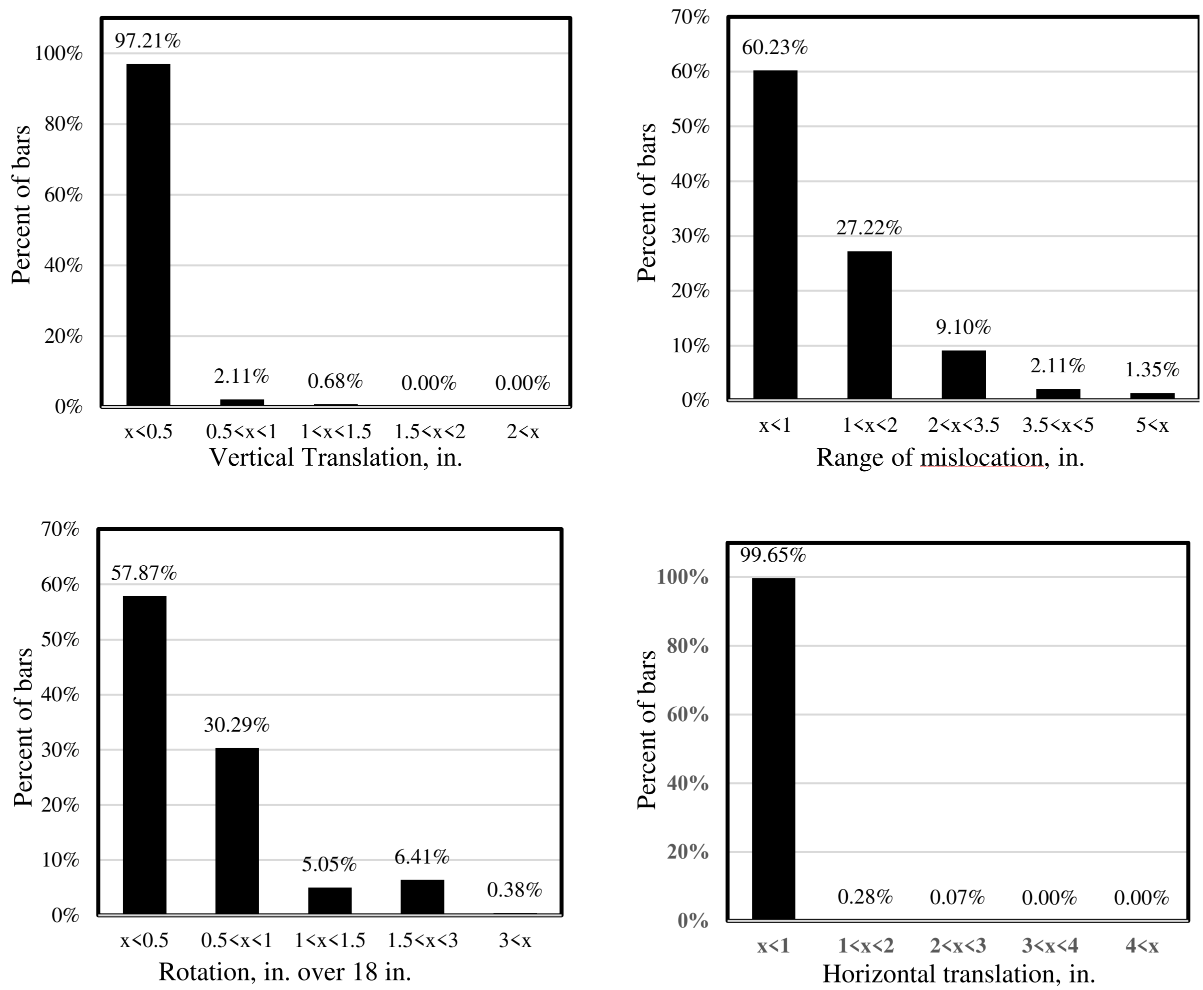
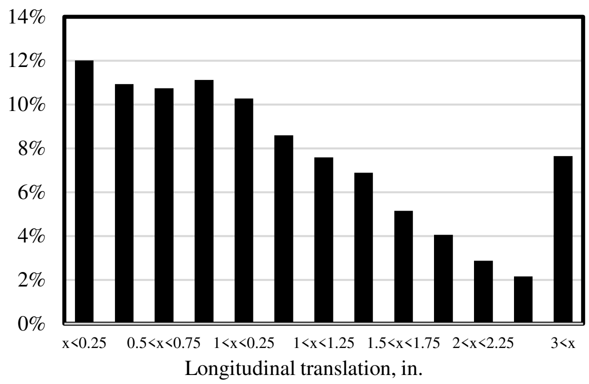
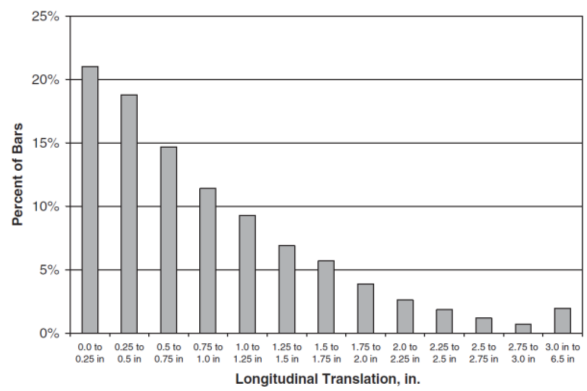


