Use of Magnetic Tomography Technology to Evaluate Dowel Placement

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16. Abstract

Extensive laboratory and field evaluations were conducted under this project to evaluate the effectiveness and limitations of the MIT Scan-2 device, which uses magnetic tomography technology to evaluate the placement of metal dowel bars in concrete pavements. The laboratory testing results confirm that the MIT Scan-2 device provides accuracy that is both reasonable and useful for horizontal and vertical misalignments within the following limits:

Depth – 100 to 190 mm (3.9 to 7.5 in)
Side shift – +100 mm (+4 in)
Horizontal misalignment – +40 (+1.6 in) plus a uniform rotation of +80 mm (+3.1 in)
Vertical misalignment – +40 mm (+1.6 in)

The estimated overall standard deviation of measurement error is 3.0 mm (0.12 in), which means that the device can provide measurement accuracy of +5 mm (0.20 in) with 95% reliability. With proper calibration to account for dowel baskets, the device can provide similar levels of accuracy for dowel bars placed either in dowel baskets or by a dowel bar inserter. This assumes that the dowels are insulated (epoxy coated or painted) and that the transport ties are cut. Field experience with the MIT Scan-2 showed that the device is reliable and easy to use. Up to 400 or more joints can be tested in an 8-hour period using a single charge of the battery. An exception is that testing during cold weather greatly reduces the battery life.

The ability to assess MIT Scan-2 results and focus, in real time, on potentially needed adjustments both in the paving equipment and hardware and in the portland cement concrete mixture proportions make the MIT Scan-2 a unique and valuable tool.

The principal limitation of MIT Scan-2 is that the presence of other metal objects (such as tie bars, nails in the joint, coins, pieces of wire, or any other metal item) near the measurement region can introduce significant errors, effectively invalidating the results.

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INTRODUCTION

The use of large-diameter dowel bars has been a long-standing recommendation for all jointed concrete pavements (JCP) subjected to high volumes of heavy truck traffic to prevent roughness caused by faulting. Implicit in this recommendation is the assumption that the dowel bars will be placed in proper position and alignment. Inadequate concrete cover can lead to steel corrosion and spalling. If the bars are not adequately centered under the joint saw cut, the bars may not be effective in providing load transfer. More critical, in terms of margin of error, is the dowel bar orientation. Misaligned dowel bars can interfere with the proper functioning of the joint, which in turn, can lead to spalling or cracking of the concrete. Severely misaligned dowel bars can also cause looseness around the dowel bars, greatly reducing their effectiveness. While the importance of achieving good dowel alignment is widely recognized, the ability to monitor the placement accuracy of dowel bars effectively has been limited by the lack of practical means of measuring the position and orientation of dowel bars embedded in concrete.

The past difficulties in measuring dowel alignment have several important consequences on concrete pavement construction:

- Limited validation testing for dowel alignment—Most agencies conduct only a limited amount of coring to evaluate dowel alignment. The obvious limitation of this approach is that dowel alignment is evaluated based on an extremely small sample. To determine whether misaligned dowels will interfere with proper functioning of a joint, the alignment of every bar in the joint must be known. To determine the quality of dowel alignment in a section of pavement (e.g., one day of paving) numerous joints must be tested. This amount of testing is not practical by coring.
- Possibility of excessively strict dowel placement tolerance—Most agencies have fairly strict tolerances on dowel placement accuracy, but those standards are based on limited laboratory and field data. In some cases, the fabrication tolerances for dowel baskets are adopted directly and used as the tolerance on dowel placement accuracy, which leaves no room for any placement error during construction. The actual dowel bar alignment needed to ensure good pavement performance is largely unknown.
- Limited usage of dowel bar inserters (DBIs)—Because of the concern over the dowel alignment and the lack of practical means of verifying dowel alignment in the past, DBI usage has not been widespread in the United States, and many highway agencies specifically prohibit the use of a DBI.

The placement accuracy of dowel bars embedded in jointed plain concrete pavements (JPCP) can now be evaluated with unparalleled accuracy and efficiency using MIT Scan-2. MIT Scan-2 is a state-of-the-art, nondestructive testing (NDT) device for measuring the position and alignment of dowel bars embedded in concrete. The device is simple to operate, is efficient, and provides accurate, real-time results in the field. This device holds the promise of greatly improving the quality of concrete pavement construction, as well as significant cost savings by preventing costly errors. The California Department of Transportation (Caltrans) was instrumental in bringing this technology to the United States (Khazanovich et al. 2003).

This study was initiated to evaluate the effectiveness and limitation of MIT Scan-2, especially as a tool for monitoring dowel placement accuracy during construction. The specific objectives include the following:

- Conduct laboratory and field evaluation of MIT Scan-2 to assess accuracy and repeatability of measurements of dowel position.
- Compare MIT Scan-2 measurements with measurements of other devices such as cover meter and ground penetrating radar (GPR).
- Demonstrate MIT Scan-2 to contractors and State department of transportation (DOT) personnel and collect their comments on the usability of this device.
- Develop recommendations for the use of MIT Scan-2 in quality assurance/quality control (QA/QC) procedures by contractors and State DOTs, and develop comprehensive training materials.

LITERATURE REVIEW

A comprehensive literature search was conducted to identify and evaluate the available devices for determining dowel bar alignment. Of the available devices, MIT Scan-2 is the only one developed specifically for detecting dowel bar alignment and optimized for that application. Other devices consist of various types of cover meter and GPR. An Internet search was performed to collect information about all the devices identified. The equipment manufacturers and distributors were also contacted to obtain additional information.

Cover Meters

Cover meters work on the same basic principle as the MIT Scan-2. The devices emit an electromagnetic pulse and detect the magnetic field induced in metal objects. Various types of cover meters are available, including the following:

- Profometer (http://www.proceq.com/pdf/PROFOMETER_5_e.pdf)
- Micro Covermeter (http://www.humboldtmfg.com/pdf1/86.pdf)
- CoverMaster (http://www.mastrad.com/cover.htm#cm9)
- Rebar locator R-HR-7000 (http://www.qualitest-inc.com/pdf/rebarlocator-Datascan.pdf)
- Fisher MODEL M-101 Rebar Locator (http://www.giscogeo.com/pages/mtlfm101.html)
- Refor 3 (http://www.nema.demon.nl/refor-en/refor3.html)

Cover meters are mainly designed for locating reinforcement in concrete structures and determining the depth of concrete cover. Many of the older devices are capable only of detecting metals close to the concrete surface (e.g., concrete cover of 75 mm [3 in.] or less) and cannot be used for determining dowel alignment at all. The newer devices listed above, however, have a detection range (range of depths) similar to that of MIT Scan-2.

All of the devices have a similar configuration, with one or more sensors for detecting the induced magnetic field. Based on the duration or intensity of the induced magnetic field, the location of embedded metal is determined. All devices provide the concrete cover and horizontal distance to the bar. To determine dowel alignment, the ends of the dowel bar have to be found and marked manually. The ends of the bar are found by finding the location where the signal drops off abruptly. The alignment is determined from the marked positions (for the horizontal alignment) and the depths measured from those locations (for vertical alignment). This process is slow and is subject to the errors introduced during marking and taking the readings precisely at the bar ends.

Because cover meters work on the same principles as the MIT Scan-2, they are subject to the same advantages and limitations as MIT Scan-2; however, some key advantages of the MIT Scan-2 method of dowel bar detection include the following:

- The weather conditions (dry vs. wet) do not affect measurement results. This is a significant limitation for GPR.
- Testing can be conducted on fresh concrete. The other devices will actually work on fresh concrete, but there are no practical means of taking measurements without marring the surface.

The main disadvantage of these devices (and MIT Scan-2) is that the presence of other metal will affect the measurement results. For accurate results using all devices, the bar diameter must be known. For highly accurate results, MIT Scan-2 requires that both the diameter and length of the bars be known and that a calibration be performed using the specific dowel bar.

Profometer, Micro Covermeter, CoverMaster, Rebar locator R-HR-7000, Fisher MODEL M-101 Rebar Locator, Refor 3, and Ferroscan all have similar features. They are user-friendly (automatically display concrete cover thickness, ability to determine horizontal location, etc.). However, locating a large number of individual dowel bars is time consuming. In addition, many of these devices do not have effective data storage systems, so the information has to be recoded manually. These devices may be effective for random checks of dowel alignments, but they are not practical for evaluating the alignment of all bars in a joint, which is needed to assess whether improperly placed dowels will interfere with the proper functioning of the joint.

Ground Penetrating Radar

GPR systems operate by transmitting polarized pulses of electromagnetic energy into the ground and then recording the energy that is reflected back to the surface. The GPR signal responds to variations in the electrical properties of subsurface materials (dielectric constant and conductivity) that are a function of material type, moisture content, and pore fluid type. Where a contrast in dielectric properties exists between adjacent materials, a proportion of the electromagnetic pulse will be reflected back. Subsurface structures are mapped by measuring the amplitude and travel time of this reflected energy.

A recent study conducted by the Missouri DOT (MDOT 2003) demonstrated that GPR can be used to assess dowel bar alignment accurately. The researchers reported the measurement accuracy of +3 mm (0.1 in.) on vertical alignment. The accuracy of detecting lateral dowel position is believed to be within 10 mm (0.4 in.). However, this method of detecting dowel alignment is sensitive to the dielectric constant of concrete, which is a function of moisture content, temperature, and antenna frequency, among others. This method cannot be used on fresh concrete or when the concrete surface is wet. Another drawback for this method is that the data processing is quite involved.

Over the past few years, significant advances have been made in GPR technology to overcome many of the past difficulties of using GPR. Signal calibration techniques have been developed that enable scan-by-scan calibration of the data obtained without requiring physical testing for material properties (core testing). The dependence on the accuracy of the material property (dielectric constant) of the test results had been a critical limitation of GPR technology in the past. The data analysis process has also been streamlined for certain applications to provide real-time results (e.g., detection of rebar location and depth on structures and bridge decks). The main advantage of the GPR technology (over the magnetic) is that the results are not affected by the presence of foreign metal. The presence of tie bars, metal covers for drainage inlets, or any other metal objects close to dowel bars poses a problem for measurements using the magnetic technology. Because of the insensitivity of the test results to the presence of foreign metal, the GPR technology is better suited for testing dowels placed in baskets. However, for testing bare bars (inserted bars), the magnetic technology may be more reliable, because the results are based on direct measurements, rather than correlation to a calibration.

MIT Scan-2

MIT Scan-2 was developed specifically for locating dowel bars placed by DBI. The device has features that make it superior to all other devices:

- In one scan, the device determines the location and alignment of all dowels along the entire joint (up to three lanes wide).
- Immediately after the measurements, preliminary results can be printed. More comprehensive analysis can be performed later.
- Multiple sensors and innovative data interpretation software make the device extremely accurate.
- The device can be used on fresh concrete.

Developed by MIT GmbH, Dresden, Germany, MIT Scan-2 was created specifically for locating steel dowel and tie bars in concrete pavements. If operated by a two-person crew, 200 or more joints can be tested using MIT Scan-2 in an 8-hour shift. Up to three lanes can be scanned at one time, and the productivity is similar for scanning one or two lanes because the measuring task takes minimal time. The device was designed to work continuously for at least 8 hours on one battery charge. The onboard computer allows the crew to perform a preliminary analysis of the test data and print the results after testing in real time. The test data are stored on a flash memory card and can be analyzed later on a more powerful computer, using more sophisticated software.

DESCRIPTION OF MIT SCAN-2

MIT Scan-2 consists of three main components, as shown in Figure 1:

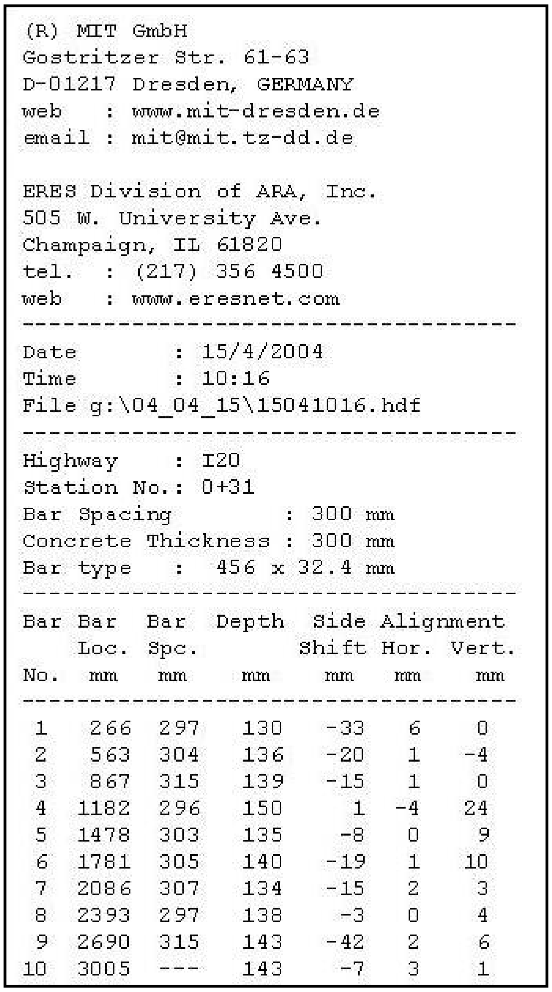
- Sensor unit (the rectangular box shown in Figure 1) that emits electromagnetic pulses and detects the induced magnetic field—The sensor unit contains five sensors: one at the center and two each to either side. The sensors are evenly spaced and are centered (approximately) along the line directly below the white line of the MIT logo on the box (Figure 1).
- Onboard computer that runs the test, collects and stores the test data, and performs the preliminary evaluation.
- Glass-fiber-reinforced plastic rail system that guides the sensor unit along the joint, parallel to the pavement surface, and at a constant elevation.

MIT Scan-2 is designed for use on construction sites without requiring any special precautions. Both the sensor unit and the onboard computer are adequately protected against dust, and they can be used in adverse weather conditions, including rain and low temperatures. The operating temperature range is from 23 ºF to 122 ºF (-5 ºC to 50 ºC). The test results are not influenced by weather conditions.

Figure 2 shows a joint being scanned using MIT Scan-2. Scanning a joint takes less than a minute. The field data analysis is fully automated, and results are produced in less than a minute after scanning. The onboard computer is equipped with a printer to provide a printed output in the field. Example field results are shown in Figure 3. The test data are stored in a PCMCIA flash memory card. Data for up to 600 joints (single lane) can be stored in the 32-megabyte (MB) memory card provided with the device. This is typically more than adequate storage, and the data can be transferred easily to a laptop computer by simply removing the PCMCIA card from the onboard computer and plugging it into the PCMCIA card slot of a laptop computer.

Figure 1. MIT Scan-2, consisting of the sensor unit (a rectangular, green box), onboard computer, and glass-fiber-reinforced plastic rail system.

Figure 2. Scanning a joint using MIT Scan-2.



```
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------------------------------------
Date        : 15/4/2004
Time        : 10:16
File g:\04_04_15\15041016.hdf
------------------------------------
Highway     : I20
Station No.: 0+31
Bar Spacing         : 300 mm
Concrete Thickness : 300 mm
Bar type   :  456 x 32.4 mm
------------------------------------
Bar Bar  Bar  Depth  Side Alignment
    Loc. Spc.        Shift Hor. Vert.
No.  mm   mm     mm    mm   mm    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
```
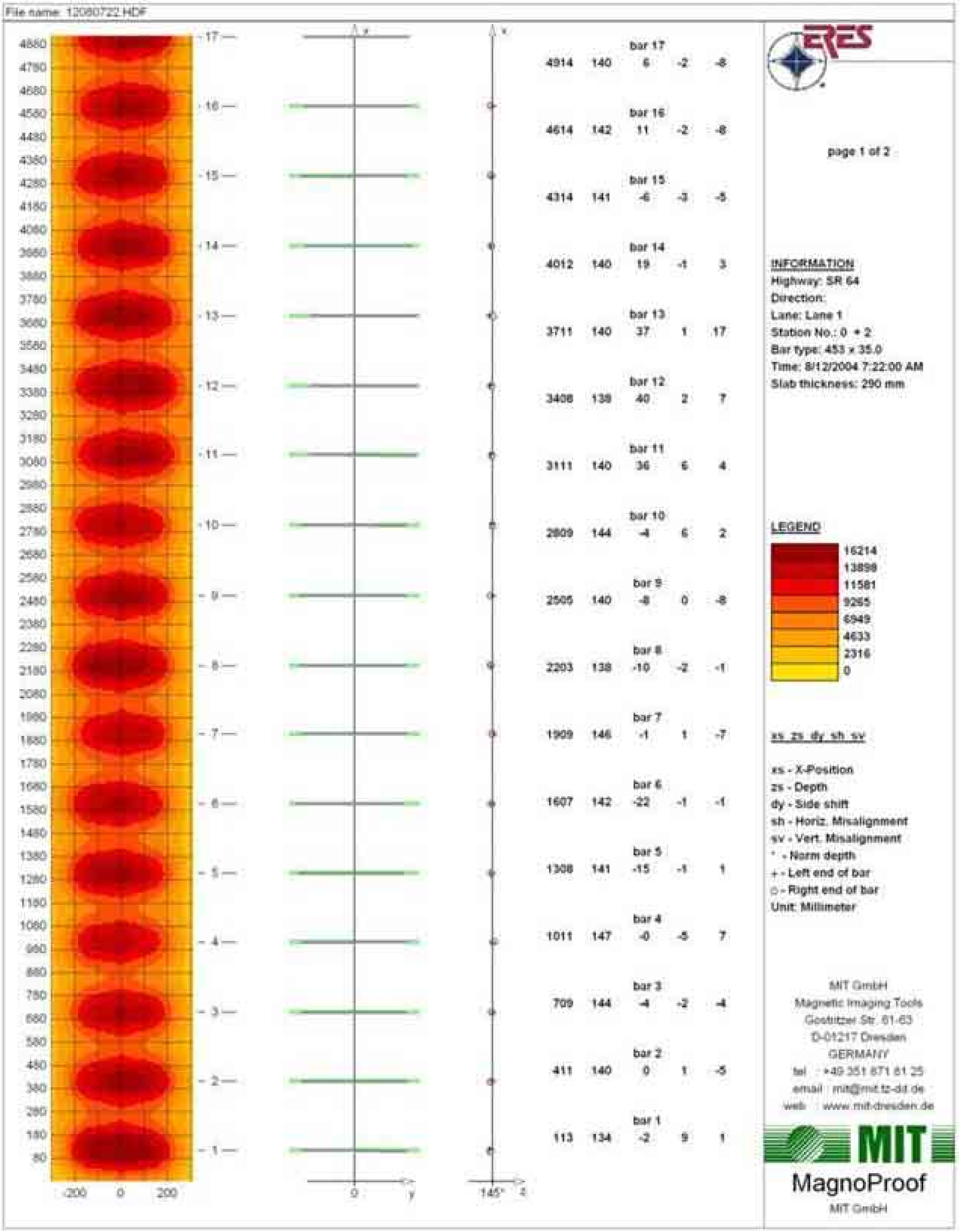

Figure 3. Example field output of MIT Scan-2.

MIT Scan-2 allows the entire joint to be scanned in one pass, providing results for all dowel bars in the joint. The field results (produced by MagnoNorm software) are accurate for the following conditions:

- Mean dowel depth 150 ± 40 mm (4.3 to 7.5 in.)
- Maximum vertical misalignment +20 mm (0.8 in.)
- Maximum horizontal misalignment +20 mm (0.8 in.)
- Maximum lateral position error (side shift) <50 mm (2 in.)

For other conditions, the accompanying PC software (MagnoProof) can be used to conduct a more comprehensive analysis. MagnoProof is also highly automated and easy to use, but it allows more manual control of the analysis process. For example, the automatic process for detecting the bar locations may not pick up a bar that is placed much deeper than the others because of the weaker signal. MagnoProof allows the users to insert or delete bars based on the observation of signal-intensity plot, which is shown on the screen. The user may also restrict the analysis region to cut out the part containing strong influence of foreign objects, which cannot be analyzed. The output options include a signal-intensity contour map and an illustration of the analysis results that shows the specified bar locations and the actual bar positions (Figure 4).



File name: 12080722.HDF

bar 17	4914	140	6	-2	-8
bar 16	4614	142	11	-2	-8
bar 15	4314	141	-6	-3	-5
bar 14	4012	140	19	-1	3
bar 13	3711	140	37	1	17
bar 12	3408	138	40	2	7
bar 11	3111	140	36	6	4
bar 10	2809	144	-4	6	2
bar 9	2505	140	-8	0	-8
bar 8	2203	138	-10	-2	-1
bar 7	1909	146	-1	1	-7
bar 6	1607	142	-22	-1	-1
bar 5	1308	141	-15	-1	1
bar 4	1011	147	-0	-5	7
bar 3	709	144	-4	-2	-4
bar 2	411	140	0	1	-5
bar 1	113	134	-2	9	1

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INFORMATION
Highway: SR 64
Direction:
Lane: Lane 1
Station No.: 0 + 2
Bar type: 453 x 35.0
Time: 8/12/2004 7:22:00 AM
Slab thickness: 290 mm

LEGEND
16214
13898
11581
9265
6949
4633
2316
0

xs zs dy sh sv

xs - X-Position
zs - Depth
dy - Side shift
sh - Horiz. Misalignment
sv - Vert. Misalignment
* - Norm depth
+ - Left end of bar
○ - Right end of bar
Unit: Millimeter

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Figure 4. Example graphical output of MagnoProof.

Technology

The fundamental operating principle behind MIT Scan-2 is pulse-induction (MIT 2002). The device emits a weak, pulsating magnetic signal and detects the transient magnetic response signal induced in metal bars. The weak magnetic field emitted by MIT Scan-2 is harmless to the surrounding area and does not affect the physical properties of the dowels or of the concrete. The response signals are measured with high precision using special receivers in the testing device. The detected signal values are recorded at a relatively high sampling rate to assure large quantities of data for mathematical evaluation. The data redundancy enables evaluation of measurements taken under less than ideal circumstances (e.g., the presence of foreign metal or magnetic aggregates).

The basis of the solution technique employed in MIT Scan-2 is magnetic tomography. In magnetic tomography the response of the investigated objects to external fields is measured 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, orientation, and type of metallic bodies in the investigated region and the indication of defects in those objects. However, when multiple objects are present, only the overall effects of all objects within the detection range can be measured. The inability to detect the response signal of individual objects separately greatly complicates data analysis. The true value of MIT Scan-2 is in the innovative techniques employed to determine the position and orientation of individual objects from the integrated signal. The innovations include the application of an array of sensors and novel filter techniques, the usage of the redundant data recorded from different positions from multiple sensors, and the use of all existing additional physical knowledge about the object in determining the position and orientation of the object scanned (Lehmann 2001).

Calibration and Validation

Each MIT Scan-2 unit is individually calibrated to each type of bar that will be detected using the device to provide very accurate results. During calibration, measurements are taken over the entire range of bar positions and orientations to correlate the response signals to the known bar positions and orientations. The testing results are used to develop a device-specific parameter file for each type of bar. The bar type is defined by the bar dimensions (diameter and length) and metal composition (e.g., steel, solid stainless steel, or stainless steel clad).