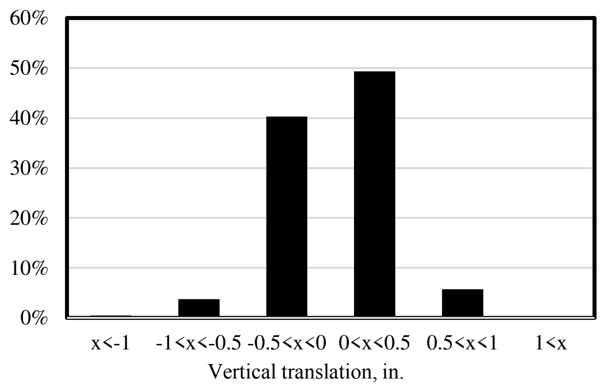
Figure 3.4 Dowel misalgnment for Norfolk project

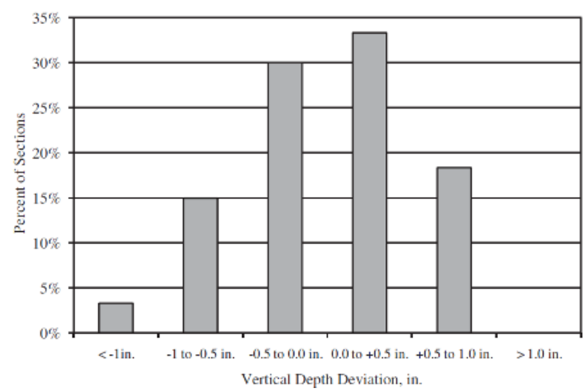
3.2 Comparison with Typical Misalignment Values