Figure 5 shows the calibration measurements being taken at the MIT GmbH laboratory. The test bench is completely free of all metal objects. The wooden vise that holds the test sample is attached to a jig that allows the bar to be positioned at any depth and lateral position (side shift) within the evaluation range, and the bar can be rotated up or down. A full factorial of readings is taken during calibration testing, except for the rotation in the horizontal direction. Horizontal alignment is determined based on the locations where the maximum signal intensity was recorded at each end of the bar as the sensor unit is pulled along the joint. The calibration results are field verified at the MIT GmbH testing facility by comparing MIT Scan-2 results to manual measurements (Figure 6) to ensure that the interaction of neighboring dowel bars does not produce additional measurement errors.

The bar type is a required input during testing, and it is important to specify the correct bar type to obtain meaningful results. However, the field data and calibration data are kept separately in the MIT Scan-2 data files, and the calibration information is applied at data analysis time. If an incorrect bar type is specified during testing, the correct bar type can be substituted during data analysis using MagnoProof. However, it is important to note that the correct bar type must be specified to obtain accurate results. The accuracy of the results obtained using an incorrect bar type is unpredictable.

Figure 5. Calibration measurements being taken at MIT GmbH laboratory.

Figure 6. Test track at MIT GmbH for validation of calibration results.

Operation

MIT Scan-2 is easy to operate and requires minimal maintenance. Only two preparations are required prior to field testing:

- Charging batteries—The sensor unit contains a maintenance-free, lead-acid battery, which takes about 4 hours to fully charge. The battery in the onboard computer takes about 10 hours to fully charge using the charger supplied with the computer. Alternatively, an external charger may be used to charge the battery in about 2 hours.
- Ensuring that the flash memory has enough room for new data—The memory card can be removed and plugged into any compatible laptop computer for managing data files. The data should be downloaded onto a laptop computer or other permanent storage device after each day of testing, and the flash memory card kept clear to provide room for future test data.

In the field, the setup process consists of assembling the rail system and connecting the onboard computer to the sensor unit. The sensor unit takes 5 min to warm up. If measurements are taken while the unit is not warmed up, additional errors may be introduced.

The measuring process involves setting the rails on the joint to be scanned, entering the pavement information into the onboard computer, and then pulling the unit along the joint. The details of operating MIT Scan-2 are provided in Appendix A: MIT Scan-2 Operations Guide.

MIT Scan-2 keeps track of both joint number and station. Both numbers are automatically incremented or decreased (the joint number by 1, and the station number by the joint spacing) after testing each joint according to the user settings. Prior to testing, it is highly recommended to number the joints in the test section to ensure that the recorded joint numbers correspond to the correct joints. Marking every 5th joint is adequate for this purpose.

Productivity

After the initial setup, testing takes 1 to 2 min per joint, depending on the number of lanes being tested. The setup process, including assembling the rail system and marking the joints to be scanned, takes about 30 min. Up to three lanes can be scanned together in a single pass, and testing multiple lanes together does not drastically slow the rate of testing (in terms of number of joints tested, counting one pass as one joint). However, longer rails are more cumbersome to move and slow the rate of testing (again, counting one pass as one joint). To prevent damage to the rail system, one person per lane-width is needed to move the rail. For example, one person can move the rail for a single lane. When testing two lanes at a time, two people are needed to move the rail without causing damage.

The maximum rate of testing is also limited by the file naming convention used by MIT Scan-2, which uses the minute during which the test is conducted as a part of the file name. MIT Scan-2 produces two files for each joint scanned: a binary file (*.hdf) containing the raw data and a text file (*.txt) containing the field data analysis results. The file names are generated based on the date and time as follows:

> *ddMMhhmm.**—*dd* is the date, *MM* the month, *hh* the hour, and *mm* the minute.

Because the minute of the testing time is used in the file name, no more than one test can be conducted per minute. Therefore, the maximum productivity is 60 joints per hour. In general, this restriction is not a limiting factor when testing multiple lanes, but it does affect productivity when testing a single lane.

Although up to 60 joints can be tested in an hour, this rate of testing cannot be sustained throughout a work day, even when testing a single lane. Field experience shows that a good average daily productivity is about 200 joints for two lanes and moderately more (e.g., 250 joints) for a single lane.

LABORATORY EVALUATION

Verifying the accuracy and reliability of MIT Scan-2 was one of the main objectives of this study. The manufacturer-specified measurement tolerances for MIT Scan-2 are as follows:

• Repeatability	2 mm (0.08 in.)
• Horizontal and vertical alignment	±4 mm (0.16 in.)
• Side shift	±8 mm (0.31 in.)
• Depth (cover)	±4 mm (0.16 in.)

The above values are the observed maximum variations, not standard deviations. The standard deviations are approximately one-third of the values listed above. Tests were conducted to verify these values and also to determine the conditions under which the specified levels of accuracy are valid.

The following series of tests was conducted:

- Repeatability—tests to determine the magnitude of random error on repeated testing.
- Effects of cover material and testing conditions—Because MIT Scan-2 operates on an electromagnetic field, the presence or absence of nonconducting material does not affect the results. Tests were conducted to verify that the test results are independent of the cover material and presence of water.
- Operating range—tests to determine the range of testing conditions under which MIT Scan-2 provides accurate results.

Based on the test results, the overall standard deviation of the measurement error and the confidence interval of MIT Scan-2 results were determined.

Most of the laboratory testing was conducted at the MnRoad facility. MnRoad constructed a slab with slots and simulated joints cut into the test slab (Figure 7) for this study. The dowels were placed in the slots at various depths and orientation. Measurements were then taken using MIT Scan-2 and compared to manual measurements. The slots provided a stable platform for holding the dowels in place during hand measurements and during MIT Scan-2 testing (Figure 8). For example, shifting the rail, rather than moving the dowel bar, ensured that the orientation of the dowel bar remained constant throughout the series of testing that was conducted to evaluate the effects of side shift.

Figure 7. Saw cut being made on test slab to simulate a joint at the MnRoad facility.

Figure 8. Dowel bar wedged in a slot of the test slab at the MnRoad facility.

Repeatability

Repeated measurements were taken with the test sample fixed in place to verify the reproducibility of the MIT Scan-2 test results. Both the rail and the test sample were left undisturbed through each series of tests. For each series, 10 repetitions of measurements were taken. The results of these tests are summarized in Table 1. As reported by MIT GmbH, the range of random variations in the test results does not exceed 2 mm (0.08 in.) on repeated testing.

Table 1. Repeatability Test Results

Series	Trial	Misalignment, mm		Side shift, mm	Depth, mm
		Horizontal	Vertical		
1	1	6	-15	-6	108
	2	5	-15	-6	108
	3	7	-15	-6	108
	4	6	-15	-6	108
	5	6	-15	-6	108
	6	6	-15	-6	108
	7	5	-15	-6	108
	8	6	-15	-6	108
	9	6	-15	-6	107
	10	5	-15	-6	107
Result	**Min**	**5**	**-15**	**-6**	**107**
	Max	**7**	**-15**	**-6**	**108**
	Range	**2**	**0**	**0**	**1**
2	1	5	-7	2	123
	2	5	-6	1	123
	3	5	-7	2	123
	4	5	-7	2	123
	5	6	-7	2	123
	6	5	-6	1	123
	7	5	-7	2	123
	8	5	-7	1	123
	9	5	-7	2	123
	10	5	-7	2	123
Result	**Min**	**5**	**-7**	**1**	**123**
	Max	**6**	**-6**	**2**	**123**
	Range	**1**	**1**	**1**	**0**
3	1	3	-13	-30	104
	2	3	-13	-30	104
	3	3	-13	-30	104
	4	2	-13	-30	104
	5	3	-13	-30	104
	6	3	-13	-30	104
	7	3	-13	-30	104
	8	3	-13	-30	104
	9	3	-13	-30	104
	10	3	-13	-30	104
Result	**Min**	**2**	**-13**	**-30**	**104**
	Max	**3**	**-13**	**-30**	**104**
	Range	**1**	**0**	**0**	**0**

Effects of Cover Material and Testing Conditions

Because MIT Scan-2 operates on an electromagnetic field, the presence or absence of nonconducting material does not affect the results. This characteristic of MIT Scan-2 has several important practical implications, including the following:

- Validation testing can be conducted in open air, which greatly facilitates the ability to verify MIT Scan-2 results with manual measurements.
- The presence of water on the pavement surface does not affect the results. Therefore, testing can be conducted in the rain, if needed.
- The changing moisture content in concrete, as the concrete cures, will not affect the test results. Testing can be conducted on concrete at any age, including concrete during its plastic stage.

Several tests were conducted to verify that MIT Scan-2 test results are unaffected by the cover material and the presence of water. The dowel slots in the test slab were filled with aggregate and/or water for this test, shown in progress in Figure 9. The results are summarized in Table 2 for the test using the aggregate cover and in Table 3 for the presence of water. The results are within the repeatability error of MIT Scan-2.

Further evidence that the cover material does not affect MIT Scan-2 results is provided in the results of a field test conducted by the Ontario Ministry of Transportation, in which pavement joints were exposed after scanning to verify MIT Scan-2 results (Figure 10). The results from this test are summarized in Table 4.

Figure 9. Dowel covered with aggregate for the evaluation of the effects of cover material.

Table 2. Effects of Cover Material on MIT Scan-2 Results

	Misalignment, mm			
Cover	**Horizontal**	**Vertical**	**Side shift, mm**	**Depth, mm**
None	8	-15	-10	158
Aggregate	6	-15	-10	158
Difference	**-2**	**0**	**0**	**0**

Table 3. Effects of Water on MIT Scan-2 Results

		Misalignment, mm			
Trial	**Wet/Dry**	**Horizontal**	**Vertical**	**Side Shift, mm**	**Depth, mm**
1	Dry	1	-9	9	115
	Wet	0	-9	11	116
	Difference	**-1**	**0**	**2**	**1**
2	Dry	1	-1	-20	126
	Wet	1	-1	-19	126
	Difference	**0**	**0**	**1**	**0**
3	Dry	7	-12	-10	129
	Wet	7	-12	-11	129
	Difference	**0**	**0**	**-1**	**0**

Figure 10. Exposed dowel bars for validation of MIT Scan-2 results.

Table 4. Comparison of MIT Scan-2 Results and Manual Measurements From Exposed Joints

Joint	Bar No.	Depth, mm			Horizontal misalignment, mm			Vertical misalignment, mm			Side Shift, mm		
		MIT	M*	D*	MIT	M	D	MIT	M	D	MIT	M	D
1	1	133	128	**5**	-7	-2	**-5**	-11	-11	**0**	-4	4	**-8**
	2	129	125	**4**	-9	-7	**-2**	1	-1	**2**	12	24	**-12**
	3	132	128	**4**	-10	-10	**0**	7	6	**1**	10	21	**-11**
	4	136	134	**2**	-31	-30	**-1**	10	7	**3**	36	42	**-6**
	5	141	133	**8**	-37	-30	**-7**	-11	-14	**3**	1	9	**-8**
	6	139	136	**3**	-70	-26	**-44**	34	33	**1**	26	29	**-3**
	7	145	143	**2**	-27	-22	**-5**	3	1	**2**	18	29	**-11**
	8	142	139	**3**	-39	-34	**-5**	7	5	**2**	40	46	**-6**
	9	138	132	**6**	-8	-5	**-3**	-6	-8	**2**	16	23	**-7**
	10	144	140	**4**	6	6	**0**	6	6	**0**	10	17	**-7**
2	1	117	111	**6**	3	0	**3**	-1	-2	**1**	9	13	**-4**
	2	116	113	**3**	6	5	**1**	6	8	**-2**	3	7	**-4**
	3	117	111	**6**	7	10	**-3**	2	1	**1**	6	7	**-1**
	4	115	111	**4**	0	0	**0**	-2	-2	**0**	9	5	**4**
	5	119	113	**6**	-5	-7	**2**	-4	-5	**1**	-2	-5	**3**
	6	114	112	**2**	-5	-5	**0**	1	0	**1**	18	18	**0**
	7	117	113	**4**	2	5	**-3**	4	3	**1**	-8	-8	**0**
	8	119	116	**3**	4	6	**-2**	6	4	**2**	34	32	**2**
	9	119	113	**6**	2	-1	**3**	1	-1	**2**	1	-5	**6**
	10	119	112	**7**	1	1	**0**	8	2	**6**	3	-10	**13**

*M = manual measurement; D = difference

The relatively large error in the depth results may be attributable to the effects of variations in the composition of the dowel bar metal. The variation in dowel length also affects the depth results, but dowel bar lengths typically do not deviate by more than 6 mm (0.2 in.) from the nominal length, and the resulting error from this source is less than 1 mm (0.04 in.). According to MIT GmbH, variations in metal composition can cause more significant errors. The key factor is the carbon content, which may not be controlled in low-cost steel and may vary from steel mill to steel mill. The error in absolute depth has a negligible effect on the alignment results, because the alignment results depend mainly on the ratio of the signal amplitudes, not the absolute signal strength. Hardware and software enhancements included in the MIT Scan-2 compensate automatically for the effects of variations in metal composition.

Operating Range and Accuracy

A comprehensive series of tests were conducted to verify the accuracy of MIT Scan-2 results. Several factors are known to affect the accuracy of MIT Scan-2 results, including the bar depth, magnitude of position error (side shift), and amount of misalignment. The effects of these factors on MIT Scan-2 results were evaluated systematically to verify the accuracy of MIT Scan-2 and to determine the operating range of MIT Scan-2. Within the operating range, the device is expected to provide the specified level of accuracy. The measurement errors were determined by comparing MIT Scan-2 results to manual measurements.

The range of values of the test parameters for the testing program was selected in consideration of both the MIT Scan-2 specifications and the application requirements. According to manufacturer specifications, the device provides the specified accuracy under the following conditions:

- Dowel bar depth 150 ± 40 mm (4.3 to 7.5 in.)
- Horizontal and vertical misalignment less than ±40 mm (1.6 in.)
- Lateral shift (side shift) less than ±80 mm (±3.2 in.)

When the above conditions are satisfied, the manufacturer-specified accuracy is within 4 mm (0.16 in.) on rotation and bar depth.

The ranges of values of the key parameters specified for MIT Scan-2 are adequate to cover most situations for highway applications, except for the following:

- The upper limit of 190 mm (7.5 in.) for depth may not be sufficient for testing on projects where the dowel bars are placed too deep. While most specifications require the bars to be placed within 25 mm (1 in.) of mid-depth, it may be permissible to allow a deeper placement, as long as adequate concrete cover is provided. If a minimum cover of 76 mm (3 in.) were accepted, the dowel bars can be placed as deep as 235 mm (9.25 in.) in 330-mm (13-in.) pavements.
- The horizontal misalignment range of ±40 mm (±1.6 in.) is not sufficient for testing skewed joints. Skewed joints need to be tested with the rail set parallel to the joint saw cut, which leaves the dowel bars at an angle with respect to the rail. The results thus obtained will show a uniform apparent horizontal misalignment corresponding to the skew angle in addition to the actual horizontal misalignment. The apparent horizontal misalignment corresponding to the typical joint skew angle (1 in 6) is 76 mm (3 in.) for 450-mm (18-in.) dowel bars. MIT Scan-2 must be able to accommodate this additional amount of apparent horizontal misalignment to enable testing on skewed joints.

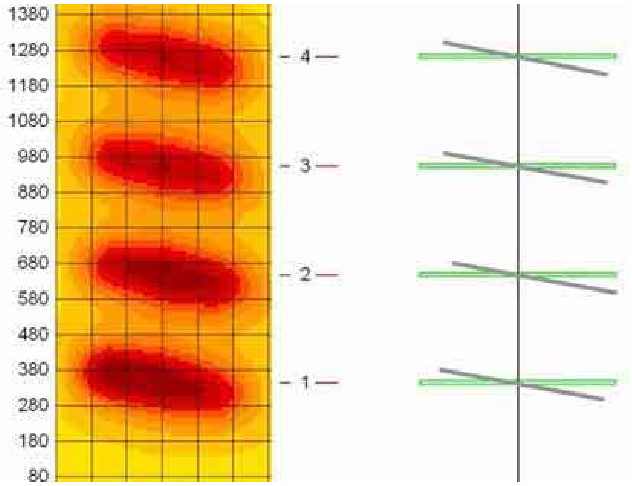


Figure 11. Apparent horizontal misalignment due to joint skew.

During the course of this study, MIT GmbH made software enhancements to allow testing on skewed joints. To verify that the results for skewed joints are accurate to the same degree as the results for square joints, the evaluation range for horizontal misalignment was extended to ±120 mm (4.7 in.).

The limits on the range of depths, however, are physical limitations (relating to the signal to noise ratio), which cannot be overcome without a hardware modification. The sensitivity of measurement errors to depth is shown in Figure 12 (supplied by MIT GmbH). The error is less than 4 mm (0.2 in.) for depths up to about 200 mm (7.9 in.). At depths above 200 mm (7.9 in.), the measurement error increases rapidly. This is only a limitation for the devices that were optimized for highway applications, where the typical bar depths range from about 100 to 165 mm (4 to 6.5 in.). For testing thicker pavements, the signal strengths can be increased to shift the zone of accurate results upward. In fact, the signal strength of the devices shipped to the United States was reduced by half from the original design to accommodate testing that included dowel baskets. Excessively high signal strength causes the response signal to saturate the sensors, making it impossible to obtain any information about the dowel position.

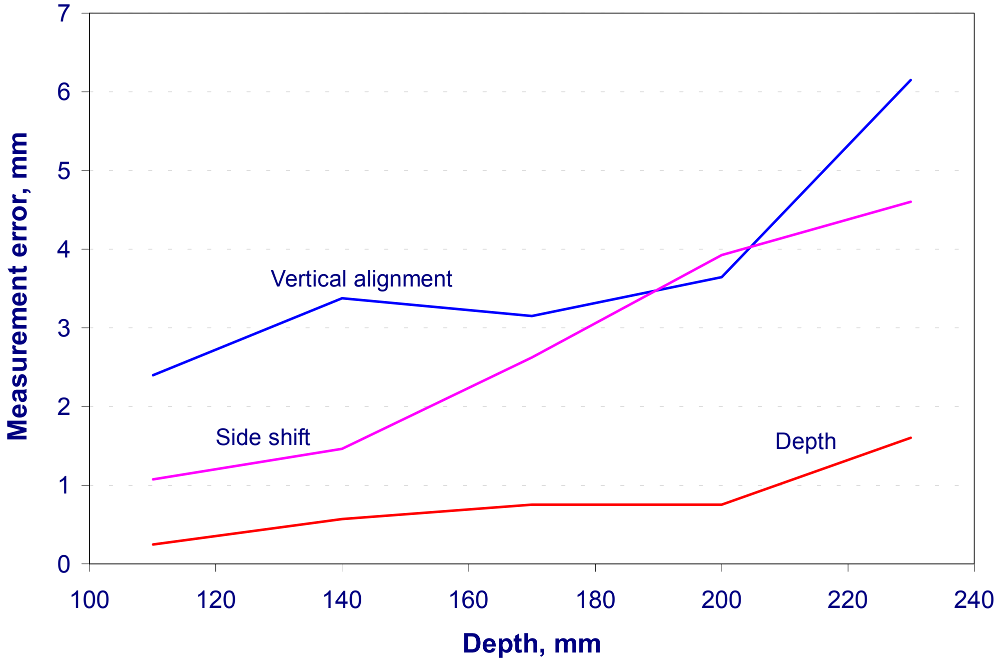


Figure 12. Sensitivity of measurement to bar depth for 32-mm (1.25-in.) dowel bar (MIT GmbH).

The accuracy of MIT Scan-2 and effects of various factors affecting the results were evaluated primarily based on tests on a single dowel bar. The only exception is the limited testing conducted to verify the minimum allowable bar spacing. MIT specifies a minimum bar spacing of 250 mm (9.8 in.). Limited testing conducted using multiple dowel bars has shown that a bar placed within 200 mm (7.9 in.) of the testing sample does increase the measurement error, but a bar placed 255 mm (10 in.) or farther away has no effect on the test results. The key parameter is the *d/z* (bar spacing over depth) ratio. The error increases with increasing depth. At shallower depths, a closer bar spacing can be accommodated. In typical highway applications, the 250-mm (9.8-in.) limit on bar spacing does not pose a problem.

The nominal ranges of the test parameters evaluated in the laboratory testing are as follows:

- Depth is 100 to 200 mm (4 to 8 in.)
- Side shift is -100 to +100 mm (-4 to +8 in.)
- Horizontal misalignment is -120 to +120 mm (-4.7 to +4.7 in.)
- Vertical misalignment is -40 to +40 mm (-1.6 to +1.6 in.)

Evaluation Results

The evaluation results are shown in Figures 13 through 22. The following can be observed from the test results:

- Within the limits of the ranges of test parameters (depth, side shift, horizontal misalignment, and vertical misalignment), the errors on horizontal and vertical misalignment results are within the MIT-specified limits of ±4 mm (±0.16 in). The only exception is that the error on vertical misalignment for the bar placed at 200-mm (7.9-in.) depth exceeds the specified limit. The errors that exceed -4 mm (-0.16 in.) in Figures 14, 16, and 18 are for the bar depth of 200 mm (7.9 in.).
- The measurement error on both horizontal and vertical misalignment is independent of all other parameters (i.e., side shift, depth, horizontal misalignment, and vertical misalignment), except that the error on vertical misalignment is higher for depth greater than 200 mm (7.9 in.). Figures 13 through 20 do not show any trend in the measurement error in either horizontal or vertical misalignment as a function of side shift, depth, horizontal misalignment, or vertical misalignment.
- Figure 21 shows a bias in the depth results. As discussed earlier, the greater error on depth results may be due to the differences in metal composition between the calibration bar and the test sample. The average error in depth measurement is -4.3 mm (-0.17 in.). The standard deviation of the depth error is 1.4 mm (0.06 in.). The depth results may be shifted due to variations in metal composition.
- Figure 22 shows a bias in the side shift results. The average error in side shift measurement is -4.4 mm (-0.17 in.). The standard deviation of the side shift error is 4.1 mm (0.16 in.). Side shift is difficult to measure precisely by hand without the aid of instrumentation such as those built into the MIT test track (Figure 6). The results of the tests conducted at the MIT test track do not show any bias in side shift measurements, and the results are within the specified range.

The laboratory testing results confirm that MIT Scan-2 provides accuracy that is both reasonable and useful for horizontal and vertical misalignments within the following limits:

- Depth 100 to 190 mm (3.9 to 7.5 in.)
- Side shift ±100 mm (±4 in.)
- Horizontal misalignment ±40 (±1.6 in.) plus a uniform rotation of ±80 mm (±3.1 in.)
- Vertical misalignment ±40 mm (±1.6 in.)

Note that the operating range for horizontal misalignment is a range of misalignment (±40 mm [±1.6 in.]) plus a uniform rotation. Although the laboratory evaluation covered the full range of horizontal misalignment (±120 mm [±4.7 in]), the tests were conducted using a single dowel bar. In an actual joint, extreme horizontal misalignments can cause the ends of neighboring bars to come very close to each other, which in turn can cause additional error due to overlapping response signal. On skewed joints, the magnitude of apparent horizontal misalignment is large, but a major portion of the registered horizontal misalignment is due to a uniform rotation caused by joint skew, which does not cause a problem for neighboring dowel bars. For the actual misalignment, the range originally specified for horizontal misalignment (±40 mm [±1.6 in.]) is more than adequate to cover all practical cases. If the actual horizontal misalignment exceeds ±40 mm (±1.6 in.), the exact quantitative results are not important; it is sufficient to know that the horizontal misalignment is large.

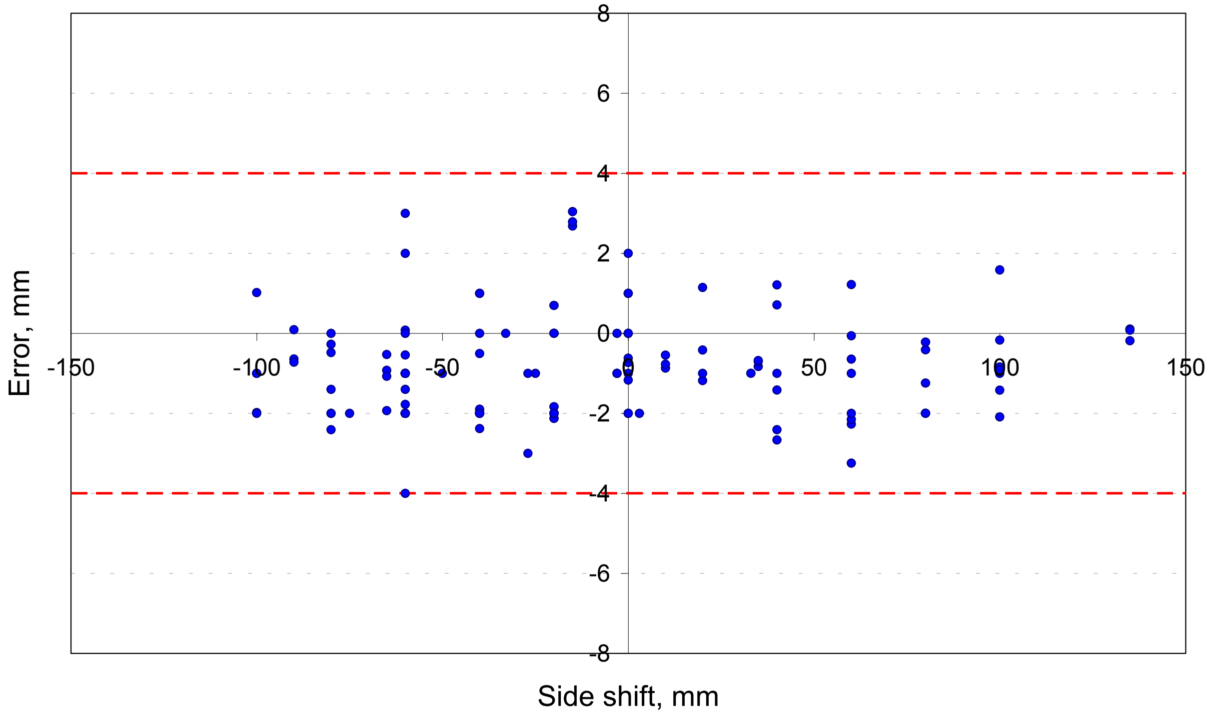


Figure 13. Measurement error on horizontal misalignment as a function of side shift.

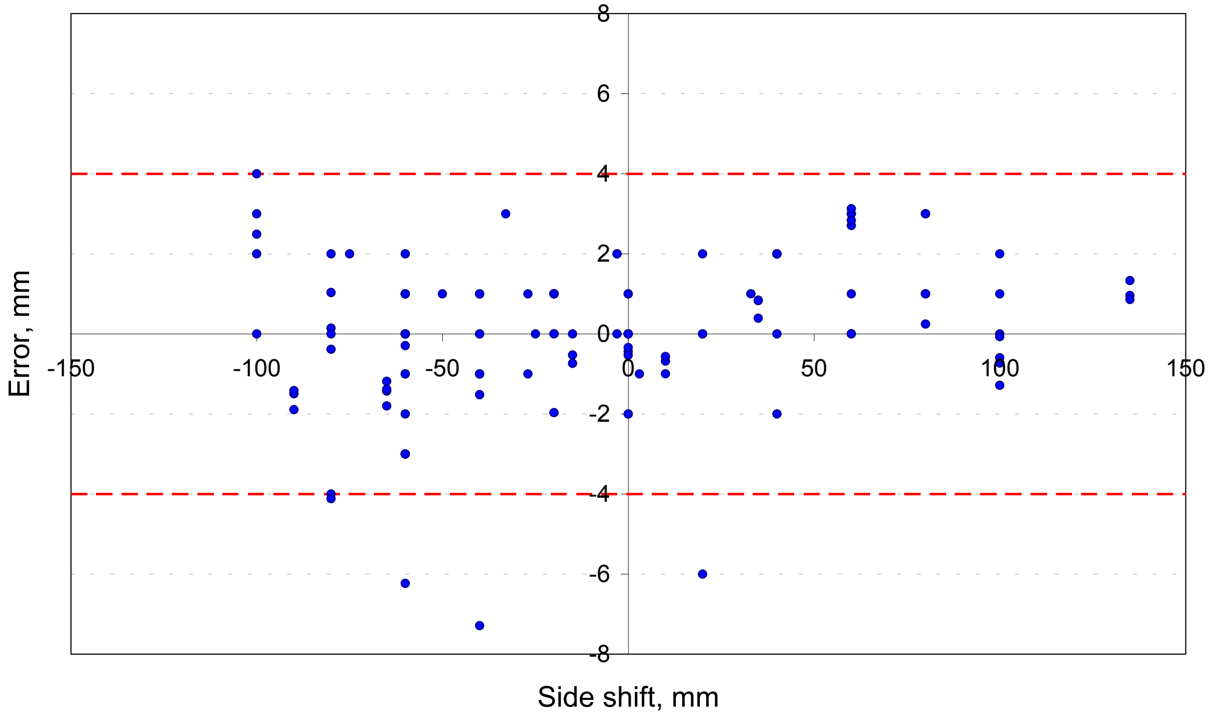


Figure 14. Measurement error on vertical misalignment as a function of side shift.

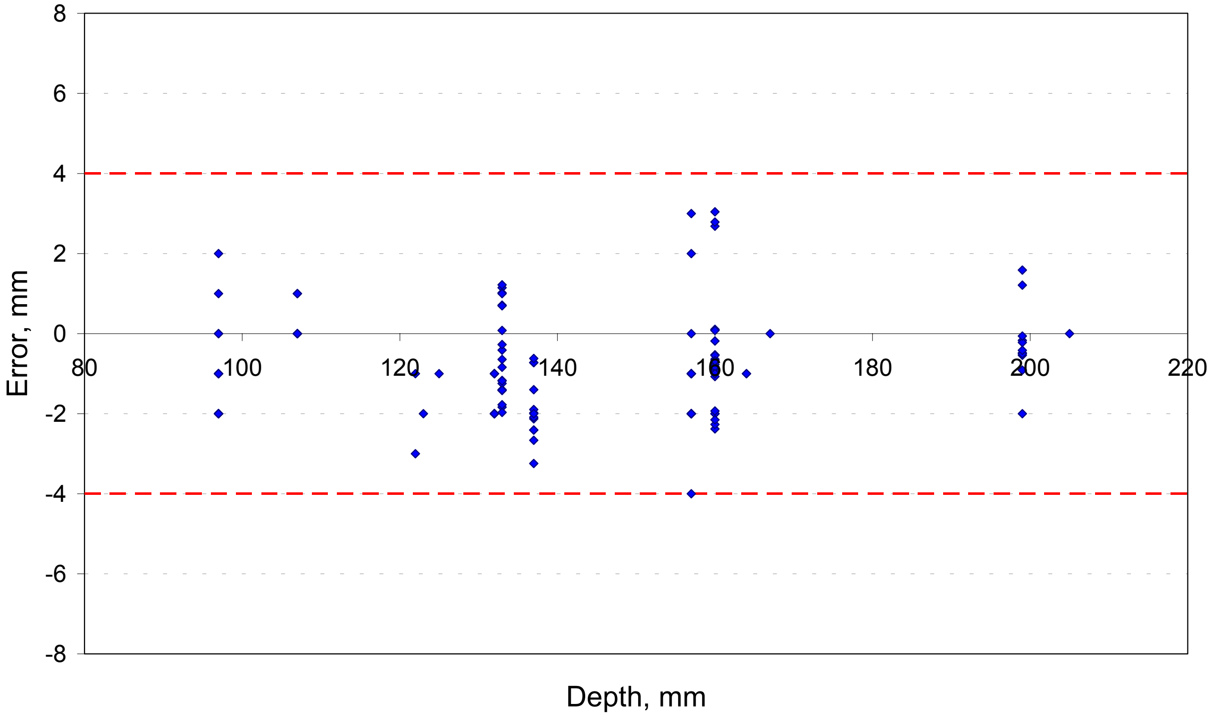


Figure 15. Measurement error on horizontal misalignment as a function of bar depth.

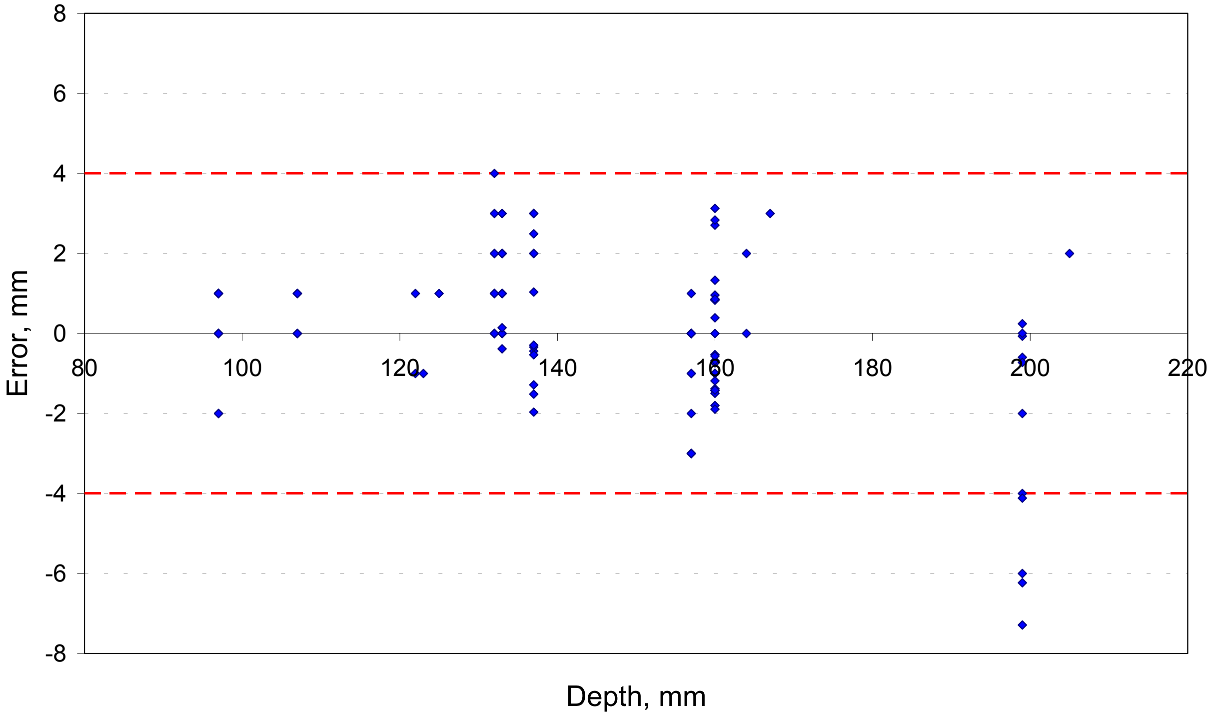


Figure 16. Measurement error on vertical misalignment as a function of bar depth.

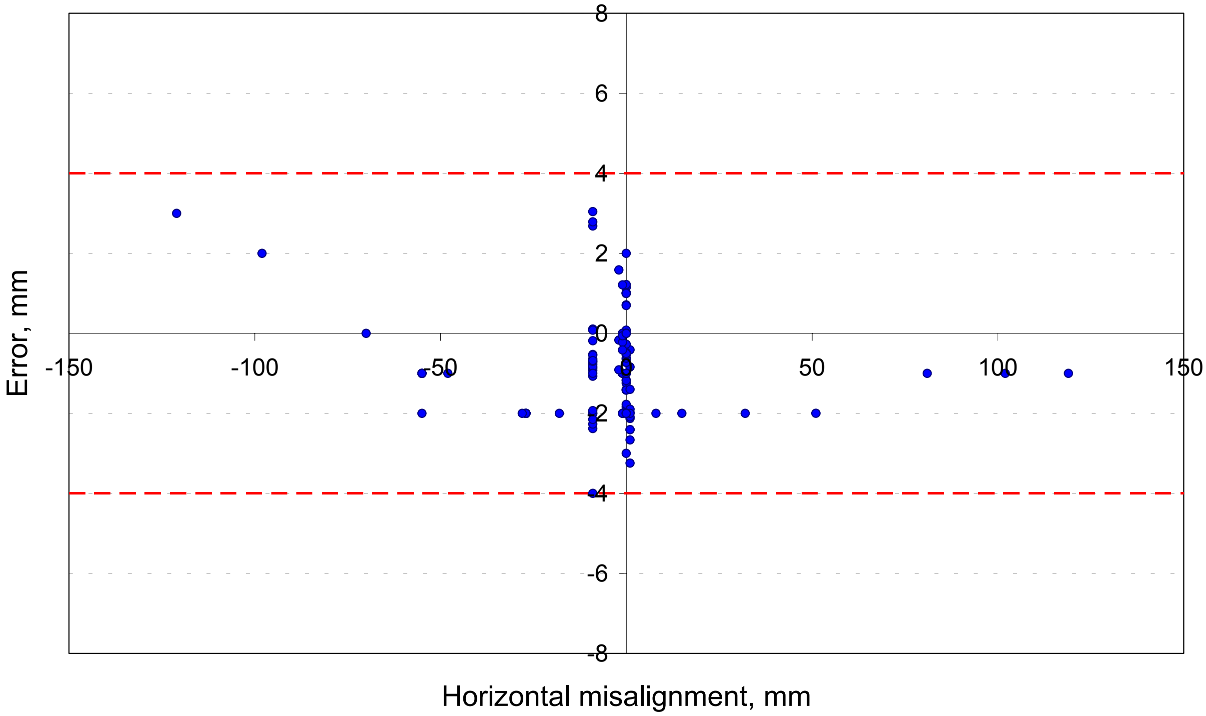


Figure 17. Measurement error on horizontal misalignment as a function of horizontal misalignment.

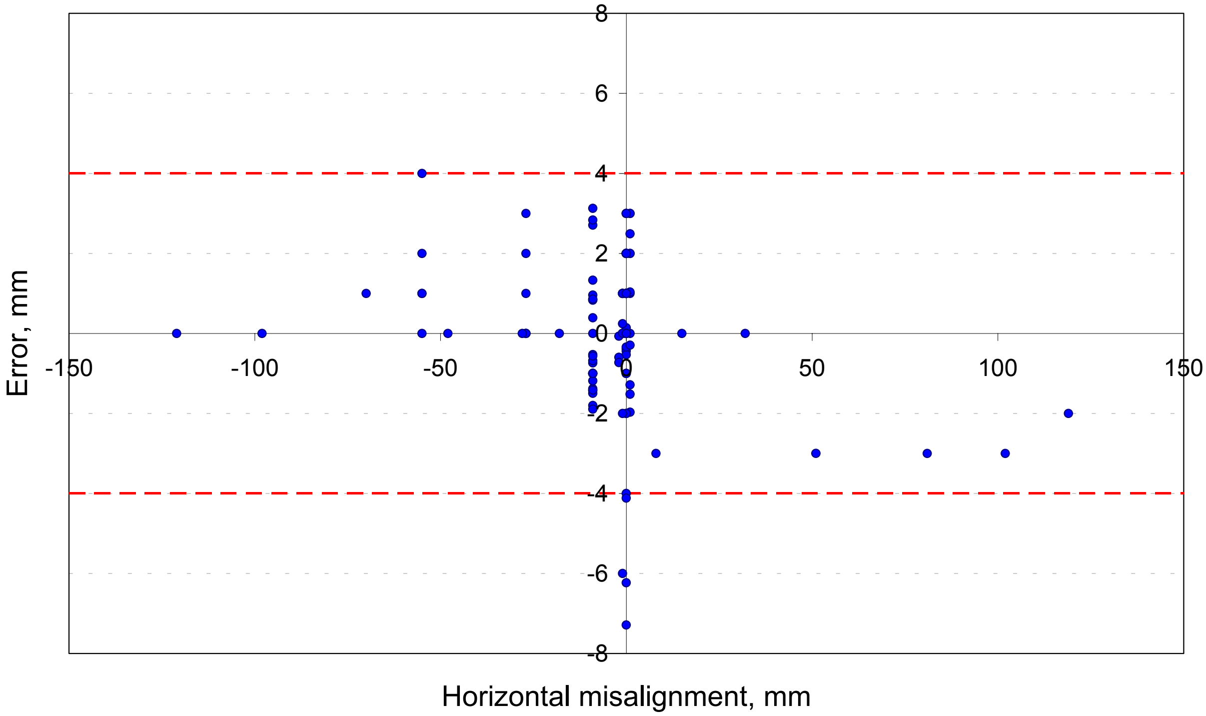


Figure 18. Measurement error on vertical misalignment as a function of horizontal misalignment.

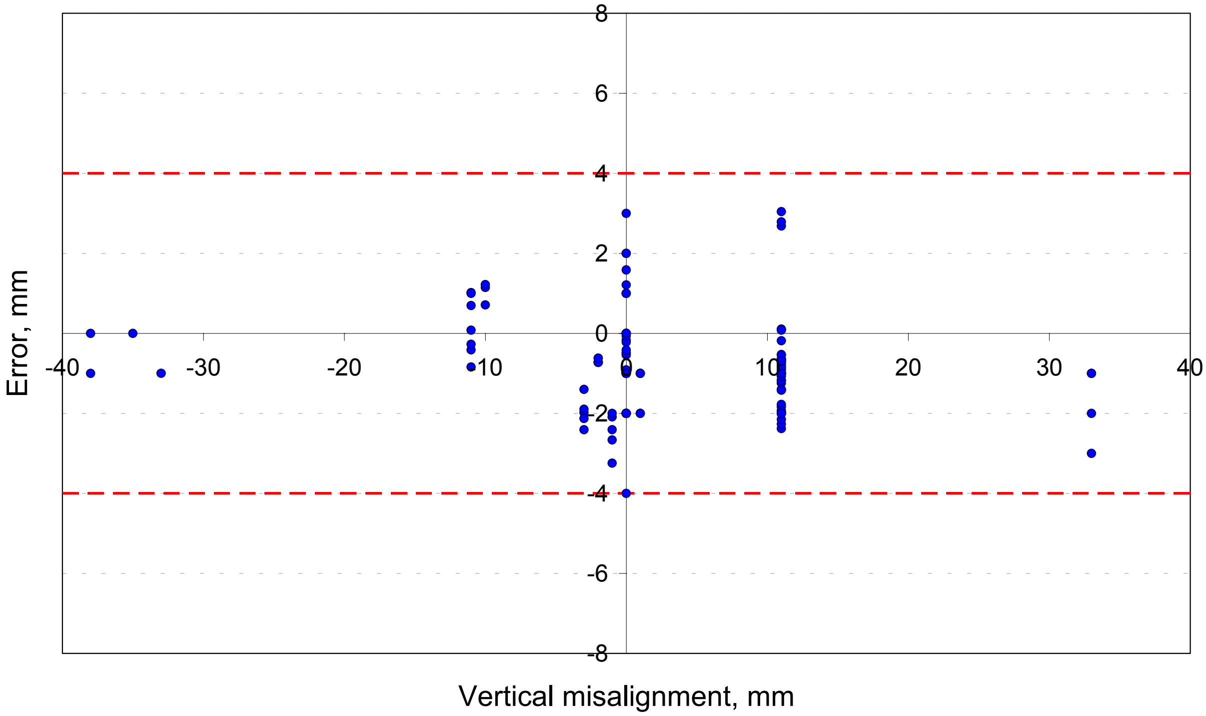


Figure 19. Measurement error on horizontal misalignment as a function of vertical misalignment.

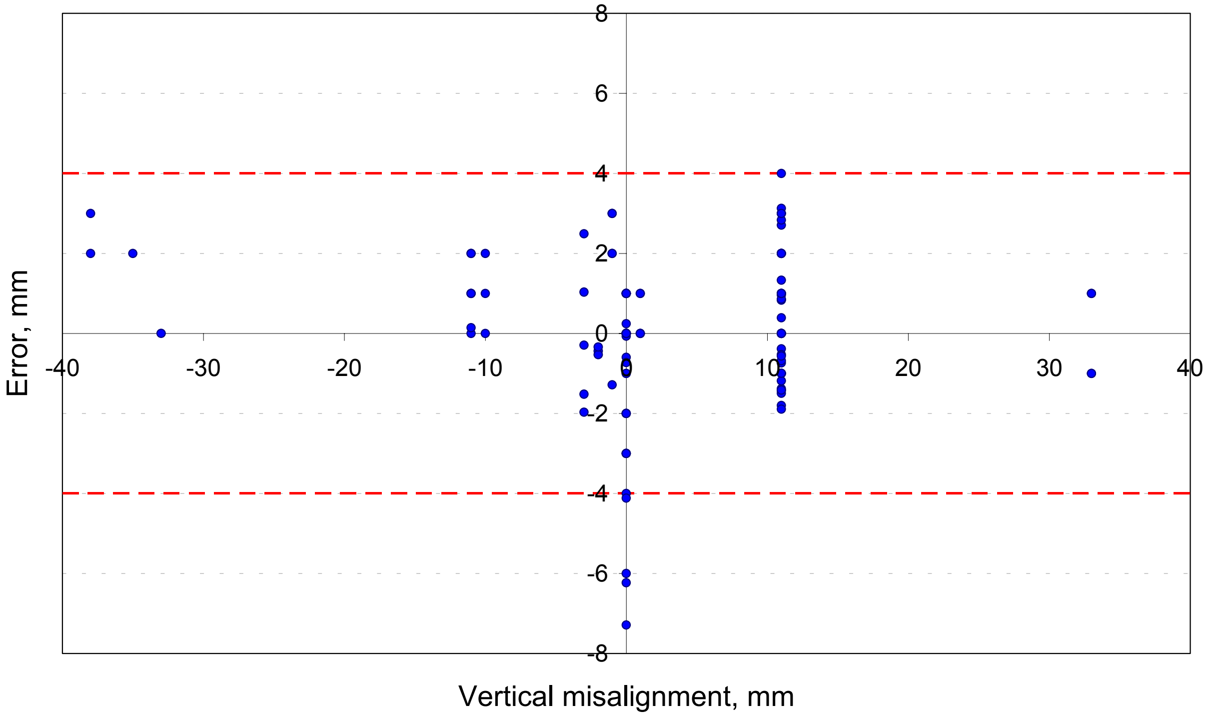


Figure 20. Measurement error on vertical misalignment as a function of vertical misalignment.