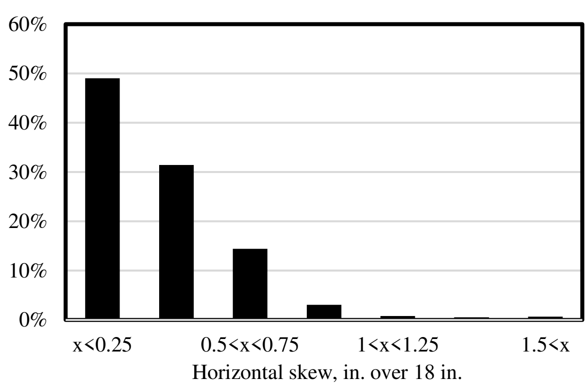
To compare the performance of the DBI used in these 4 projects with typical DBI and dowel basket practices, misalignment graphs of all projects have been juxtaposed with data from the study by Khazanovich et al. (2009) for over 2,300 joints. Figure 3.5 shows that longitudinal translation values of the dowels placed by the DBI are higher than the average reported by the NCHRP study. This could have happened due to inaccurate marking of the joints for saw-cut operations, as well as using a defective DBI. The vertical translation of the dowels, however, was better than NCHRP values, which could mean that the concrete mix used with the DBI was stable enough to hold the dowels in place after insertion. Horizontal skew and vertical tilt values for the scanned joints are comparable with average values reported by Khazanovich et al. (2009).

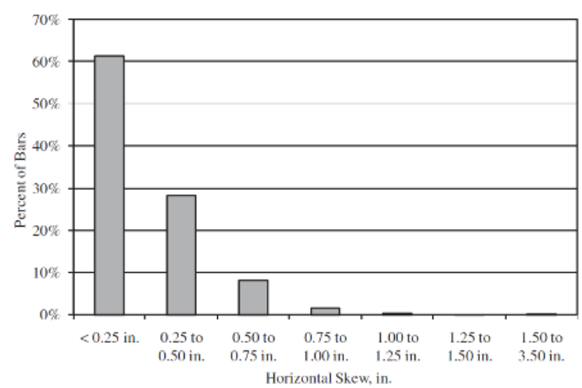












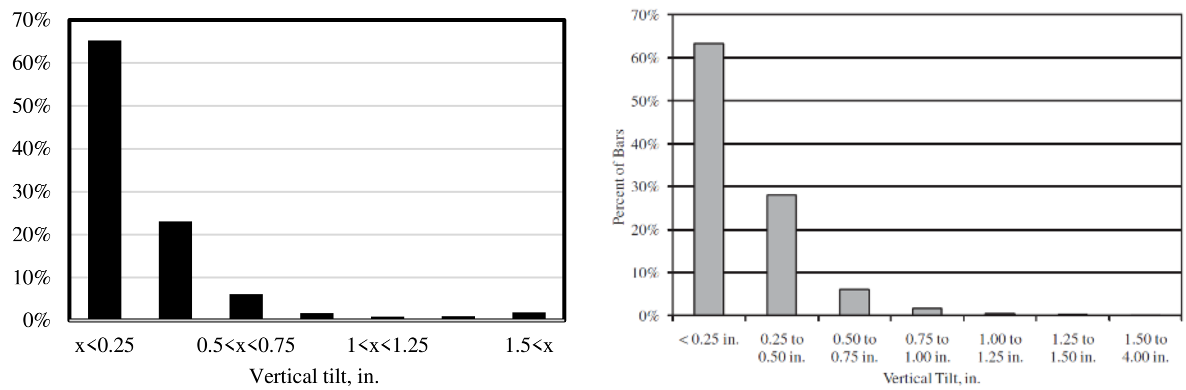


Figure 3.5 Comparison of MIT Scan-2 data with results of NCHRP study

3.3 Comments on MIT Scan-2 Data

Interference from tie bars were observed in approximately 20% of the joints in the Norfolk project. Figure 3.6 shows examples of the interferences in two of the joints. Such joints have been excluded from the data investigation and analysis due to high measurement errors, which make the results unreliable.