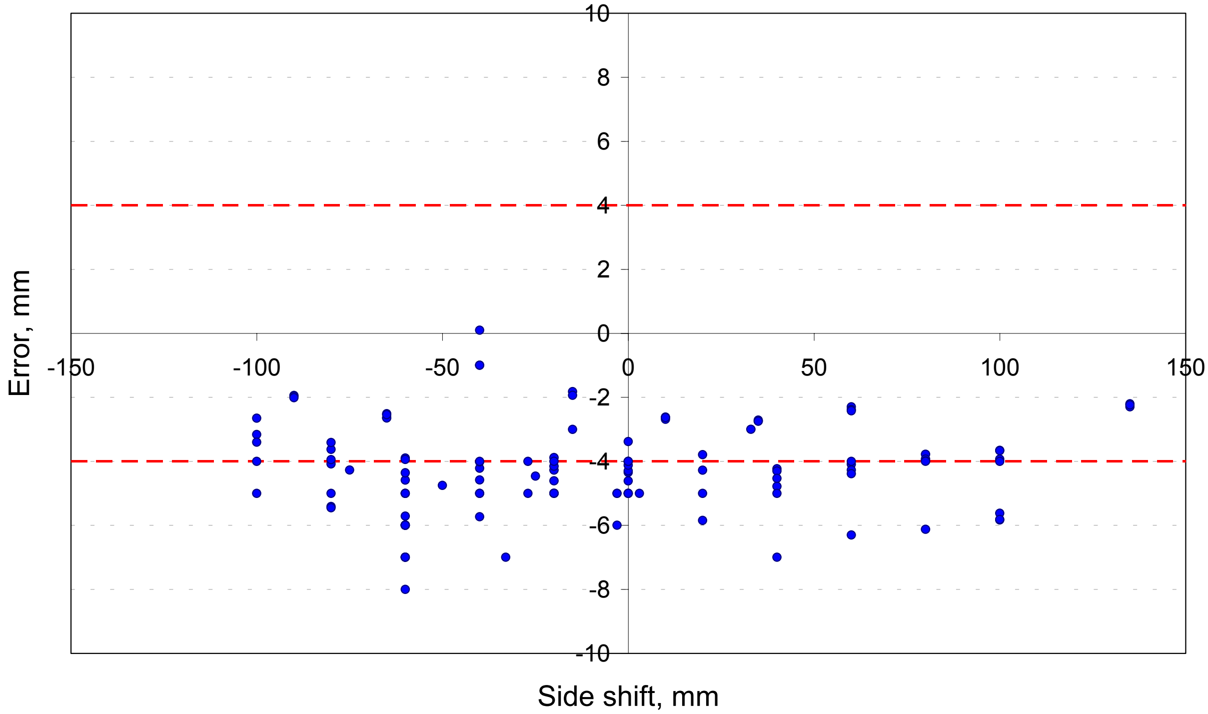


Figure 21. Measurement error on bar depth as a function of side shift.

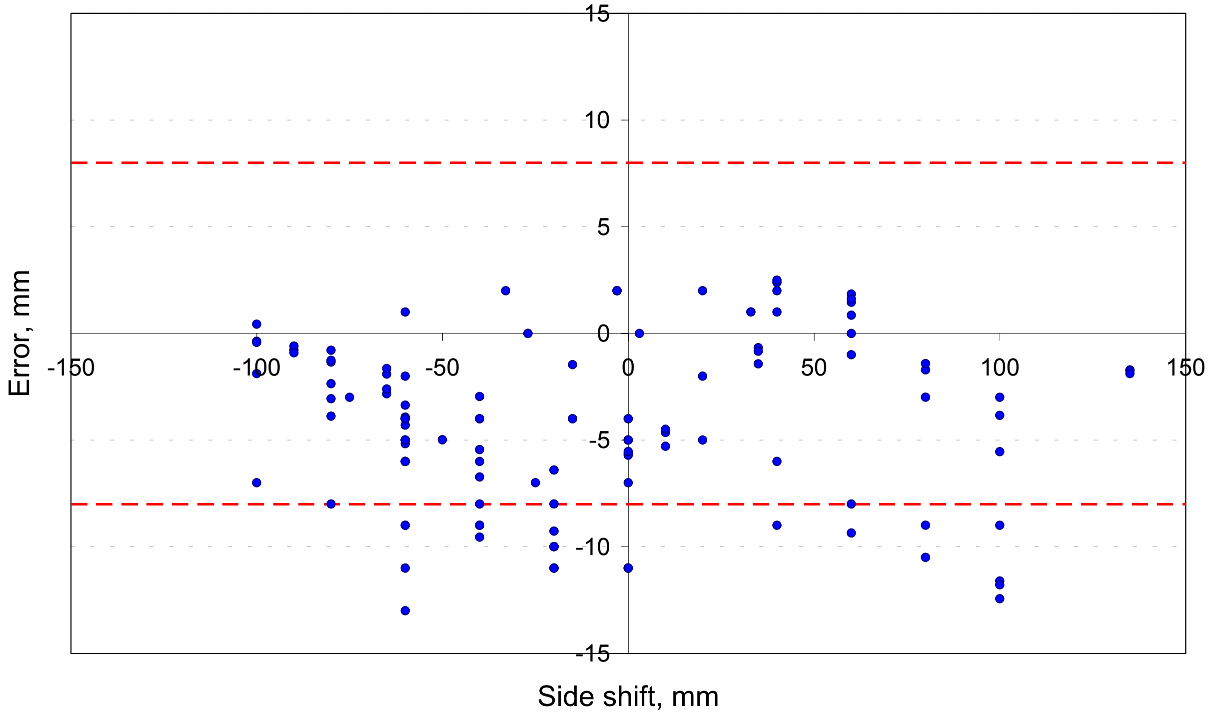


Figure 22. Measurement error on side shift as a function of side shift.

Accuracy of MIT Scan-2

The overall standard deviation and confidence interval for horizontal and vertical alignment results of MIT Scan-2 were determined based on laboratory testing results and consideration of other sources of error. The laboratory testing results confirmed that the repeatability error and device error are within the MIT-specified limits as follows:

- Repeatability error: 2 mm (0.08 in.) or ±1 mm (0.04 in.)
- Device error: ±4 mm (0.16 in.)

Other sources of error include the following:

- Rail flex—The plastic rail flexes under the weight of the sensor unit and may hinge at the joints. MIT estimates a maximum error of 2 mm (0.08 in.) from this source.
- Uneven surface or debris on the pavement surface—With careful observation, any large particles on the pavement surface can be detected and cleared from underneath the rails. However, additional random variation in vertical displacement of up to about 2 mm (0.08 in.) may still be possible due to fine particles on the surface or roughness due to tining.

The magnitudes of errors listed above are peak-to-peak values. The peak-to-peak values are conservatively assumed to represent 95-percentile values. The standard deviation of measurement error from each source was obtained by dividing the peak-to-peak error values by the standard normal variate corresponding to 95 percent probability (1.64). Assuming all sources of errors are independent, the overall variance was obtained by summing the component variance. The components of measurement error on rotation (horizontal and vertical alignment) are summarized in Table 5. The overall standard deviation of measurement error is 3.0. Since the uneven surface will have minimal effect on horizontal alignment, the overall standard deviation for horizontal misalignment may be somewhat less than that for vertical misalignment, but the difference is not significant (2.8 mm [0.1 in.], rather than 3.0 mm [0.12 in.]).

Table 5. Sources of Error and Overall Standard Deviation

Source of Error	Peak-to-Peak Error, mm	Standard Deviation, mm	Variance
Device error	4	2.4	5.91
Repeatability	1	0.6	0.37
Rail flex	2	1.2	1.48
Uneven surface	2	1.2	1.48
Overall variance			**9.24**
Overall standard deviation, mm		**3.0**	

Based on overall standard deviation of 3.0 mm (0.12 in.), MIT Scan-2 may be expected to provide measurement accuracy of ±5 mm (0.20 in.) with 95 percent reliability. However, it is important to note that any metal objects (tie bars, nails in the joint, coins, pieces of wire, or other metal) near the measurement region can introduce significant errors. The influence of the foreign metal objects cannot reasonably be incorporated in the overall standard deviation of measurement errors. The presence of significant metal objects (e.g., tie bars, nails, pieces of wire, or other significant mass of metal) essentially invalidates the results for the bars within the influence region of the metal objects. In most cases, the presence of foreign metal objects is easily detectable on the signal intensity plot. Whenever MIT Scan-2 results indicate a large dowel misalignment, close inspection of the signal intensity plot and the evaluation results is advisable to ensure that the results are real and not due to external influence.

The most problematic of the external influences is the presence of tie bars in close proximity of the joint being evaluated. Typically, but not always, the presence of tie bars is clearly visible on the signal intensity plot (Figure 23). Figure 24 shows a case in which the presence of tie bars is not easily discernible from the signal intensity plot. In this case, the only indication of external influence is the sudden jump in side shift results that are not consistent with the signal intensity plot, as indicated in Table 6. If tie bars occur at a consistent location (relative to the dowel bars), the effects of tie bars can be filtered out. But the tie bar locations are highly variable. The inability to obtain accurate results for dowel bars influenced by tie bars is a critical limitation of MIT Scan-2.

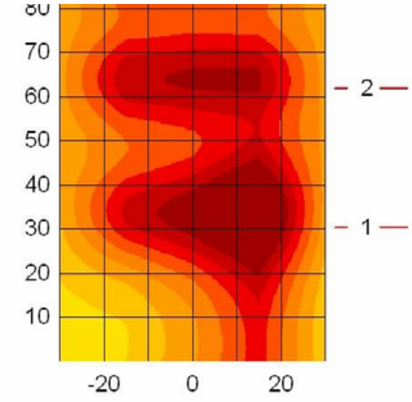
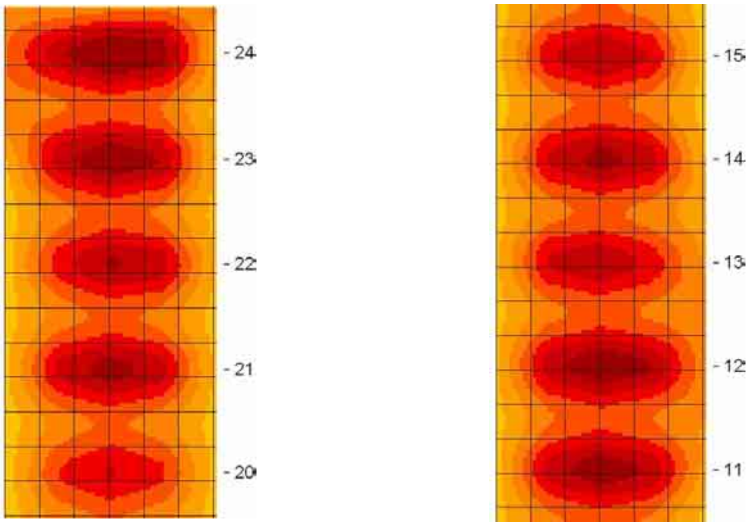


Figure 23. Presence of tie bar directly over the outer dowel bars.



(a)

(b)

Figure 24. Influence of the presence of foreign metal: (a) tie bar at the lane-shoulder joint affecting the results for bars 23 and 24; (b) tie bar at the longitudinal joint affecting the results for bars 11–13.

Table 6. Results for a Joint Influenced by the Presence of Tie Bars at the Centerline Joint and at the Shoulder Joint

		Misalignment, mm			
Bar No.	Location, cm	Horizontal	Vertical	Side Shift, mm	Depth, mm
1	9.9	12*	6	-33	136
2	39.2	3	-1	-18	149
3	69.0	4	-15*	-21	151
4	99.0	3	-5	4	146
5	129.0	1	-2	-23	145
6	159.0	4	-2	-19	143
7	188.9	3	-1	-18	143
8	218.7	2	0	-3	145
9	248.5	2	6	-19	148
10	278.6	-1	-5	-4	144
11	308.7	3	11*	32	144
12	338.9	3	20*	48	144
13	369.0	10	39*	54*	155
14	399.3	5	0	11	146
15	429.3	3	-1	3	150
16	459.3	1	-2	3	150
17	489.2	0	-6	2	145
18	519.6	0	4	6	150
19	549.9	0	-4	1	147
20	580.3	-1	1	10	157
21	610.1	3	-4	1	145
22	640.5	6	-12*	6	148
23	670.8	5	-11*	-8	143
24	701.6	-5	-51*	-66*	146

Note: Underline indicates side shift results that are not consistent with the signal intensity plot.
*Out-of-specification results relative to typical State DOT requirements.

Validation of the Laboratory Testing Results

The accuracy of MIT Scan-2 results, determined based on laboratory testing, were verified using the results of testing conducted at the MIT GmbH test track (Figure 6). The test track offers the means of taking very accurate measurements of the actual dowel bar positions under simulated field conditions. A factorial of tests was conducted covering the full operating range of MIT Scan-2 using seven dowel bars. In each case, six of the dowel bars were placed with similar side shift and minimal misalignment, and the position of one of the middle dowels was varied according to the factorial design of the testing program. This test simulates the conditions in real joints, in which most of the bars are in good alignment but one bar has a varying degree of misalignment. The results of this test will show the effects of any influence of neighboring dowel bars on measurement accuracy.

The results of the validation tests are shown in Figures 25 through 34. Similar to the laboratory testing results, this series of tests showed that, within the operating range, the magnitudes of measurement errors are independent of other selected parameters. For example, Figure 25 shows that the errors in horizontal misalignment results are not dependent on side shift. Similarly, Figure 27 shows that the errors in horizontal misalignment results are not dependent on depth. Figure 33 still shows a slight bias in the depth results, but not to the extent shown in Figure 21. Figure 34 shows that the side shift results are well within the specified range of accuracy, which suggests that the bias shown in Figure 22 for the laboratory testing may very well be due to errors in manual measurements.

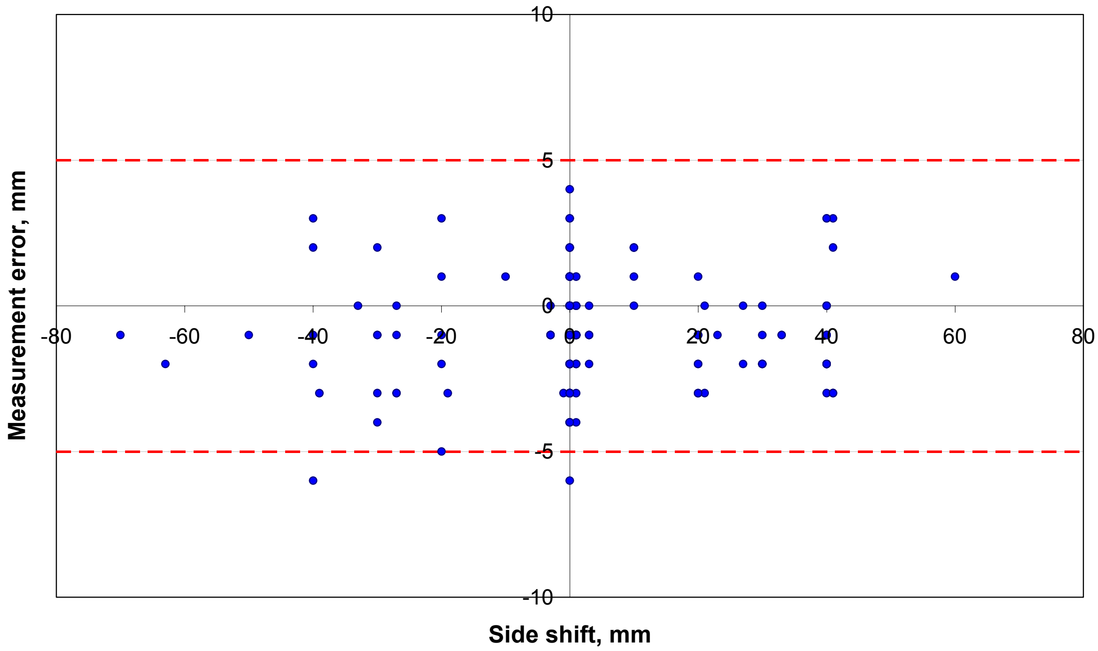


Figure 25. Measurement error on horizontal misalignment as a function of side shift (MIT test track).

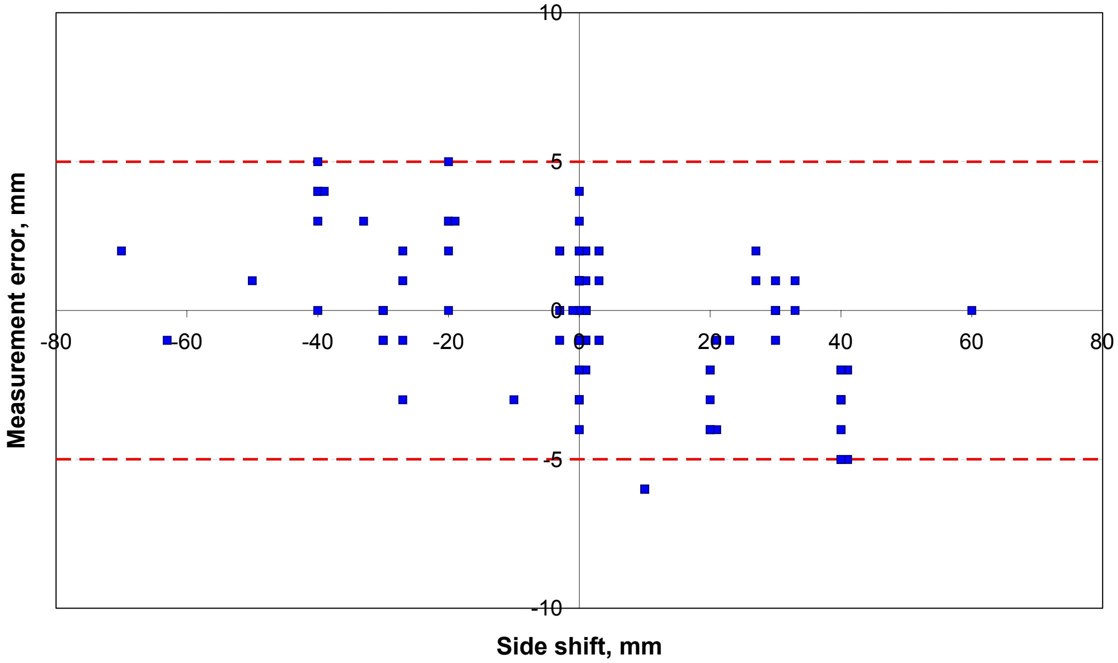


Figure 26. Measurement error on vertical misalignment as a function of side shift (MIT test track).

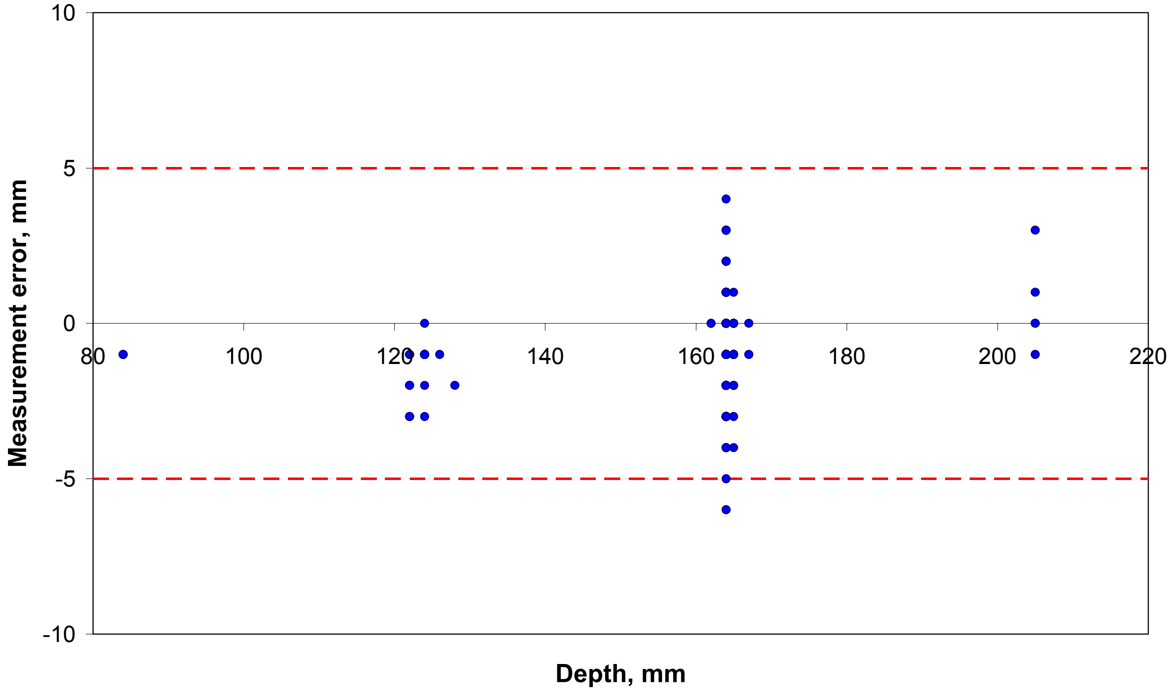


Figure 27. Measurement error on horizontal misalignment as a function of depth (MIT test track).

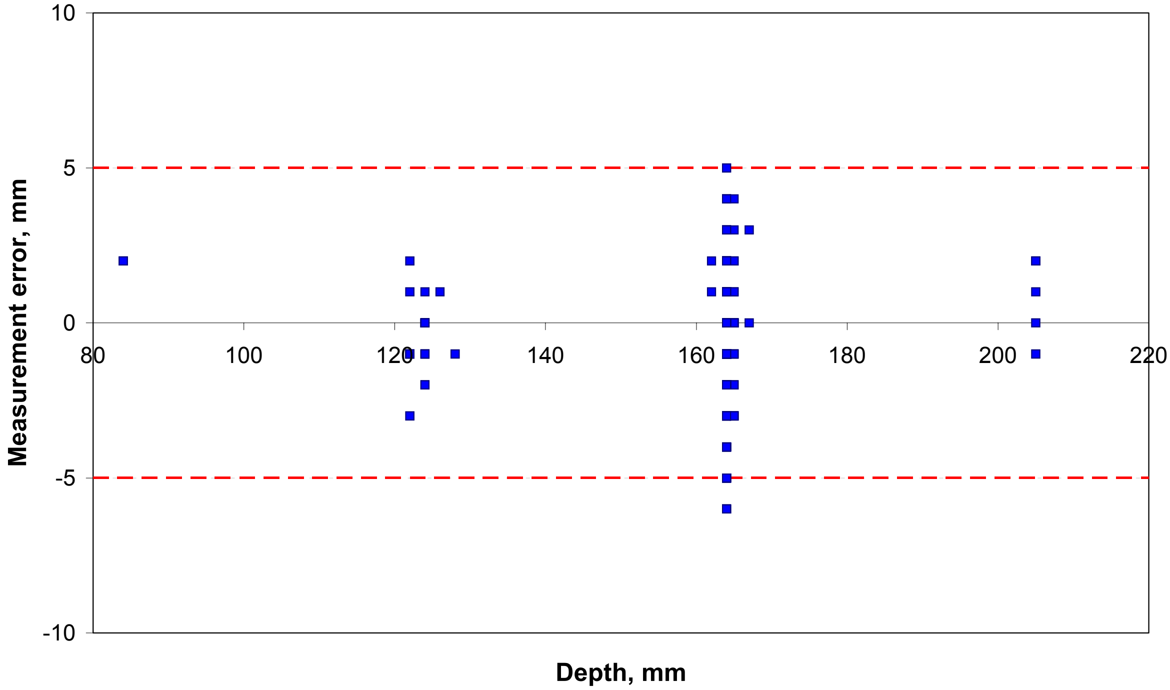


Figure 28. Measurement error on vertical misalignment as a function of depth (MIT test track).

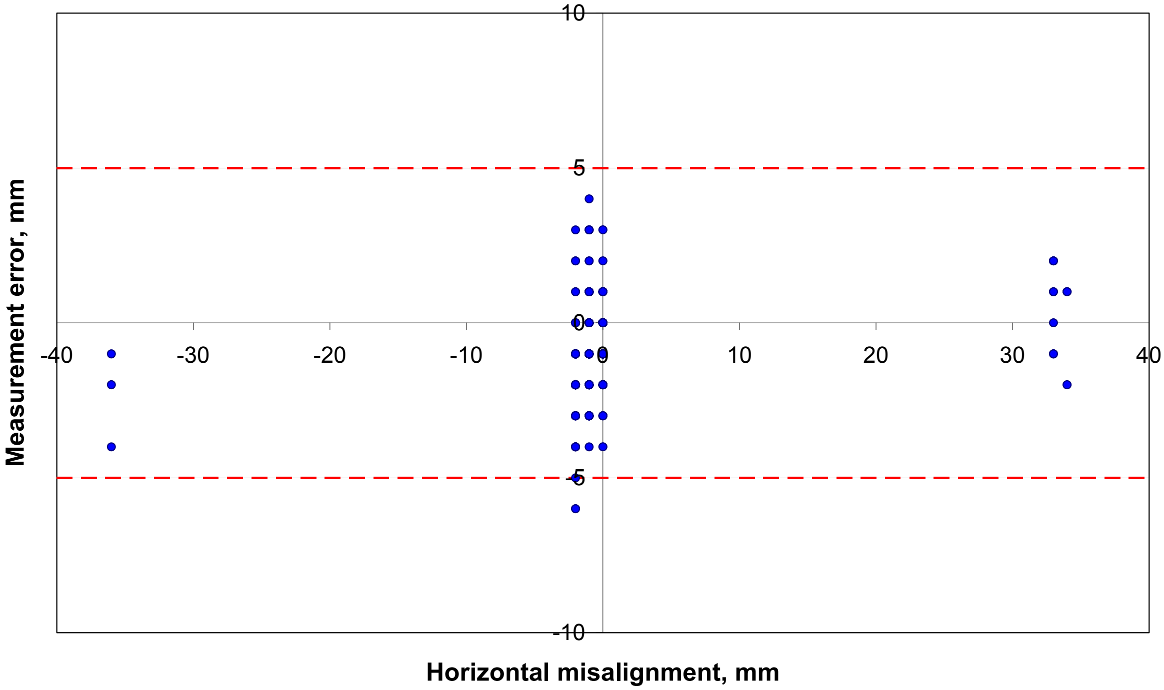


Figure 29. Measurement error on horizontal misalignment as a function of horizontal misalignment (MIT test track).

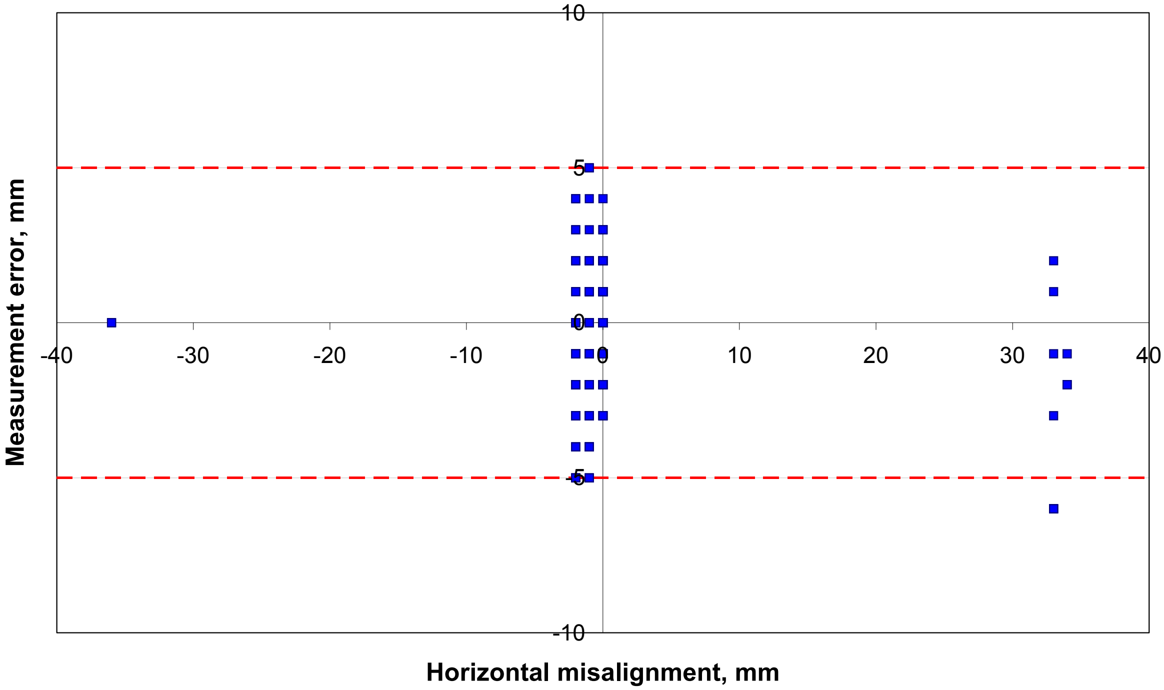


Figure 30. Measurement error on vertical misalignment as a function of horizontal misalignment (MIT test track).

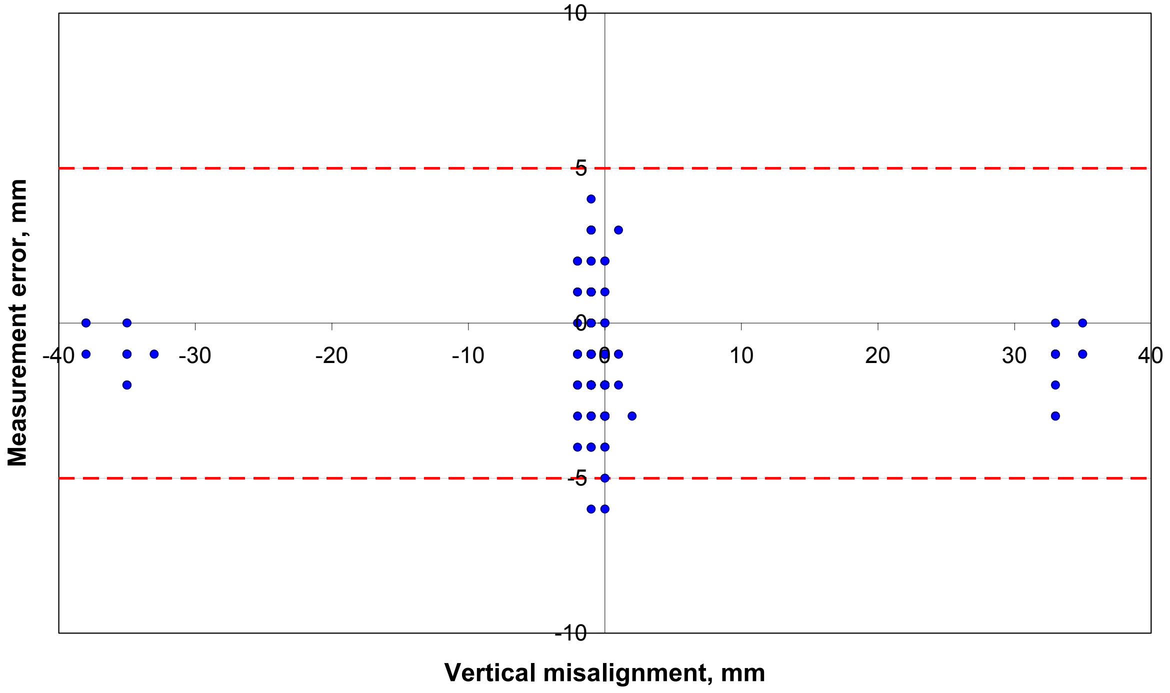


Figure 31. Measurement error on horizontal misalignment as a function of vertical misalignment (MIT test track).

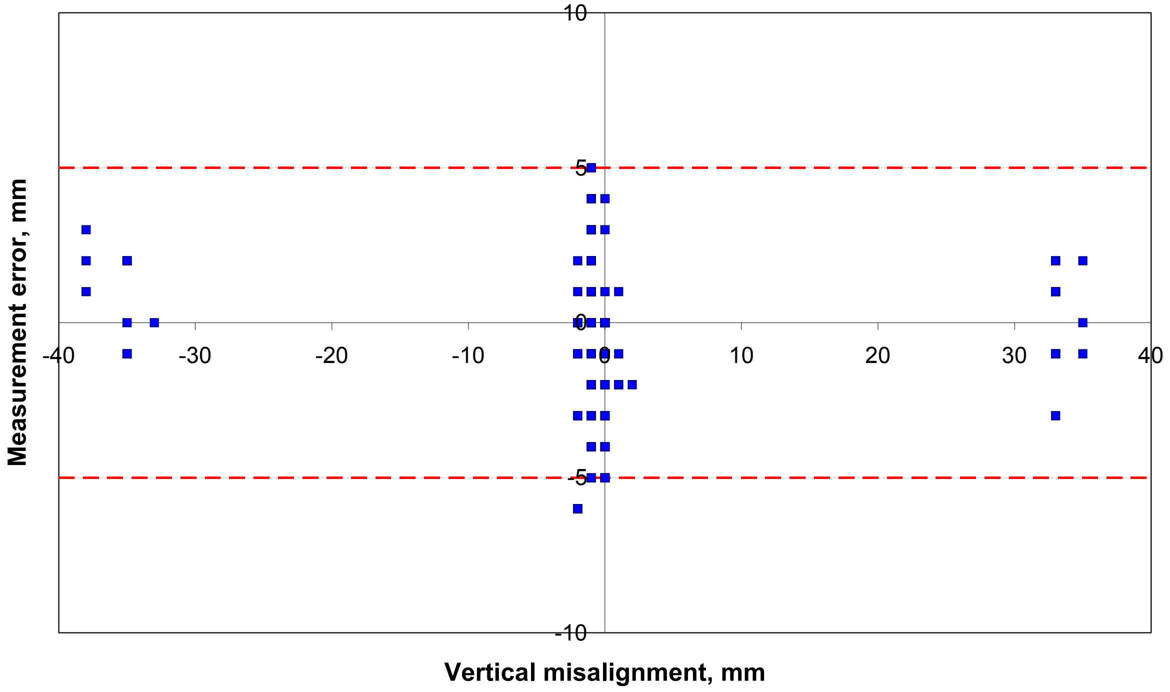


Figure 32. Measurement error on vertical misalignment as a function of vertical misalignment (MIT test track).

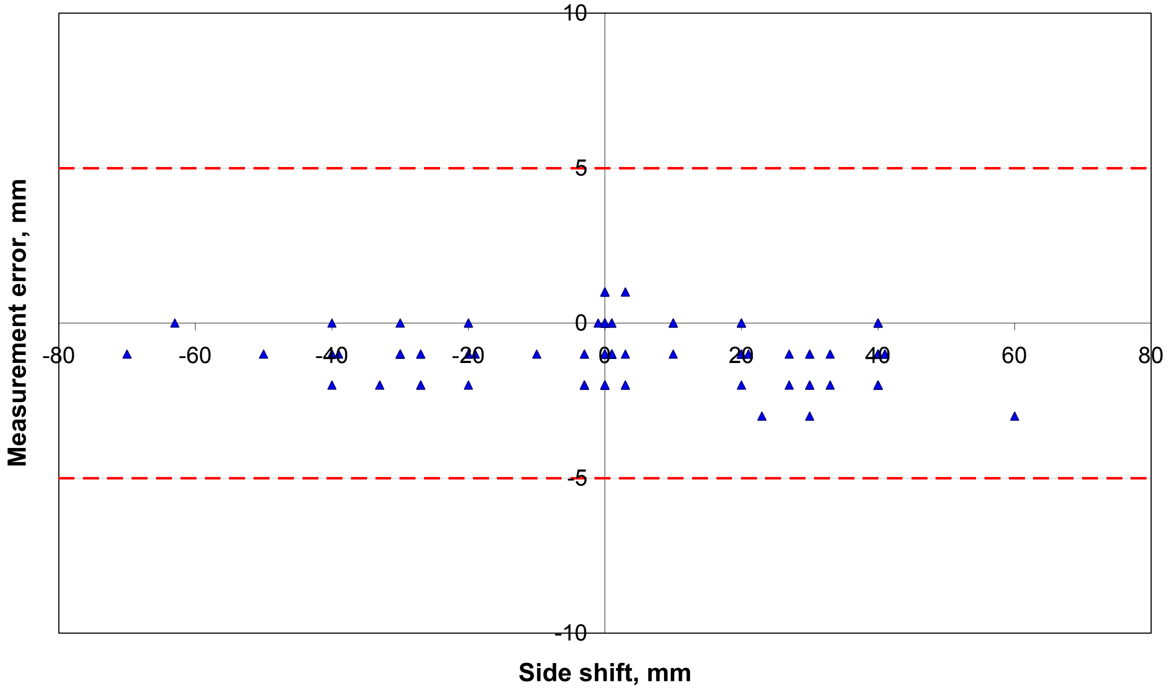


Figure 33. Measurement error on depth as a function of side shift (MIT test track).

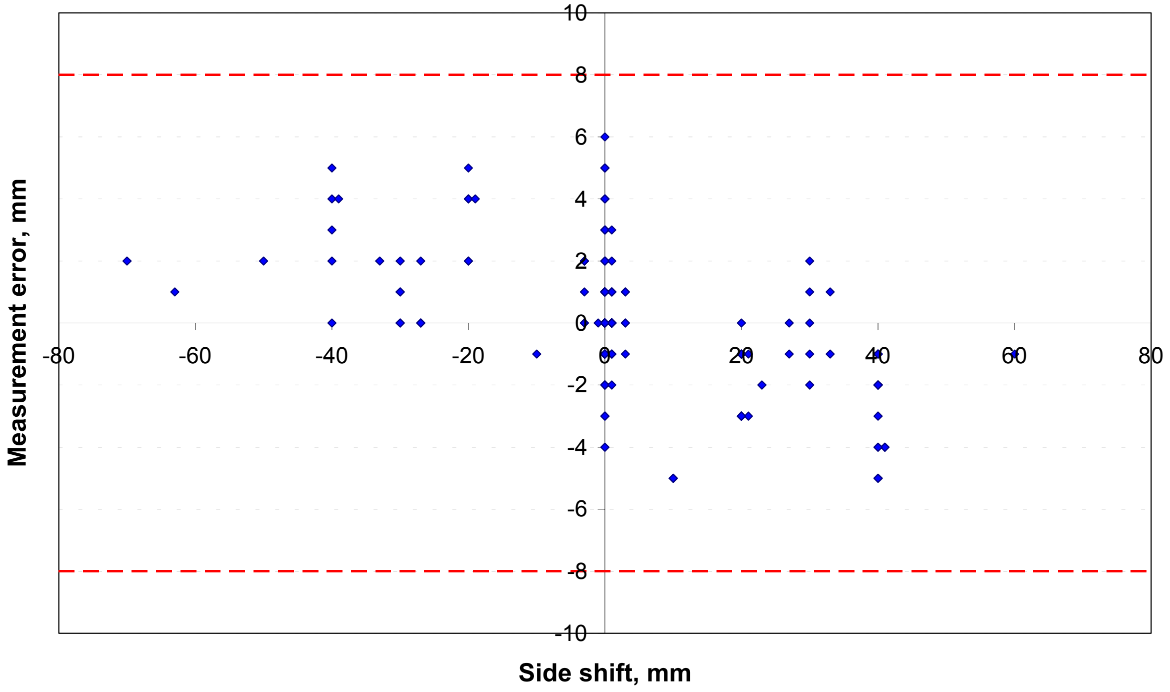


Figure 34. Measurement error on side shift as a function of side shift (MIT test track).

The validation test results confirmed the findings of the laboratory evaluation, that MIT Scan-2 provides accuracy of ±5 mm (±0.2 in.) with 95 percent reliability. The measurement errors exceeded ±5 mm (±0.2 in.) on a few occasions. However, the error in horizontal misalignment measurements exceeded ±5 mm (±0.2 in.) only 0.6 percent of the time, and the error in vertical misalignment measurements exceeded ±5 mm (±0.2 in.) only 1.2 percent of the time. As noted under laboratory testing, it is important to remember that the conclusions regarding the accuracy and reliability of MIT Scan-2 are valid only in the absence of any external influence (mainly, the presence of foreign metal, such as tie bars in close proximity).

Dowels Placed in Baskets

For dowel bars placed in baskets, the presence of the metal basket interferes with MIT Scan-2 results. However, if the transport ties in the basket are cut, good results can be obtained, even without any special considerations for the dowel basket. Without basket calibration, the results for dowel baskets are more sensitive to side shift. If the basket is well centered under the joint saw cut (e.g., side shift less than about ±38 mm [1.5 in.]), the horizontal and vertical misalignment results are very good. The reported depth is less (by about 6–7 percent), because the presence of the additional metal (basket) makes the bars appear closer to the surface. With specific calibration and basket software, a similar level of accuracy can be obtained for dowel baskets as for bare bars.

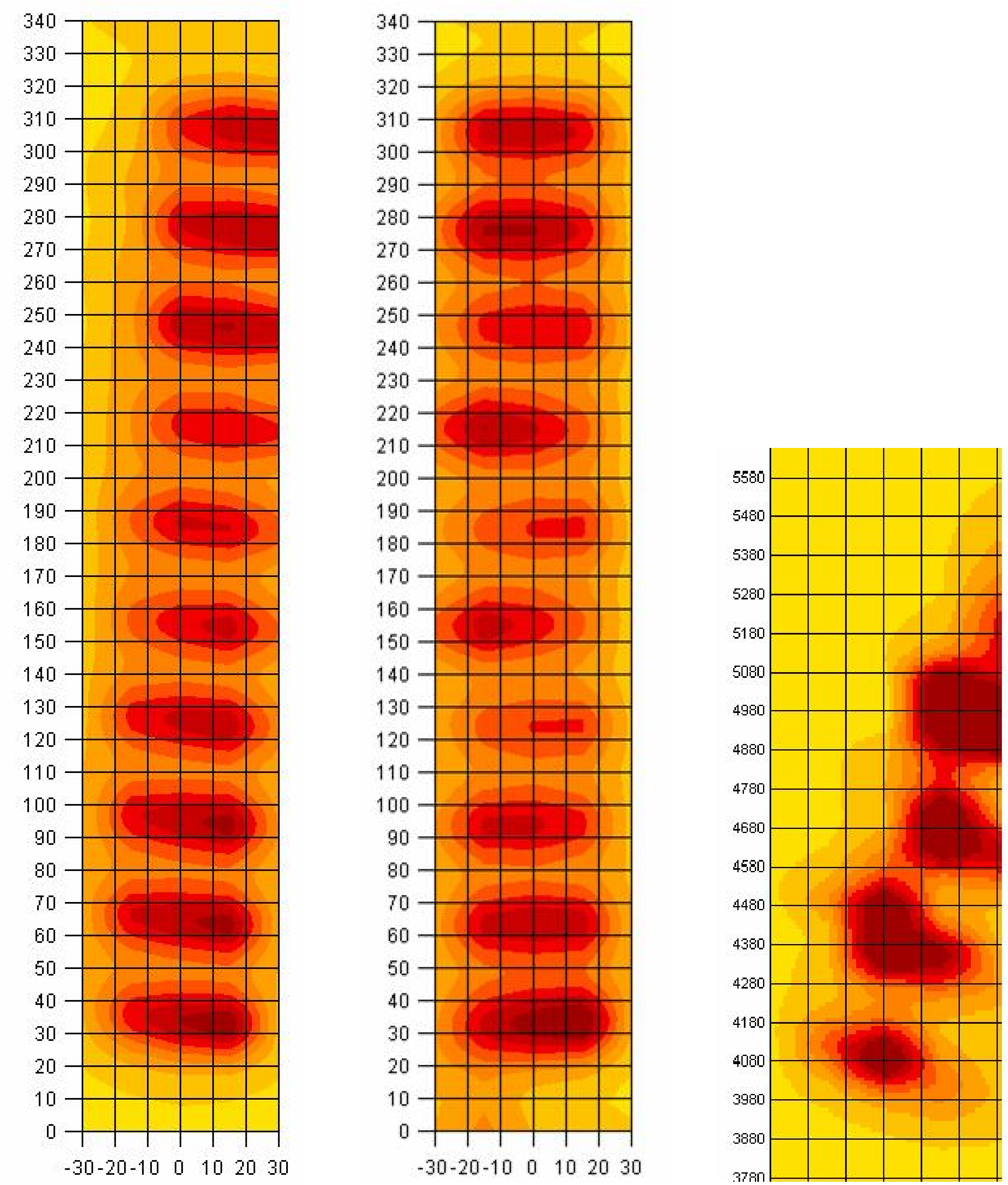
MIT GmbH is developing a special version of MagnoProof and MagnoNorm to handle dowel baskets. For accurate quantitative results, the basket software must be used with specific calibration for the type of basket scanned. Because dowel baskets are calibrated as a whole unit, the baskets for different size dowel bars must be calibrated separately.

Limited testing was conducted using the beta-test version of the basket software. The results for a test conducted in open air are summarized in Table 7. As shown in Table 7, when the basket is calibrated, a similar level of accuracy can be obtained for dowel baskets as for bare bars.

Table 7. Basket Evaluation Results

Horizontal alignment, mm			Vertical alignment, mm			Depth, mm		
Actual	MIT	Error	Actual	MIT	Error	Actual	MIT	Error
13	15	**2**	6	7	**1**	125	126	**1**
10	9	**-1**	0	3	**3**	115	115	**0**
8	9	**1**	-2	1	**3**	108	108	**0**
8	6	**-2**	1	2	**1**	98	101	**3**

For dowel baskets, the qualitative results from MIT Scan-2 (e.g., approximate numerical results and graphical output) can be as useful as the more precise numerical results obtained by having the correct basket calibration. In general, with proper inspection prior to paving, excellent dowel alignment can be achieved as long as the basket does not move during paving. The type and number of pins used to anchor the basket in place is the critical factor. If the basket is properly anchored, the dowel alignment will not change during paving. However, if the baskets are not adequately anchored, the basket can deform, burst open, or move during paving. The occurrences of such problems are very easy to detect from graphical output of MIT Scan-2. Figure 35 provides examples, clearly visible in the graphical output, of the problems resulting from inadequate anchoring of dowel baskets. These types of problems cause severe dowel misalignment, which can also be reliably detected from the approximate numerical results obtained using standard calibration (i.e., without basket-specific calibration).