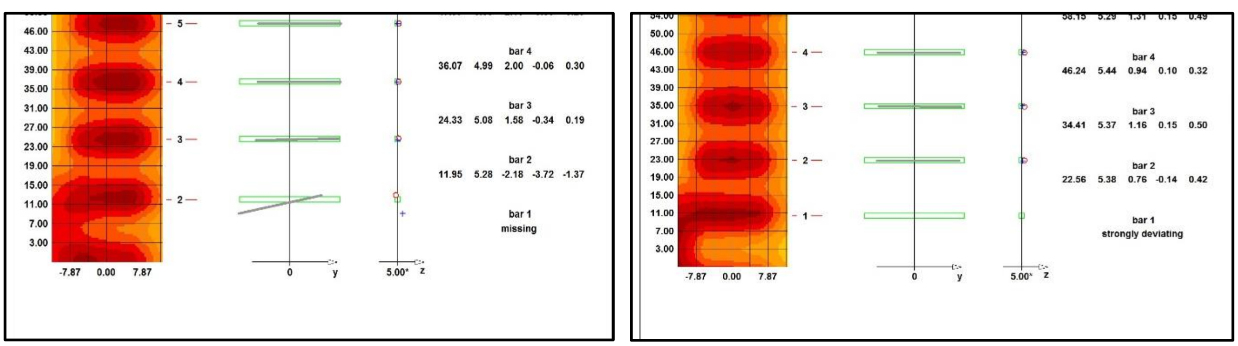


Figure 3.6 Tie bar interference

A few instances of the MagnoProof software mistakenly identifying the dowels as missing or strongly deviating was also encountered during data investigation. Examples of such joints are shown in figure 3.7. Such occurrences, together with the existence of foreign metals that can affect the results, show that the results provided by the software are not always correct, and manual inspection of individual joint contours is necessary for a reliable quality assurance approach.

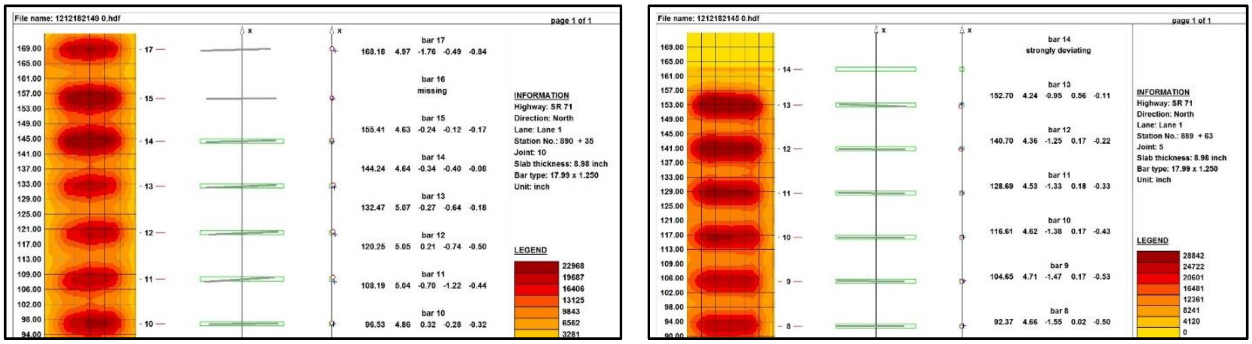


Figure 3.7 Erroneous dowel indentification by MagnoProof software

Chapter 4 Field Performance Investigation and Data Analysis

In order to find the relation between dowel misalignment and pavement performance, two of the four projects, Norfolk and Hooper, were selected for field observation. Spalling and cracking of pavements as well as faulting values on the right wheel path were recorded for 112 joints out of the 127 scanned joints of Hooper project, and 117 joints out of 175 scanned joints of Norfolk project. Since the pavement and traffic conditions for the two projects were not similar, the data from the projects were not pooled together for analysis.