(a) (b) (c)

Figure 35. Examples of problem baskets: (a) basket is deformed, (b) basket is pulled apart, and (c) basket is severely deformed and rotated almost completely off of the joint.

FIELD TESTING AND DEMONSTRATIONS

Several site visits were made to demonstrate MIT Scan-2 to State DOT and FHWA personnel, as well as to contractors and representatives of concrete paving trade organizations. These site visits were also instrumental in fulfilling various aspects of field evaluation of MIT Scan-2, including the following:

- Compare MIT Scan-2 results with those provided by other NDT devices, including GPR and cover meters.
- Evaluate functional aspects of MIT Scan-2, such as battery life, data storage capacity, and the range of operating environmental conditions.
- Identify any need for software modifications or enhancements to improve how the operation of MIT Scan-2 fits U.S. practices.
- Determine productivity of MIT Scan-2.
- Determine reliability of data storage.

South Carolina was the first State to use MIT Scan-2 in an actual construction project to monitor dowel alignment. Reconstruction of I-95 through Florence was the first project in South Carolina that was constructed using a DBI. The dowel alignment was closely monitored using MIT Scan-2. That experience provided valuable preliminary information on the operation of MIT Scan-2 and the monitoring of dowel alignment. Based on the information obtained through field testing and demonstrations, experience from other projects involving MIT Scan-2, and the lessons learned from the South Carolina experience, guidelines for evaluating dowel alignment using MIT Scan-2 were developed and are provided in Appendix B, Guidelines for Evaluating Dowel Alignment Using the MIT Scan-2 Device.

Site Visits

The States visited include Iowa, Kansas, Minnesota, Missouri, Nevada, North Carolina, and Pennsylvania. The sites were selected based mainly on the agency interest and geographical distribution. In many cases, the site visits were used to provide answers to the questions that had been raised about dowel bar alignment or tie bar position.

Iowa

In Iowa, the DOT had some concern over the dowel bar alignment when cracking occurred along the ends of the dowels at a few transverse joints in a newly constructed JPCP. The MIT Scan-2 results showed that the dowel bar alignments were in fact very good. Testing the four joints in question and two longitudinal joints (for tie bars) took less than 15 min, and the results conclusively showed that the dowel bars are in very good alignment. No other method of testing would have been able to provide the same information so easily in such a short time.

Kansas

In Kansas, a project under construction was suspected of having problems with tie bar position. The DOT conducted GPR testing to determine the extent and severity of the problem, and this provided the opportunity to compare MIT Scan-2 and GPR results. A short section of the project was scanned using MIT Scan-2 to compare the results with those obtained using GPR. The very first joint scanned showed a significant discrepancy between GPR and MIT Scan-2 results. An open-air demonstration was conducted to verify that the MIT Scan-2 results are accurate. A scan of several joints in a row revealed that for some of the joints, the results compared very well.

Table 8 provides a summary of the comparison for 10 joints. The joints were matched by examining the bar location pattern. The variations in the tie bar position served as a fingerprint to match the joints between GPR and MIT Scan-2 testing results. Since consecutive joints were tested, only the location of the first joint tested using MIT Scan-2 needed to be located in the GPR test results. Table 8 shows that where good agreement exists in the detected bar positions, good agreement in bar depths is observed.

Because MIT Scan-2 results are a direct interpretation of the magnetic signals detected during testing, the bar location reported by the device is highly reliable. On the other hand, the GPR results depend on material properties used in the data evaluation. Since the material properties can vary significantly along the length of a project, localized errors are possible. Some of the bar positions reported by GPR appear to be in error. For example, in slab 7, GPR reported only three tie bars, and the bar spacing in slabs 8, 9, and 10 is highly variable, ranging from 0.5 to 129 cm (0.2 to 51 in.). Results are shown graphically in Figure 36.

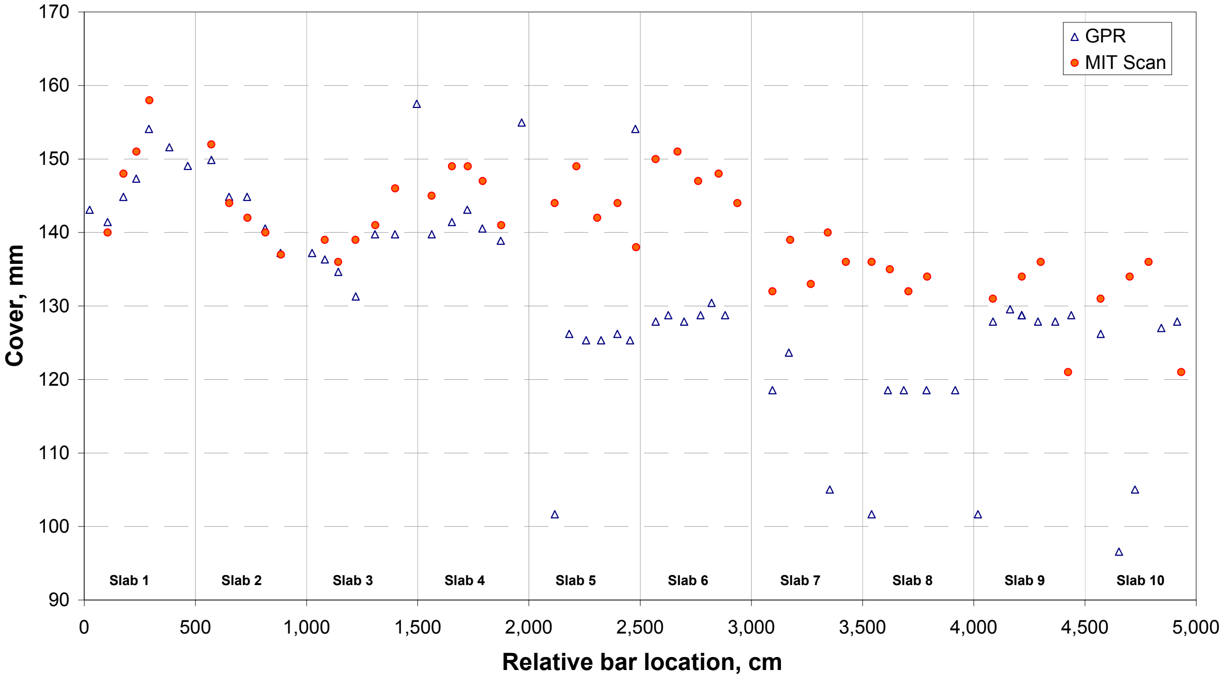


Figure 36. Comparison of GPR and MIT Scan-2 results from Kansas.

Table 8. Comparison of GPR and MIT Scan-2 Results From the Kansas Project

Slab	Approximate joint location (station), m	GPR			MIT Scan-2	
		Bar loc. cm	Dist. to next bar, cm	Cover depth, mm	Bar loc. cm	Cover depth, mm
1	33,330.0	24.2	80.9	143		
		105.2	70.8	141	105.2	140
		176.0	57.7	145	177.0	148
		233.8	57.3	147	234.9	151
		291.1	91.9	154	293.3	158
		383.1	82.7	152		
		465.8	34.8	149		
2	33,335.0	572.1	79.6	150	572.1	152
		651.8	81.0	145	651.9	144
		732.8	80.5	145	734.3	142
		813.4	69.6	141	814.9	140
		883.0	115.2	137	884.8	137
3	33,340.0	1,024.7	57.2	137		
		1,082.0	60.2	136	1,082.0	139
		1,142.2	78.4	135	1,142.4	136
		1,220.7	86.9	131	1,220.2	139
		1,307.6	89.9	140	1,308.7	141
		1,397.6	97.9	140	1,398.1	146
		1,495.5	23.3	158		
4	33,345.2	1,562.8	90.3	140	1,562.8	145
		1,653.2	69.5	141	1,654.0	149
		1,722.7	67.8	143	1,724.6	149
		1,790.6	82.3	141	1,792.3	147
		1,872.9	94.0	139	1,875.3	141
		1,967.0	34.0	155		
5	33,350.2	2,115.7	65.3	102	2,115.7	144
		2,181.1	75.4	126	2,213.4	149
		2,256.5	67.4	125	2,307.1	142
		2,324.0	73.8	125	2,398.7	144
		2,397.8	56.8	126	2,481.5	138
		2,454.7	23.8	125		
		2,478.5		154		
6	33,355.2	2,569.6	56.8	128	2,569.6	150
		2,626.5	70.8	129	2,667.7	151
		2,697.3	73.8	128	2,761.2	147
		2,771.2	49.6	129	2,853.1	148
		2,820.8	61.0	130	2,937.4	144
		2,881.9		129		
7	33,360.2	3,094.9	73.4	119	3,094.9	132
		3,168.4	184.2	124	3,174.2	139
		3,352.6		105	3,267.4	133
					3,344.3	140
					3,424.7	136
8	33,365.1	3,540.7	73.3	102	3,540.7	136
		3,614.1	71.3	119	3,622.6	135
		3,685.4	102.1	119	3,706.1	132
		3,787.6	128.8	119	3,790.3	134
		3,916.4		119		
9	33,370.1	4,018.8	67.4	102		
		4,086.3	76.7	128	4,086.3	131
		4,163.0	52.2	130	4,216.7	134
		4,215.3	0.5	129	4,301.2	136
		4,215.8	72.5	129	4,424.1	121
		4,288.4	78.0	128		
		4,366.4	71.6	128		
		4,438.1		129		
10	33,375.1	4,570.8	81.8	126	4,570.8	131
		4,652.7	72.0	97	4,701.1	134
		4,724.7	118.7	105	4,785.8	136
		4,843.5	70.8	127	4,932.9	121
		4,914.3		128		

Minnesota

Prior to laboratory testing at the MnRoad facility, a short presentation was made to the MnRoad and MnDOT staff, followed by a demonstration. MnDOT has a cover meter, and the results of MIT Scan-2 were compared with the data collected using the cover meter. The results were described in the Literature Review section. The depth measurements were nearly identical. To measure dowel alignment using a cover meter, the ends of the dowel bar needed to be located and marked manually by finding the location where the signal drops off abruptly. While accurate results could be obtained using a cover meter, testing a large number of bars using this device is not practical. As noted in the Literature Review, cover meters are subject to the same limitations as MIT Scan-2: presence of other metal objects will affect the measurement results.

Missouri

The Missouri DOT was interested in a demonstration of MIT Scan-2, and a site visit could be conveniently coordinated with the visits to Kansas, Iowa, and Minnesota. A short presentation was made at the DOT office, followed by an open-air demonstration and a field demonstration. The field demonstration was made on an on-ramp under construction near the DOT office. Several transverse joints were scanned, along with one longitudinal joint. The dowel alignment was not a concern on this project. The scan results showed no major problem with dowel alignment. One noticeable feature on this project was that all joints had at least a few uncut ties, clearly visible on the signal intensity plot (Figure 37).

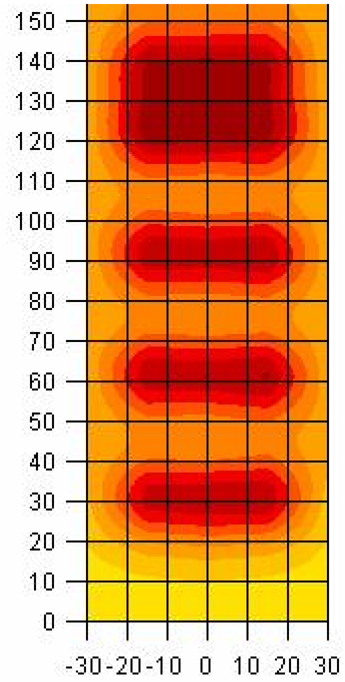


Figure 37. Signal intensity plot showing uncut ties between location 110 and 150 (cm).

Nevada

Field tests were conducted on an I-80 reconstruction project in Reno. This was an opportunity to evaluate the feasibility of using MIT Scan-2 to evaluate alignment of dowel bars placed in baskets. This series of tests demonstrated that MIT Scan-2 is a valuable tool for identifying alignment problems of dowel baskets even without the basket software. The test results showed that the problems that develop in dowel baskets tend to be more obvious, larger scale problems that are easy to detect from the graphical output of MagnoProof (Figure 35). In general, the problems appear to be results of the baskets bursting open or deforming during concrete placement due to inadequate anchoring.

On this project, the baskets were originally anchored using only four pins per basket, one at each corner. MIT Scan-2 test results showed that these were not sufficient to hold the basket in place. Many baskets burst open, causing large misalignments. The most common problems observed from this project are shown in Figure 35b. Such problems are also clearly evident in the numerical results obtained using the standard software. The numerical results obtained without the proper calibration must be considered qualitative, but the results still provide an adequate degree of accuracy to clearly delineate the baskets that have problems and those that exhibit very good alignment.

After discovering the problem with the basket anchoring practice, the process was modified to pin every other dowel on each side of the basket (10 pins per basket). This change resulted in immediate and drastic improvement in dowel alignment. A comparison of the dowel alignment trends before and after the change is shown in Figure 38. Severely misaligned dowel bars can cause a joint to lock. Figure 38 shows that anchoring the baskets using only 4 pins per basket caused 11.5 percent of dowel bars to be misaligned by 20 mm (0.78 in.) or more. This is a severe case of dowel misalignment. If uniformly distributed, the 11.5 percent would place at least one severely misaligned dowel bar in every joint. By contrast, the baskets anchored using 10 pins per basket had exceptional alignment. No bars were misaligned by more than 20 mm (0.78 in.), and only 0.2 percent of the bars were misaligned by more than 15 mm (0.59 in.). These results represent about the best dowel alignment that could possibly be achieved in the field using either baskets or DBI. All sections anchored using 10 pins per basket showed similar results on this project.

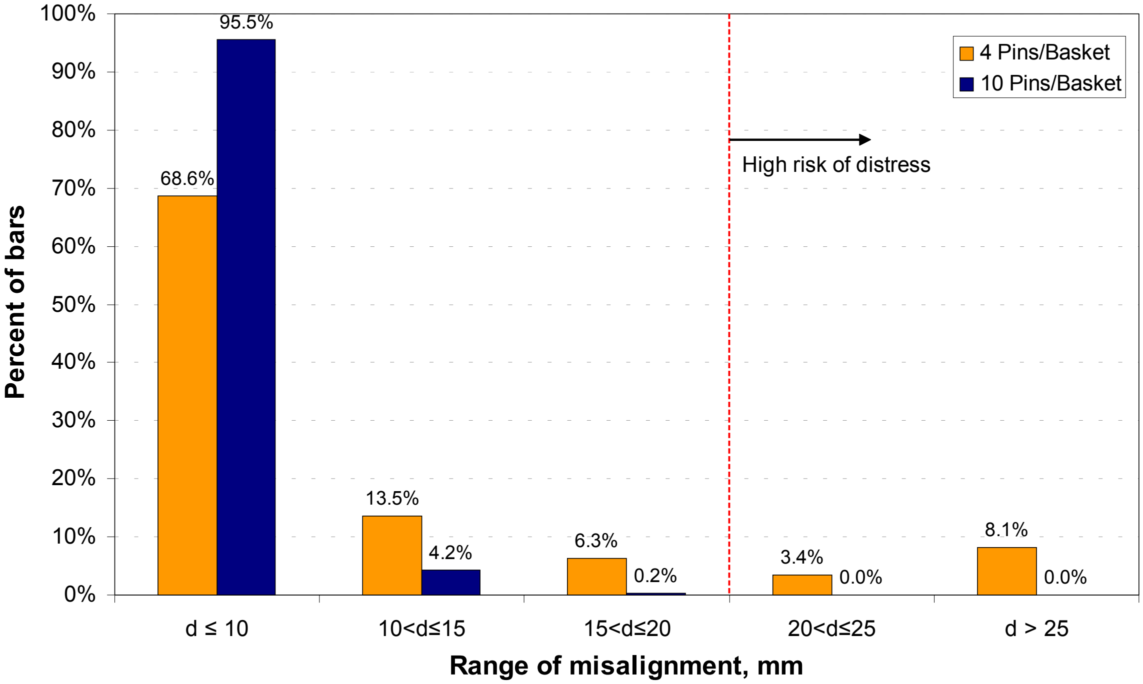


Figure 38. Comparison of dowel alignment for baskets anchored using 4 pins/basket and 10 pins/basket.

Both the magnitude of misalignment and the number of dowel bars in each range of misalignment affect the functioning of a joint. Also, if a joint is locked due to one or more severely misaligned bars, the negative effect of additional misaligned bars may be minimal. In an attempt to quantify the potential effect of dowel misalignment on pavement performance, an index referred to as the "Joint Score" was developed to reflect the risk of joint locking. The index is determined based on the magnitude of misalignment and the number of dowel bars in each range of misalignment. An index of 10 or greater may suggest a high risk of joint locking. A full description of the index is provided in Appendix B. In Figures 39 and 40 a joint-by-joint evaluation of MIT Scan-2 data from the Nevada field test sections is shown using the Joint Score concept.

Figure 39 shows a high percentage of joints (27 percent) with a Joint Score greater than 10 for the section that was anchored using 4 pins per basket. The dramatic improvement in dowel alignment obtained when more pins were used (10 per basket) to hold the baskets securely in place is clearly shown in Figure 40. On this project, anchoring the baskets using 10 pins per basket completely eliminated the dowel misalignment problem. MIT Scan-2 was instrumental in both identifying the problem and verifying the improvement achieved after modifying the basket anchoring practice.

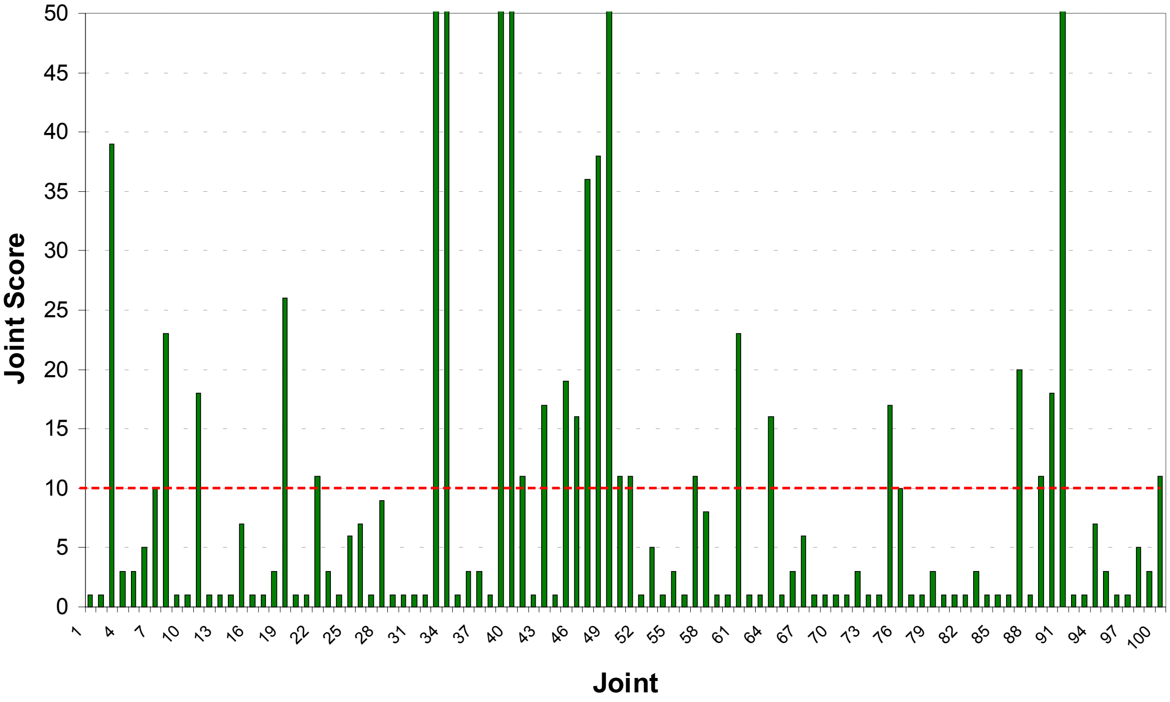


Figure 39. Joint-by-joint evaluation results for the baskets anchored using 4 pins per basket, showing a significant number of potentially locked joints (Joint Score > 10).

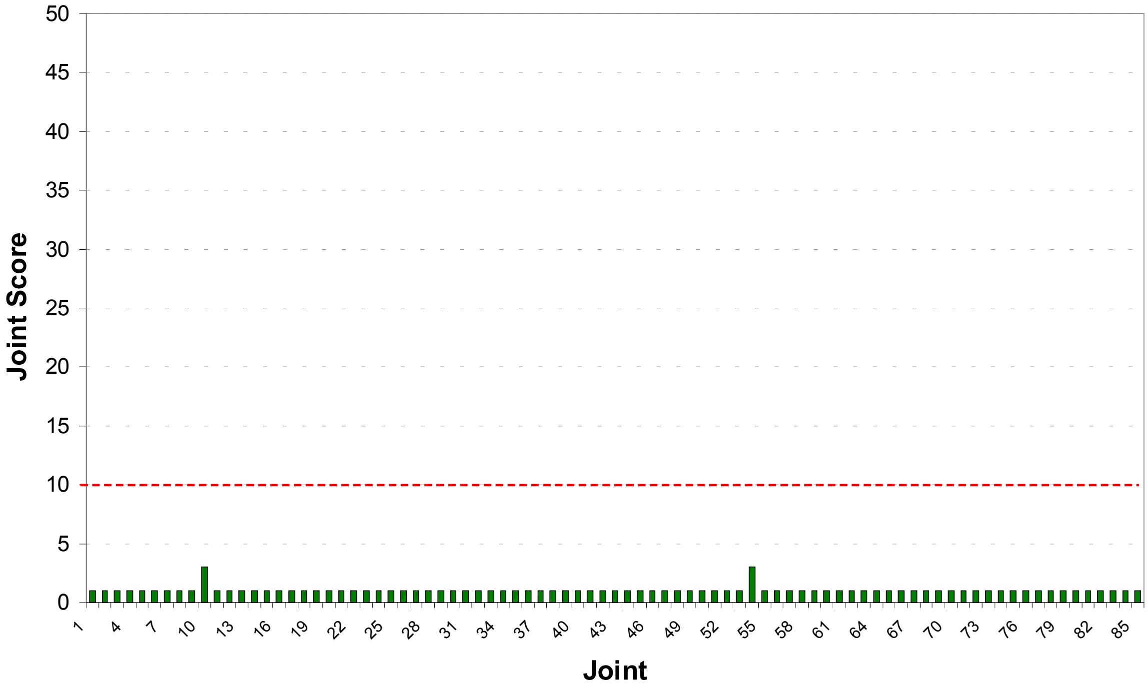


Figure 40. Joint-by-joint evaluation results for the baskets anchored using 10 pins per basket, showing outstanding dowel alignment.

North Carolina

The North Carolina DOT was interested in a demonstration of MIT Scan-2 to determine its suitability for use during construction to monitor dowel alignment. The demonstration was particularly timely, because the DOT was contemplating whether to allow the contractor to use a DBI on an upcoming construction project (US-64 Knightdale Bypass). In the past, the DOT had not allowed the use of DBI. However, with the availability of practical means of verifying dowel alignment, the DOT was open to considering the DBI option.

Similar to other demonstrations, a short slide presentation was made, followed by an open-air demonstration. Shortly after this demonstration, the DOT approved the use of DBI with the condition that the contractor document dowel positions. On that project, both the contractor and the State used MIT Scan-2 to monitor dowel alignment.

For the contractor, MIT Scan-2 was also instrumental in refining paving operations. Problems with equipment adjustment were easily detected using the MIT Scan-2 results. For example, a consistently large misalignment at one particular bar position suggested that the DBI forks at that position needed adjustment. For construction using a DBI, concrete mixture proportions have a significant effect on dowel placement. The portland cement concrete (PCC) mixture must be stable enough to hold the dowel bars in place after the insertion, and the mixture must be workable enough to ensure that no voids are left behind as the dowel bars pass through the concrete to their final positions. The ability to rapidly monitor dowel placement results at consecutive joints was helpful in adjusting the mixture proportions (Figure 41). This project demonstrated the usefulness of the MIT Scan-2 for process control in real time.

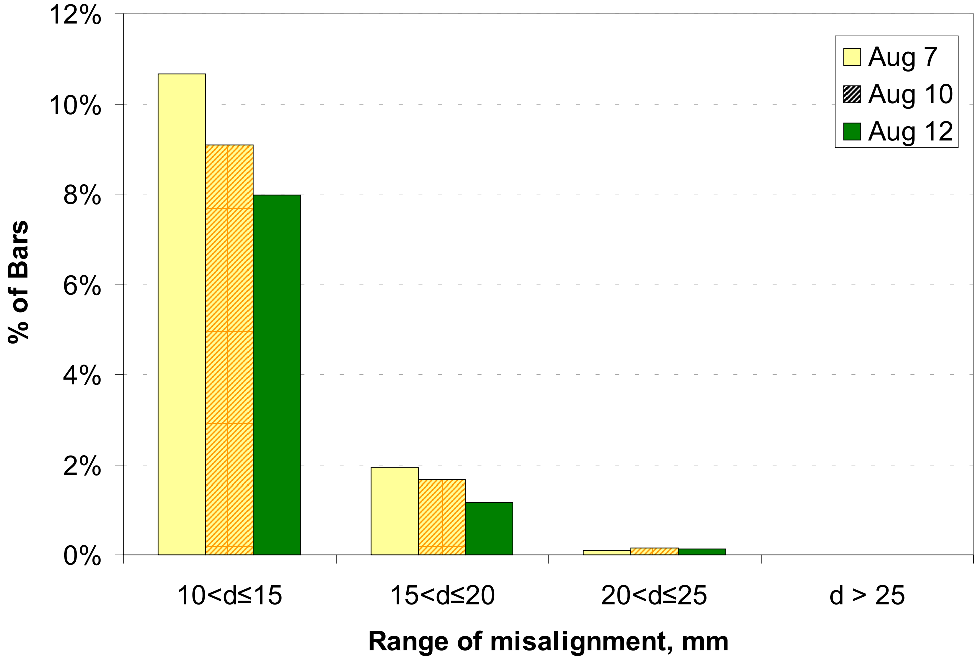


Figure 41. The effects of mix optimization on dowel alignment on the US-64 Bypass project.

Pennsylvania

MIT Scan-2 was demonstrated at a project site in Pennsylvania where cracking had developed on an I-81 reconstruction project. Because the cracking initiated at the ends of the outermost dowel, dowel misalignment was one of the suspect causes. Fifty joints were scanned using MIT Scan-2 in about an hour. The results showed that while the dowel alignment on this project is not exemplary, dowel misalignment is not likely to have been a contributing factor on the observed cracking.

The results are shown in Figures 42 and 43. As shown in Figure 42, this project contains what would appear to be a significant percentage of misaligned bars (misalignment > 20 mm [0.78 in.]). The Joint Scores for this project show that several joints on this project may be locked, but field experience shows that occasional locked joints can be tolerated (Yu 2005). Also, the joint locations on this project where cracking occurred did not have a high Joint Score.

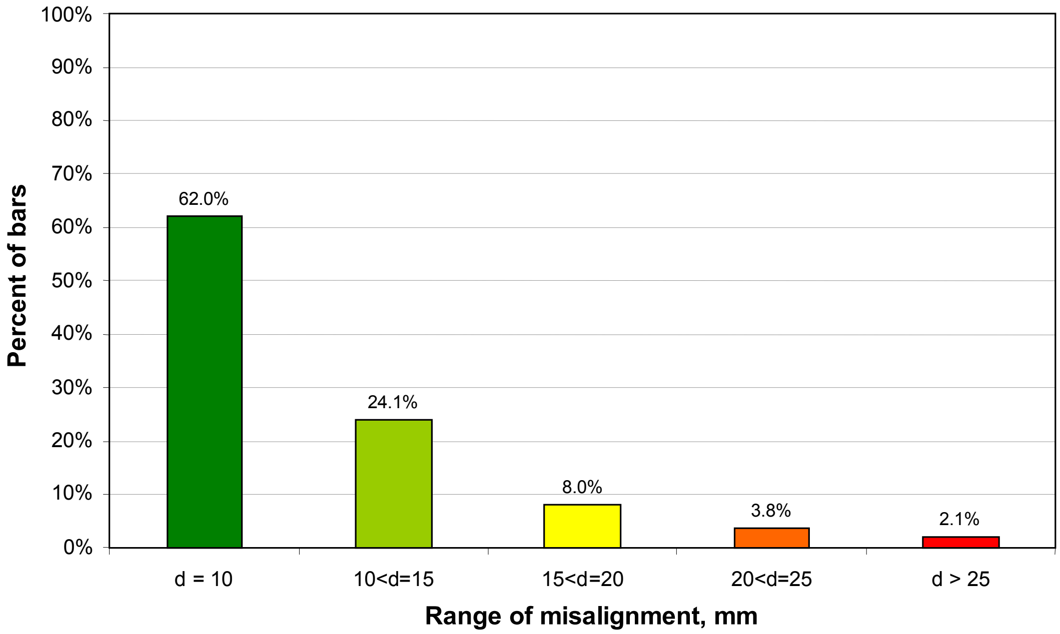


Figure 42. Distribution of dowel misalignment in the I-81 project in Pennsylvania (maximum of either horizontal or vertical misalignment).

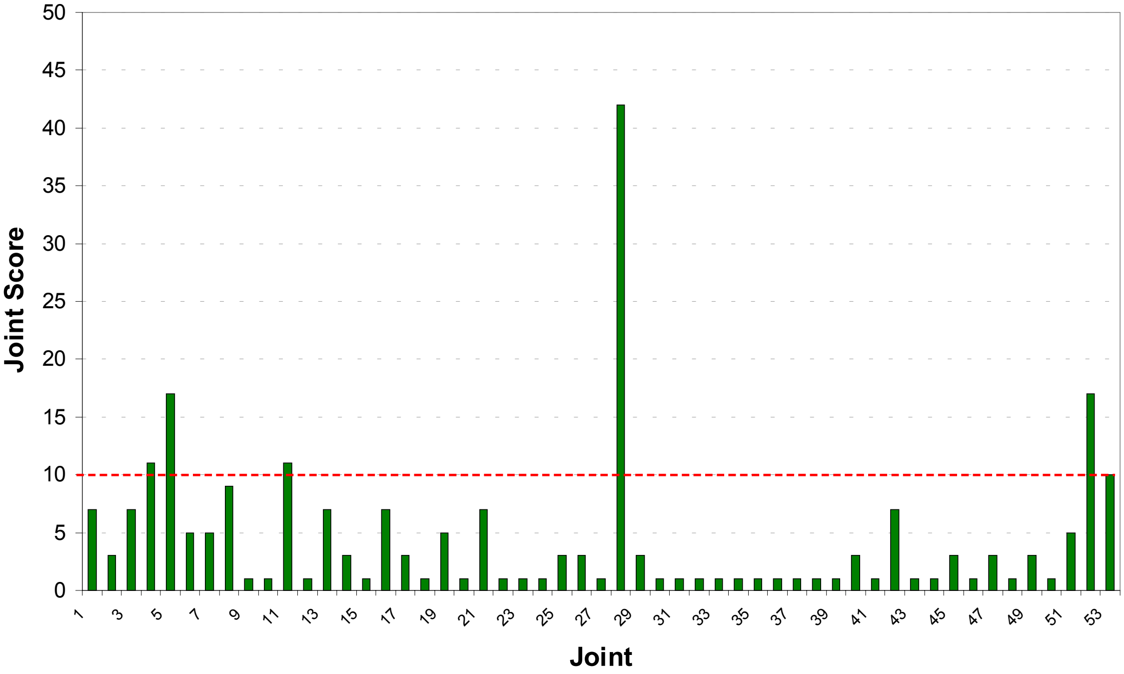


Figure 43. Joint Scores for the I-81 project in Pennsylvania.

CONCLUSIONS

Extensive laboratory and field evaluations were conducted under this project to evaluate the effectiveness and limitations of the MIT Scan-2, which uses magnetic tomography technology to evaluate the placement of metal dowel bars in concrete pavements. The laboratory testing results confirm that the MIT Scan-2 provides accuracy that is both reasonable and useful for horizontal and vertical misalignments within the following limits:

- Depth 100 to 190 mm (3.9 to 7.5 in.)
- Side shift ±100 mm (±4 in.)
- Horizontal misalignment ±40 (±1.6 in.) plus a uniform rotation of ±80 mm (±3.1 in.)
- Vertical misalignment ±40 mm (±1.6 in.)

The uniform rotation of ±80 mm (±3.1 in.) mentioned above refers to the ability to handle skewed joints.

The estimated overall standard deviation of measurement error is 3.0 mm (0.12 in.), which means that the device can provide measurement accuracy of ±5 mm (0.20 in.) with 95 percent reliability.

With proper calibration to account for dowel baskets, the device can provide similar levels of accuracy for dowel bars placed either in dowel baskets or by a DBI. This assumes that the dowels are insulated (epoxy-coated or painted) and the transport ties are cut.

Field experience with MIT Scan-2 showed that the device is reliable and easy to use. Up to 400 or more joints can be tested in an 8-hour period using a single charge of the battery. An exception is that testing during cold weather greatly reduces the battery life.

MIT Scan-2 can also be a useful tool for contractors in identifying the adjustments needed in the paving process. For example, a consistently large misalignment at one particular bar position at consecutive joints suggested that the DBI forks at that position needed adjustment. Similarly, the ability to rapidly monitor dowel placement results at consecutive joints is very helpful in adjusting the concrete mixture proportions. For dowels in baskets, significant misalignments would immediately draw attention to the procedures used to secure the basket to the base as well as the integrity of the basket itself. The ability to assess MIT Scan-2 results and focus, in real time, on potentially needed adjustments both in the paving equipment and hardware and in the PCC mixture proportions makes MIT Scan-2 a unique and valuable tool.

The principal limitation of MIT Scan-2 is that the presence of other metal objects (such as tie bars, nails in the joint, coins, pieces of wire, or any other metal item) near the measurement region can introduce significant errors, effectively invalidating the results. Although the presence of such metal objects is easily detectable on the signal intensity plot, the loss of information for the affected bars is a limitation. The most problematic of the metal objects may be the tie bars between lanes; however, the detection of a tie bar within the influence region of the scanned joint may itself be an indication of a problem, because most States require tie bars to be at least 500 mm (20 in.) away from transverse joints.

APPENDIX A

MIT Scan-2 Operations Guide

MIT Scan-2 Operations Guide

INTRODUCTION

MIT Scan-2 is a magnetic imaging tool specifically developed for measuring dowel and tie bar alignments in PCC pavements. The device consists of the scan unit, onboard computer (Casio IT2000), and rail system as shown in Figure A1.

MIT Scan-2 emits electromagnetic pulse and detects the induced magnetic field. Consequently, any metallic objects within proximity of the scan unit influence the measurement results. To obtain reliable results, the surface of the joint to be scanned must be free of any metallic objects (e.g., coins, pocket knife, keys). If the inspectors are wearing steel-toed boots, the boots must be kept a minimum 3 ft (0.9 m) away from the scan unit during measurements.

Figure A1. MIT Scan-2 device.

PREPARATION

Preparation consists mainly of charging batteries and management of flash memory on IT2000.

Charging Battery

The scan unit and onboard computer have batteries that require charging:

- Scan unit—The scan unit contains a maintenance-free, lead-acid battery. This battery should only be charged using the charger supplied with the unit. The charger connects to the power/data port near the handle. The charger should be protected from moisture, dust, and excessive heat. The cooling vents on the charger should not be covered, and charging should be stopped for a minimum of 2 hours if condensate forms on the charger. When the battery is fully charged, the indicator on the charger turns green. The battery charges in about 4 hours.
- Casio IT2000—The onboard computer contains a lithium-ion battery. This battery is compatible with Sony F-550 (camcorder battery). The supplied charger fully charges the battery in about 10 hours. The power indicator on IT2000 turns green when the battery is fully charged. The IT2000 battery can also be removed and charged using an external charger, which fully charges the battery in about 2 hours.

MIT Scan-2 is designed to function for a minimum of 8 hours on a single charge of battery.

Memory Management

The MIT Scan-2 testing data are stored in a flash memory card on IT2000. The unit is supplied with a 32-megabyte (MB) flash memory card, which can hold data for about 600 joints (one lane). The memory card plugs into the PCMCIA port at the bottom of IT2000. This card can be removed and plugged into any laptop computer for managing data files. The testing data should be periodically downloaded onto a laptop or other permanent storage device, and the flash card cleared to provide room for data from future testing. MIT Scan-2 uses the following conventions for data storage:

- All scan data are stored in the flash memory card (PCMCIA card).
- Data for each day's testing are stored in a single folder that is named as follows:

  yy_mm_dd (year_month_day)—for example, data from March 31, 2003 would be stored in a folder named *03_03_31*.
- Each scan produces the following binary file:

  ddMMhhmm.HDF (day, month, hour, minute)—for example, data from 1:16 p.m. on March 31 would be stored under file *31031316.HDF*.
- If the scan results are successfully analyzed by the onboard computer (IT2000), the following text file is produced:

  ddMMhhmm.TXT (day, month, hour, minute)—for example, data from 1:16 p.m. on March 31 would be stored under file *31031316.TXT*.

IMPORTANT: The flash card also contains the calibration files (***.CPF**), which **must be present in the root directory** of the flash card for the unit to collect meaningful data. There is a calibration file for each type of bar that can be scanned as well as the default calibration file ***spf.cpf***, which is **required** for the unit to function.

After the data are downloaded from the flash memory card, the memory card should be firmly reseated and locked into the PCMCIA port of IT2000. A loosely placed memory card can cause IT2000 to shut down during testing.

DEVICE SETUP

The setup activities for MIT Scan-2 consist of the following:

- Powering on the scan unit.
- Assembling and placing the rail system.
- Placing the IT2000 on the scan unit.
- Connecting the data cable and switching on IT2000.

Powering on the Scan Unit

The power switch on the scan unit is located to the right of the handle. When the power is on, the switch is illuminated. This should be the first task in setting up MIT Scan-2, because the unit takes 5 to 10 minutes to warm up. If the measurements are taken while the unit is not warmed up, they will be inaccurate. The readiness of the unit can be verified by setting up, and then testing, the same joint 3 times without moving the rail. If the unit is properly warmed up, the maximum difference in measurements for any dowel should be 2 mm (0.08 in.) or less.

Assembling and Placing the Rail System

The rail system for MIT Scan comes in 3-ft (0.9-m) tube sections connected by tie sections. The outside edge of the first tie should be placed flush with the pavement edge, and the rail assembly should be placed centered across the joint being scanned, as shown in Figure A2.

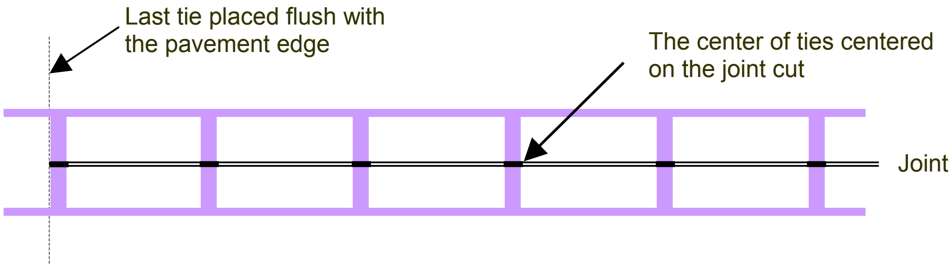


Figure A2. Illustration of proper rail placement.

Placing the IT2000 on the Scan Unit

After the rail system is assembled, the scan unit should be placed on the rail and IT2000 placed on the scan unit at the designated place. The location of IT2000 is marked with rubber stoppers, as shown in Figure A3, and Velcro is used to hold the onboard computer in place.

Figure A3. Proper placement of IT2000.

Connecting the Data Cable

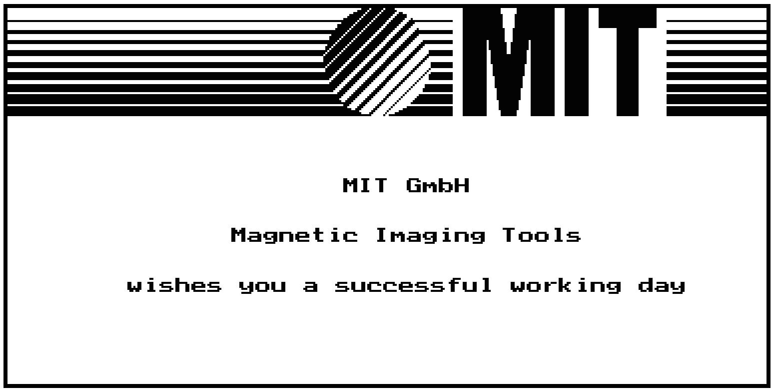
A special cable connects the scan unit and IT2000 for data communication. Both ends of the connectors have notches for proper alignment of the connectors. If the connectors are properly aligned, they should slip in without much resistance. Do not force the connectors. At the scan-unit end, the connector is threaded for secure connection. To connect:

- Connect the cable to the scan unit first, and lock it in place by turning the rotating sleeve clockwise (Figure A4-a).
- Connect the IT2000 end, flat side up (Figure A4-b).

Switch on the IT2000 after installing the data cable. Figure A5 shows the screen that displays if all sensors and communication between the scan unit and IT2000 are working properly.

(a) (b)

Figure A4. Connecting the data cable (a) at the scan-unit end and (b) at the IT2000 end.



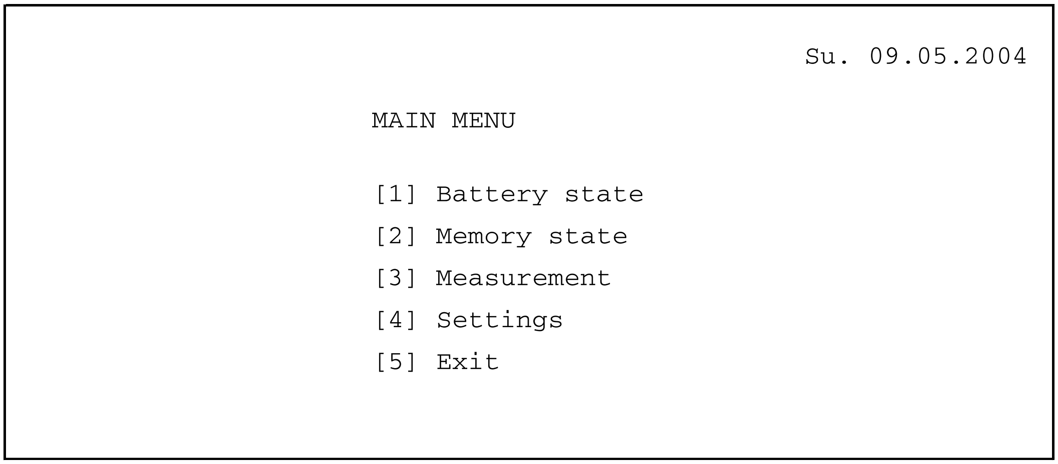
```
MIT GmbH

Magnetic Imaging Tools

wishes you a successful working day
```

Figure A5. IT2000 display at power-up, when the sensors and communication link between IT2000 and the scan unit are working properly.

PREMEASUREMENT TESTING

The software that controls the testing and data acquisition activities, as well as preliminary data analysis, is called MagnoNorm. Figure A6 shows the Main Menu of MagnoNorm, which includes the following:

- [1] Battery check—utility to check charge state of batteries on the IT2000 and on the scan unit.
- [2] Memory state—utility to check the memory status of flash memory on the IT2000.
- [3] Measurement—the option to initiate the measurement task.
- [4] Settings—utility for setting various testing parameters.
- [5] Exit—the option to end the testing and turn off the IT2000.



```
                                        Su. 09.05.2004

                     MAIN MENU

                     [1] Battery state
                     [2] Memory state
                     [3] Measurement
                     [4] Settings
                     [5] Exit
```

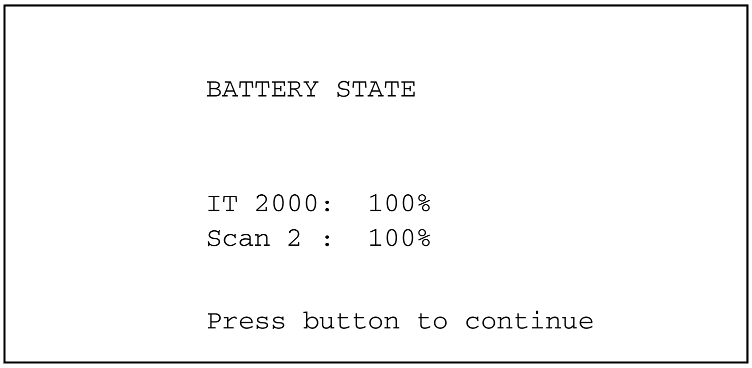
Figure A6. Main menu of MagnoNorm, the software on IT2000 that controls the testing and data acquisition process, as well as preliminary data analysis.

The testing involves the following tasks:

- Checking battery and memory status.
- Checking and setting date and time.
- Entering setup information.
- Entering project information in MagnoNorm.
- Scanning the joint.
- Data analysis.

Checking Battery and Memory State

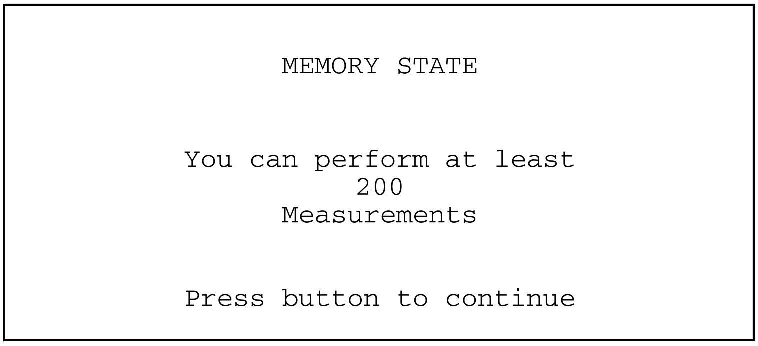
Although not required, these tasks are important to verify that the system is functioning properly and that adequate space is available for storing the scan data. Figure A7 shows the Battery State screen; the check Memory State screen is shown in Figure A8.



```
BATTERY STATE


IT 2000:  100%
Scan 2 :  100%


Press button to continue
```

Figure A7. Battery status check screen.