Some of the joints in Norfolk project had dowel misalignments that could not be captured by typical misalignment categories, and thus these joints were not included in the data analysis task. Examples of two joints are presented in figure 4.1. From the signal intensity contour, it can be seen that some of the dowels in the joint are completely shifted and have lost their effectiveness. It is worthy to note that the joints in this figure had faulting values of 2 to 3 mm, which were among the highest faulting values observed on the Norfolk project. In spite of that, the

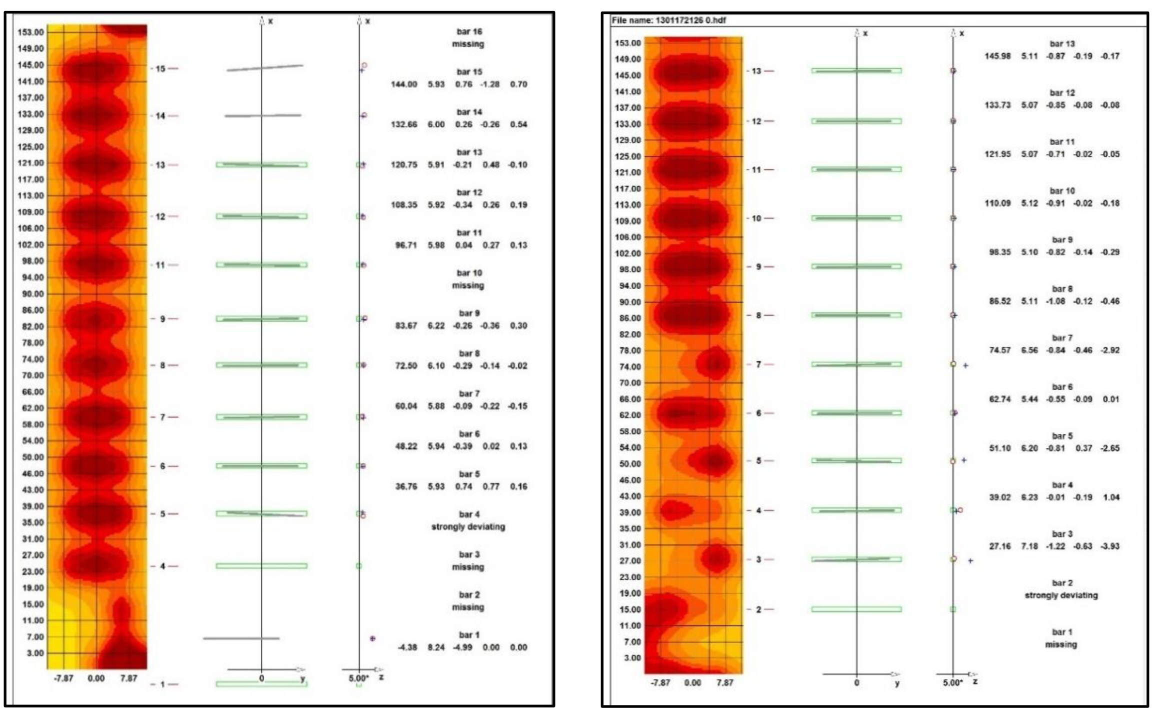


Figure 4.1 Examples of joints excluded from analysis

misalignment values reported by the MIT Scan-2 device does not capture the condition of the joint. Therefore, these joints have not been included in the analysis.

During the analysis of the scanned data of Hooper project, it was observed that one of the joints did not contain any dowels. The MagnoProof software could not produce an Excel sheet of dowel misalignment data, while the signal intensity plot of the MIT Scan-2 showed that the joint has no dowels. Field Performance measurements for the joint showed that the joint had the highest faulting value among measured joints, which was 4 mm. This may had occurred due to a mistake on the part of the DBI operator or a faulty DBI.

To investigate the effect of dowel misalignment on pavement distress, the following three data analysis tasks have been performed:

- faulting graphs,
- Student's t-test, and
- distress-misalignment tables.

4.1 Faulting Graphs

In order to analyze the effect of longitudinal translation, vertical translation, and dowel rotation on faulting at joints, faulting-misalignment graphs were developed for Hooper and Norfolk projects. Figure 4.2 shows the faulting value of each joint as a function of the average misalignment value of the joint dowels. If there is a relation between faulting and the extent of misalignment observed in the field, a trend is expected in the graphs. However, no such trend is visible, and it can be seen that higher faulting values (>2mm) occur at all ranges of dowel misalignment, which means that the high value of faulting is likely caused by factors other than dowel misalignment.

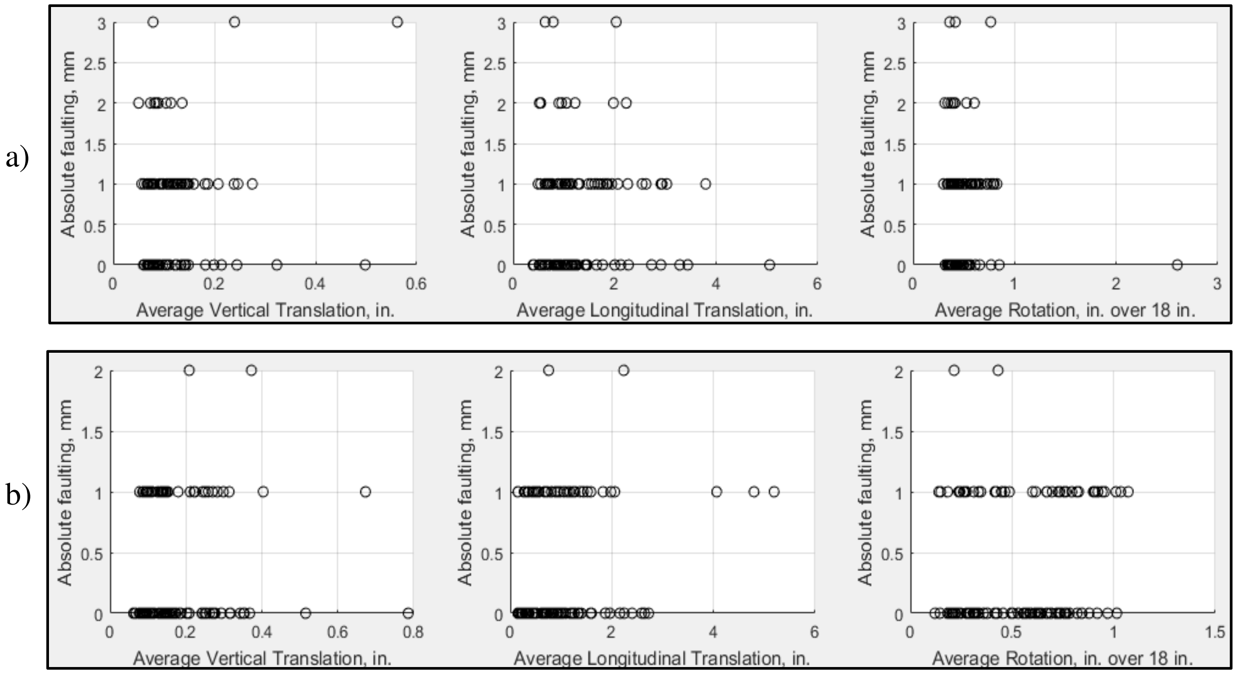


Figure 4.2 Faulting as a function of average dowel misalignment for (a) Hooper and (b) Norfolk

4.2 Student's T-test

One of the statistical methods that are used to see if two populations have equal means is the two-sample Student's t-test. The outcome of the test is a p-value, which determines the likelihood that the two groups have different means. The lower the p-value is, the more likely it is for the two groups to be different. Generally, a p-value of less than 5% is considered to indicate a significant difference between the two groups.

Joints in each of the projects were divided into two groups based on the faulting values measured in the field: those with zero faulting and those with faulting values greater than 2 mm. Then, Student's t-test was used to see if there is a significant difference in terms of dowel misalignment between these two groups. The results of the test is presented in table 4.1. The results show that there is no statistically significant difference between the misalignment values for joints with zero faulting, and joints with greater than 2mm faulting. Thus, it can be concluded that it is unlikely that dowel misalignment has contributed to faulting at the joints.

Table 4.1 Student's t-test results

	Misalignment	P-value
Hooper	Vertical Translation	0.32
	Longitudinal Translation	0.63
	Rotation	0.56

	Misalignment	P-value
Norfolk	Vertical Translation	0.2
	Longitudinal Translation	0.23
	Rotation	0.1

4.3 Distress-Misalignment Tables

The effect of dowel misalignment on spalling and cracking at joints could not be investigated using graphs or statistical tests, as they could not be quantified (the spalls were all of low severity). Therefore, an alternative approach was used. Tables 4.2 and 4.3 show the 25 joints with the highest measured average vertical translation (VT), longitudinal translation (LT), and rotational misalignment (RM), sorted from lowest to highest misalignment values for each project. If spalling or cracking were observed during field investigation, the row is marked with the letters "S" and "C," respectively. Therefore, if there is a correlation between dowel misalignment and spalling/cracking, one expects to see more distresses when moving towards the bottom of the tables. However, there was no such trend visible in either Norfolk and Hooper tables, which means that there is no significant correlation between the dowel misalignment in this range, and spalling/cracking at joints. The spalling observed during the field investigation may have been due to the joint sawing operation.

Table 4.2 Distress-misalignment for Hooper project

Vertical Translation, in.		
	Joint #	VT
	226-24	0.1401
	273-7	0.1404
S	234-98	0.1407
	258-61	0.1409
	270-54	0.1436
	273-92	0.1442
	272-7	0.1467
	274-97	0.1488
	225-99	0.1496
	298-6	0.159
	298-66	0.1591
	258-76	0.1814
C	258-51	0.1825
	258-91	0.1869
	261-68	0.1992
	258-86	0.2078
	270-79	0.214
	258-81	0.2391
	258-56	0.24
	234-53	0.2445
	298-41	0.2467
	261-73	0.275
	274-82	0.3236
	261-88	0.4983
S	274-87	0.5617

Longitudinal Translation, in.		
	Joint #	HT
	272-82	1.836
	258-61	1.8385
	272-2	1.8562
	298-41	1.8577
S	272-62	1.871
	258-71	1.9432
	272-72	1.976
	261-93	2.002
	274-72	2.0303
	226-34	2.0615
	226-19	2.1206
CS	270-89	2.2285
	261-58	2.2571
	273-2	2.2715
	274-47	2.5405
	272-52	2.6172
	271-97	2.7254
	226-29	2.9105
	261-53	2.9111
	272-7	2.9347
	226-39	3.0253
	274-62	3.2808
	261-97	3.4393
	270-84	3.791
	274-82	5.0511

Rotation, in. over 18 in.		
	Joint #	Ro
	270-59	0.5607
	272-92	0.5638
	258-91	0.5693
	270-74	0.5768
	258-86	0.5833
CS	270-89	0.6044
	234-58	0.6055
	270-94	0.6074
	234-53	0.6122
	272-87	0.6166
	226-14	0.6246
S	272-62	0.6463
	226-19	0.6566
	234-68	0.6571
	272-52	0.6685
	225-99	0.7242
	226-39	0.7335
S	226-4	0.7641
S	274-87	0.7652
	226-24	0.7684
	226-34	0.7864
	226-9	0.7997
	226-29	0.8264
	226-44	0.849
	274-82	2.6019

Table 4.3 Distress-misalignment for Norfolk project

Vertical Translation, in.		
	Joint #	VT
	169-75	0.2622
	603-90	0.2701
	135-23	0.2702
	147-90	0.2729
	135-3	0.275
	134-98	0.2756
	135-13	0.2768
	169-90	0.283
	119-90	0.2931
	440-89	0.2933
	441-21	0.2985
	503-58	0.3139
	604-6	0.3154
	119-85	0.3175
	441-5	0.3429
	604-38	0.3518
	502-78	0.3537
	120-0	0.3679
	135-8	0.3725
	440-41	0.4035
	204-70	0.5154
	135-18	0.6729
	120-5	0.7067
	134-93	0.7853
S	605-18	1.2089

Longitudinal Translation, in.		
	Joint #	LT
	387-60	1.3376
	603-90	1.3489
	503-26	1.3753
	503-42	1.3963
	135-18	1.4413
C	503-10	1.5184
	440-9	1.5818
	440-73	1.588
	582-20	1.601
	119-80	1.8282
	604-38	1.8712
S	388-56	1.8726
	204-70	1.9639
	502-94	1.9802
	532-84	2.0572
	533-64	2.1575
	603-74	2.2341
	532-68	2.2449
	388-24	2.3988
	502-46	2.5869
	387-92	2.6447
	441-37	2.7235
	503-58	4.0622
	604-22	4.7972
	604-86	5.1933

Rotation, in. over 18 in.		
	Joint #	Rotation
	388-24	0.763
	604-22	0.7656
	532-52	0.7657
	440-25	0.7674
	441-53	0.782
	388-8	0.7943
	532-84	0.8188
	532-68	0.8206
	502-62	0.8278
	441-5	0.8423
	387-12	0.845
	387-92	0.8795
	440-73	0.8994
	502-14	0.9033
	387-76	0.9091
	502-78	0.9194
C	503-10	0.9224
	503-58	0.9435
	502-94	0.956
	440-89	0.9704
	440-41	1.0111
	503-42	1.0156
	502-30	1.035
	441-21	1.0718
	120-5	1.1049

Chapter 5 Summary and Conclusions

The MIT Scan-2 results of joints that were constructed using a Dowel Bar Inserter were investigated to judge if DBIs can be reliable alternatives to dowel baskets in jointed PCC pavement construction. Moreover, a field observation of the joints was performed on two projects that had more than 7 years of service, and any ties between joint performance and dowel misalignment values were investigated. The results were expected to provide insight on the range of misalignment that would be detrimental to pavement performance, and serve as a guideline for improving Nebraska's current dowel placement specifications.

The results of the MIT Scan-2 data investigation show that the performance of the DBI in four projects was comparable to the typical dowel basket and DBI performance measured from in-service pavements by the NCHRP research project (Khazanovich et al. 2009). The longitudinal translation of dowels placed by the DBI were considerably larger than the typical values, while it performed better in terms of limiting the vertical translation of dowels compared to the results of Khazanovich et al. (2009).

No linkage was found between pavement performance and dowel misalignment levels for the 229 joints investigated in this study. No transverse cracking was observed during field investigation, and the spalling at joints is likely to be the result of joint saw-cut operations. However, measured distress from joints with missing or completely shifted dowels shows that high severity dowel misalignment has an adverse effect on joint performance. Based on this study, the following conclusions can be drawn.

5.1 Conclusions

- The MIT Scan-2 is an easy to use device which, despite occasional shortcomings such as erroneous detection of bars and the need for manual inspection of contours, can be a beneficial tool for detecting the dowel position at joints, and ensuring acceptable dowel placement practices when using a DBI. Analysis of a small number of scanned joints is fairly simple using Microsoft Excel. However, for large numbers of scanned joints, use of other software is advised for convenience. In this study, MATLAB was used to read all the Excel files and conduct the analysis.

- DBIs can perform as well as dowel baskets during dowel bar placement. However, quality assurance is necessary as the performance of DBIs can vary greatly based on the condition of the DBI as well as concrete mix properties. The use of test sections before construction could benefit the Department as it has been done by other states to assess the performance of DBIs. This has been found to be a useful approach to promote good dowel placement practices when using a DBI.
- Lack of a significant relation between joint performance and dowel misalignment values of the 229 joints in this study, and the results of national studies regarding dowel misalignments, suggest that the strict dowel placement tolerances used by many states are neither feasible, nor necessary for good joint performance.

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