- Press the Main Menu option [1] to check battery status.
- Both batteries should be fully charged to ensure 8 hours of testing before recharging.
- A display of 0 percent power for MIT Scan-2 can be a result of an improper connection. Check the connecting cable.



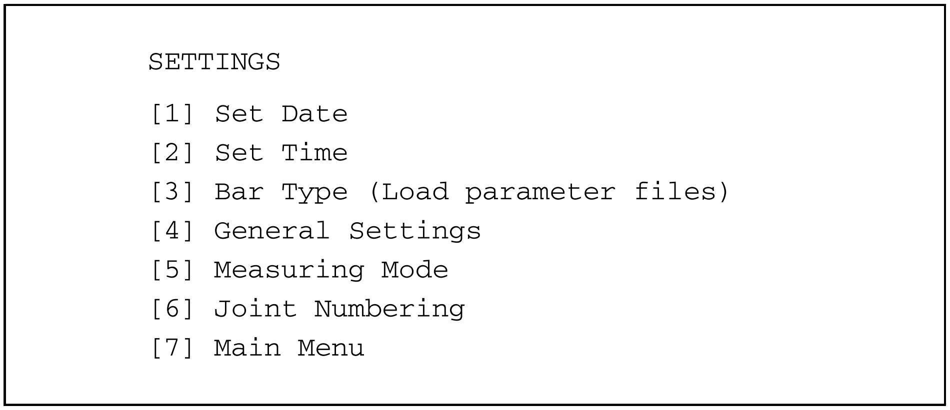
```
      MEMORY STATE


You can perform at least
           200
      Measurements


Press button to continue
```

Figure A8. Memory status check screen.

- Press the Main Menu option [2] to check memory status.
- The 32-MB flash memory card provided with IT2000 can hold data for 600 joints (one lane).
- Download the data frequently for better tracking of the testing data.

Settings

Selecting option [4] from the Main Menu brings up the Settings menu shown in Figure A9. Before each testing session, the current settings of MagnoNorm should be checked to ensure the various settings are correct, especially the Bar Type.

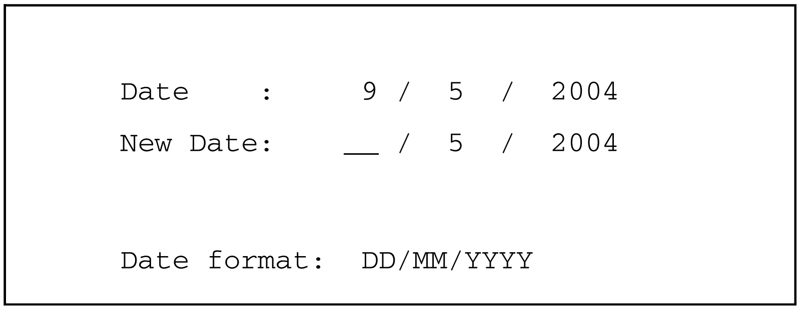


```
SETTINGS

[1] Set Date
[2] Set Time
[3] Bar Type (Load parameter files)
[4] General Settings
[5] Measuring Mode
[6] Joint Numbering
[7] Main Menu
```

Figure A9. Settings menu in MagnoNorm.

Setting Date and Time

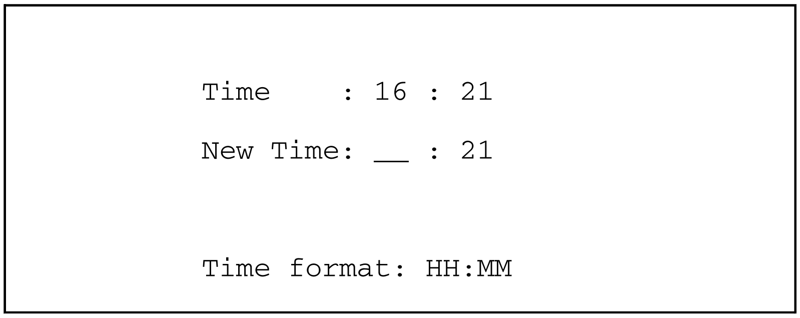
Setting the correct date (Figure A10) and time (Figure A11) prior to testing is important to keep track of the testing data, because the date and time are used in the naming of the folders and files as described above in the section on Memory Management.



```
Date     :     9 /  5  /  2004

New Date:    __ /  5  /  2004


Date format:  DD/MM/YYYY
```

Figure A10. Set date screen.

- Press Settings option [1] to set date.
- Press [Enter] after entering each number. This is a general convention on all data entry screens on MagnoNorm.



```
Time    : 16 : 21

New Time: __ : 21


Time format: HH:MM
```

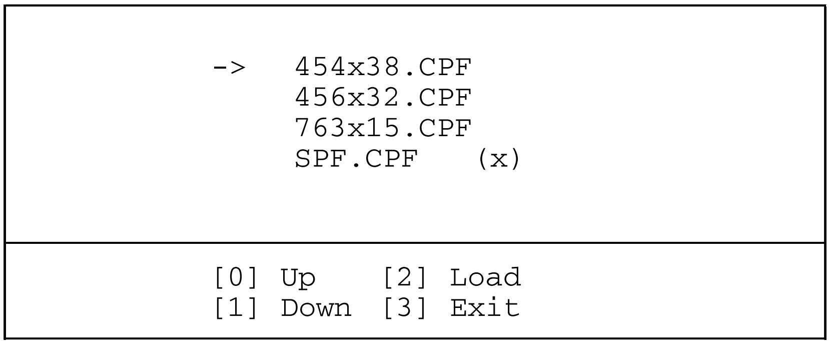
Figure A11. Set time screen.

- Press Settings option [2] to set time.

Selecting the Bar Type

Selecting the correct bar type is very important to ensure proper evaluation of the scan data. Figure A12 shows the Bar Type selection screen. The files listed on this screen (the parameter files) contain the calibration data for each bar type, and the correct quantitative evaluation is only possible for the types of bars listed on this screen. The bar types are described in terms of length and diameter in millimeters, as follows:

lll x dd.CPF—length x diameter in millimeters



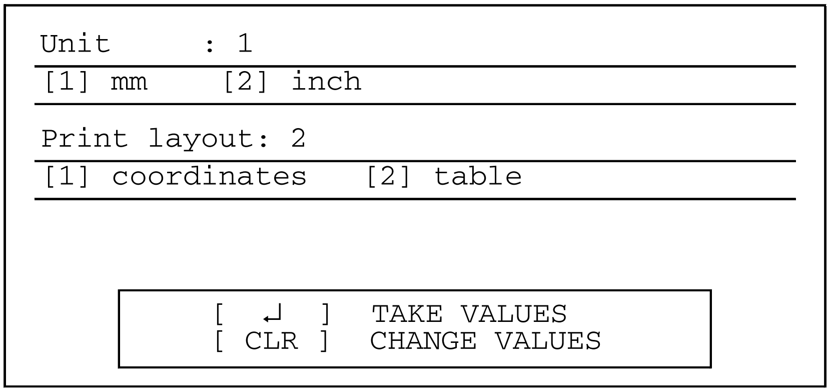
```
        ->   454x38.CPF
             456x32.CPF
             763x15.CPF
             SPF.CPF    (x)

        [0] Up     [2] Load
        [1] Down   [3] Exit
```

Figure A12. Bar type (load parameter file) screen.

- Use [0] to move up and [1] to move down.
- Press [2] to load the currently selected bar type.
- Press [3] to exit.

General Settings

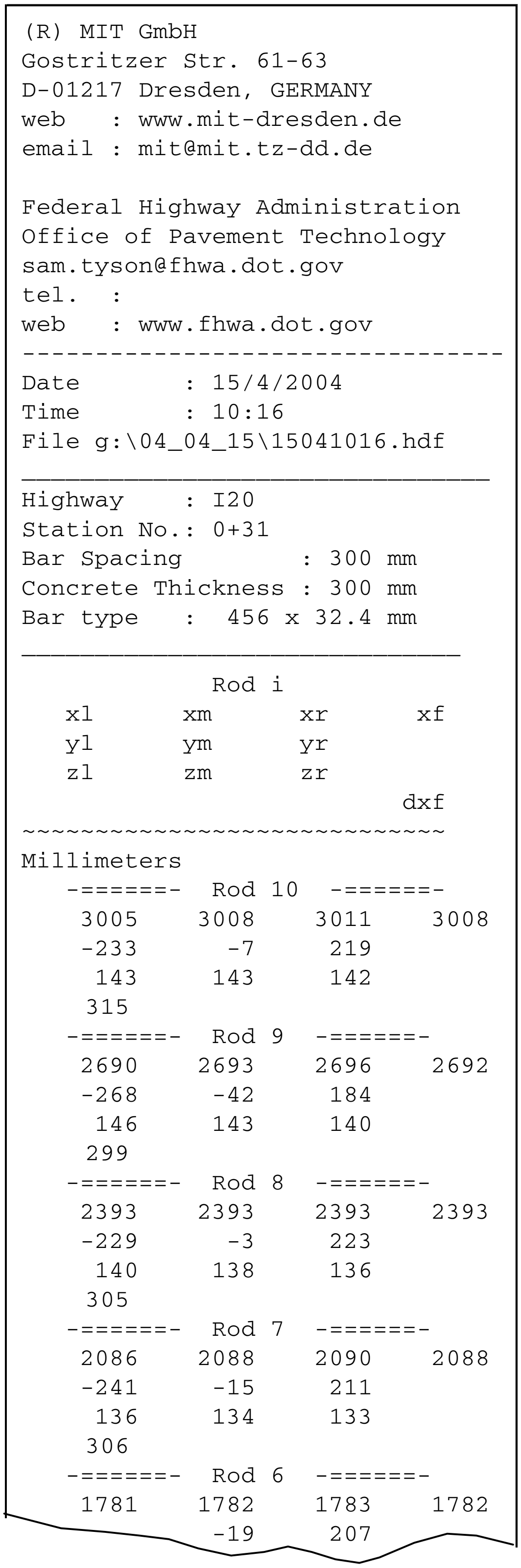
The General Settings include the unit of measure and the type of output (Figure A13). The Print Layout option affects the format of the field analysis (MagnoNorm analysis) results. Both the field output (IT2000 printouts) and the text files stored on the flash memory are presented in the format selected in the General Settings menu. The Coordinates option provides the x-y-z coordinates of left end, middle, and right end of each bar (Figure A14). The Table option provides the calculated alignment results in a tabular form (Figure A15).



```
Unit      : 1
[1] mm     [2] inch

Print layout: 2
[1] coordinates   [2] table

      [  ↵  ]  TAKE VALUES
      [ CLR ]  CHANGE VALUES
```

Figure A13. General Settings.

- Press [CLR] to change values.
- Select the desired unit and type of output, pressing [↵ Enter] after each selection.
- Press [↵ Enter] while the cursor is on the *[↵] TAKE VALUES* to exit.



```
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sam.tyson@fhwa.dot.gov
tel.  :
web   : www.fhwa.dot.gov
---------------------------------
Date       : 15/4/2004
Time       : 10:16
File g:\04_04_15\15041016.hdf
________________________________
Highway    : I20
Station No.: 0+31
Bar Spacing        : 300 mm
Concrete Thickness : 300 mm
Bar type   :  456 x 32.4 mm
______________________________
             Rod i
   xl      xm      xr      xf
   yl      ym      yr
   zl      zm      zr
                          dxf
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Millimeters
   -=======-  Rod 10  -=======-
    3005    3008    3011    3008
    -233      -7     219
     143     143     142
    315
   -=======-  Rod 9  -=======-
    2690    2693    2696    2692
    -268     -42     184
     146     143     140
    299
   -=======-  Rod 8  -=======-
    2393    2393    2393    2393
    -229      -3     223
     140     138     136
    305
   -=======-  Rod 7  -=======-
    2086    2088    2090    2088
    -241     -15     211
     136     134     133
    306
   -=======-  Rod 6  -=======-
    1781    1782    1783    1782
             -19     207
```
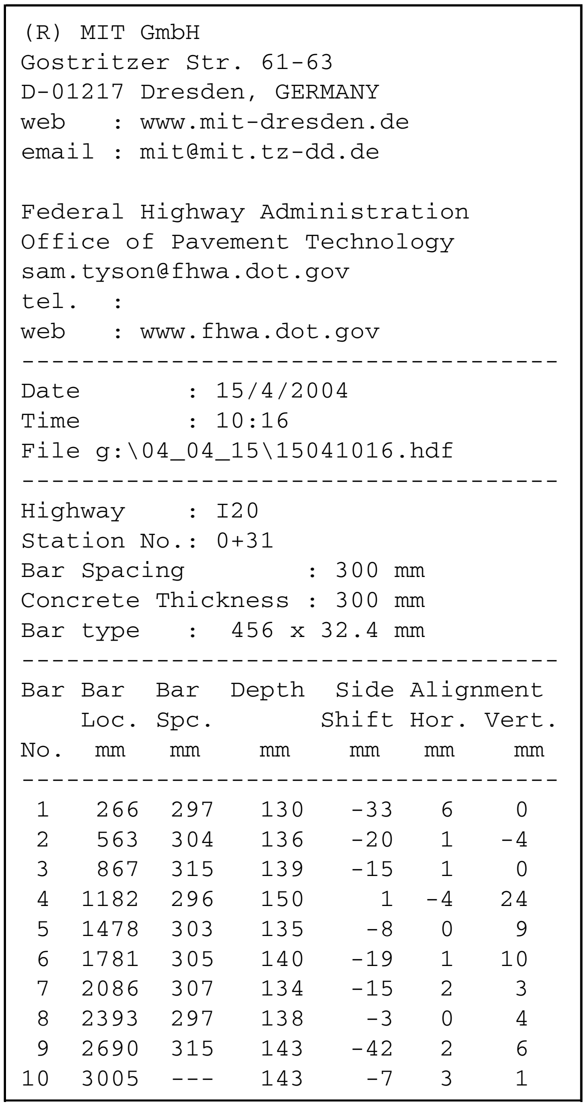

Figure A14. Example MagnoNorm printout in coordinates format, which provides the x-y-z coordinates of the left end, middle, and right end of each bar scanned.



```
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tel.  :
web   : www.fhwa.dot.gov
------------------------------------
Date       : 15/4/2004
Time       : 10:16
File g:\04_04_15\15041016.hdf
------------------------------------
Highway    : I20
Station No.: 0+31
Bar Spacing        : 300 mm
Concrete Thickness : 300 mm
Bar type   :  456 x 32.4 mm
------------------------------------
Bar Bar  Bar  Depth  Side Alignment
    Loc. Spc.       Shift Hor. Vert.
No.  mm   mm     mm    mm   mm    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
```
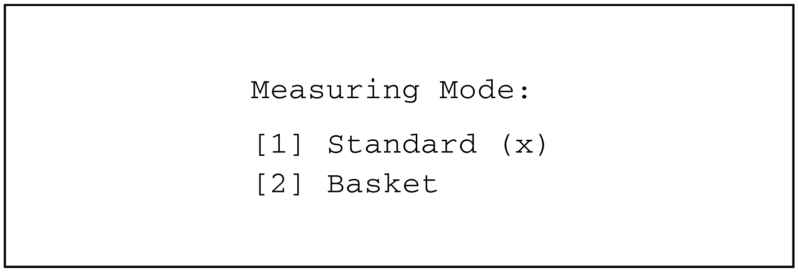

Figure A15. Example MagnoNorm printout in the table format, which provides the calculated alignment results in a compact tabular format.

Measuring Mode

Specify whether bare bars (Standard) or dowels placed in baskets (Basket) will be measured (see Figure A16).



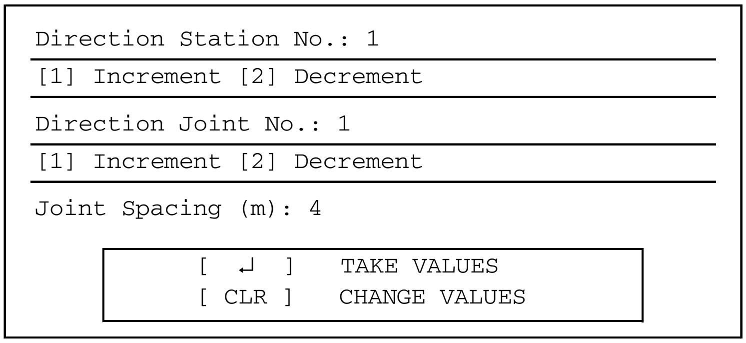
```
Measuring Mode:
[1] Standard (x)
[2] Basket
```

- Press [1] to select bare bars (Standard).
- Press [2] to select dowel basket (cut baskets only).

Figure A16. Measuring Mode screen.

Joint Numbering

Set the automatic joint and station numbering behavior from the screen shown in Figure A17.



```
Direction Station No.: 1
[1] Increment [2] Decrement
Direction Joint No.: 1
[1] Increment [2] Decrement
Joint Spacing (m): 4

        [  ↵  ]   TAKE VALUES
        [ CLR ]   CHANGE VALUES
```

Figure A17. Station and joint numbering screen.

- Select whether the station number and joint number should increase or decrease after each joint.
- Enter joint spacing.

MEASUREMENT

The Measurement option (Main Menu option [3]) should only be selected after date, time, and bar type information has been entered in the Settings menu:

The measurement screen is shown in Figure A18. The information entered on this screen is used to identify the joints tested and is printed with the analysis results. The following data are required (all numeric input):

- Highway type
- Highway number
- Highway direction
- Concrete thickness

As on other screens, press [Enter] after each input. Be sure to enter valid information on all data fields. After entering the last field (Concrete thickness), you have the option of selecting:

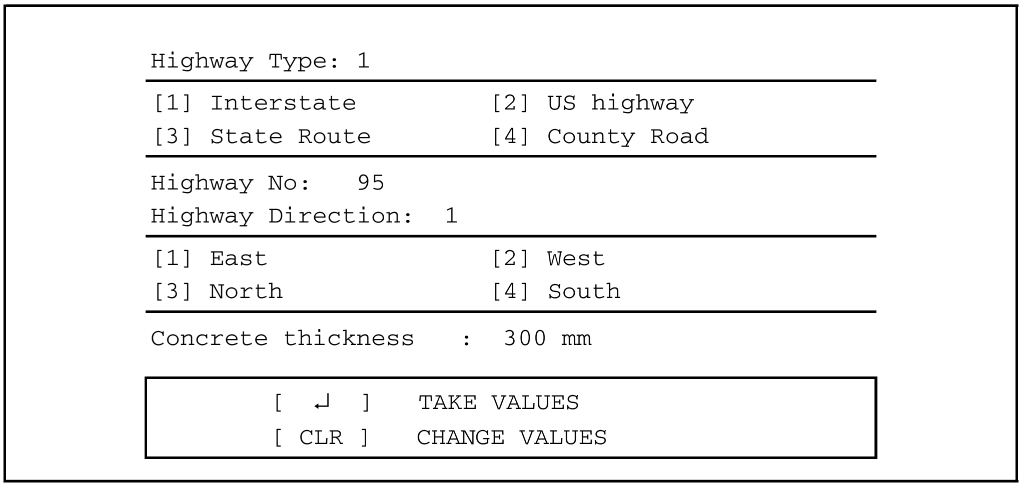
- [↵]—The entries are correct. Take the values and go to next screen.
- [CLR]—Corrections are required.

The Highway Type listed in Figure A18 can be customized by modifying the file “Highways.txt” in the Input folder. Enter the description of the four types of highways in the file “Highways.txt” in the following convention:

- Description, e.g., Interstate, U.S. highway, or State Route
- Short description, e.g., “I” for Interstate, “US” for U.S. highway, and “SR” for State Route

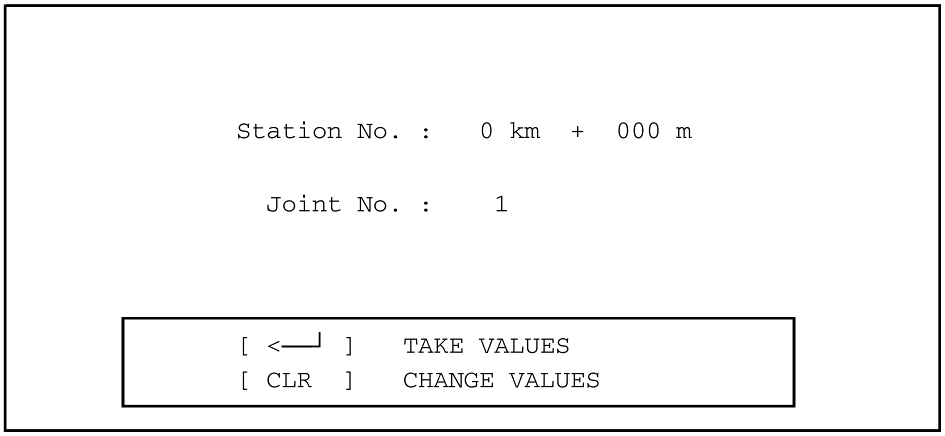
Four sets of such descriptions must be provided in “Highways.txt.”

After a successful entry of the project information, you will be prompted to enter or correct the station number (Figure A19). The station number is automatically incremented by 1 after each joint is scanned, so that the number may be conveniently used as the joint number.



```
Highway Type: 1
[1] Interstate          [2] US highway
[3] State Route         [4] County Road
Highway No:   95
Highway Direction:  1
[1] East                [2] West
[3] North               [4] South
Concrete thickness   :  300 mm
         [  ↲  ]   TAKE VALUES
         [ CLR ]   CHANGE VALUES
```

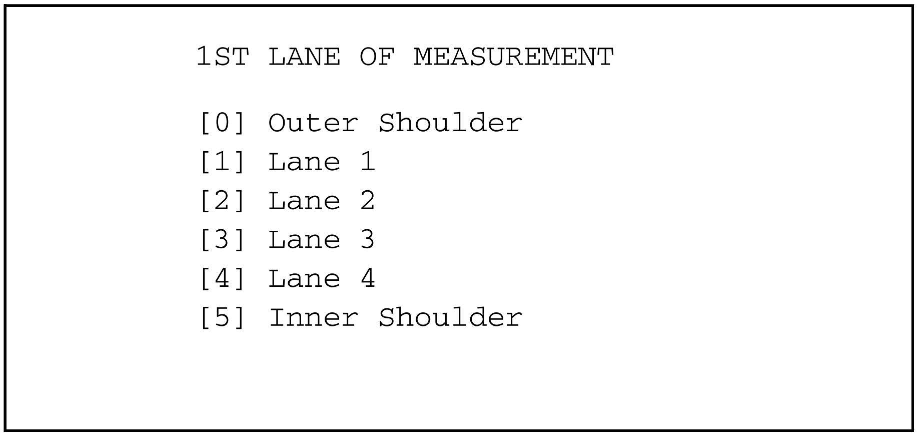
Figure A18. Project information screen that is displayed when Measurement (option [3]) is selected.



```
Station No. :   0 km  +  000 m

  Joint No. :    1

   [ <—┘ ]   TAKE VALUES
   [ CLR  ]   CHANGE VALUES
```

Figure A19. Station number entry screen. The station number is automatically incremented by 1 for convenience when used as the joint number.

Next, the lane selection menu is displayed as shown in Figure A20. When a lane is selected for the first time, you will be prompted to enter the lane width in centimeters and bar spacing in millimeters (Figure A21).

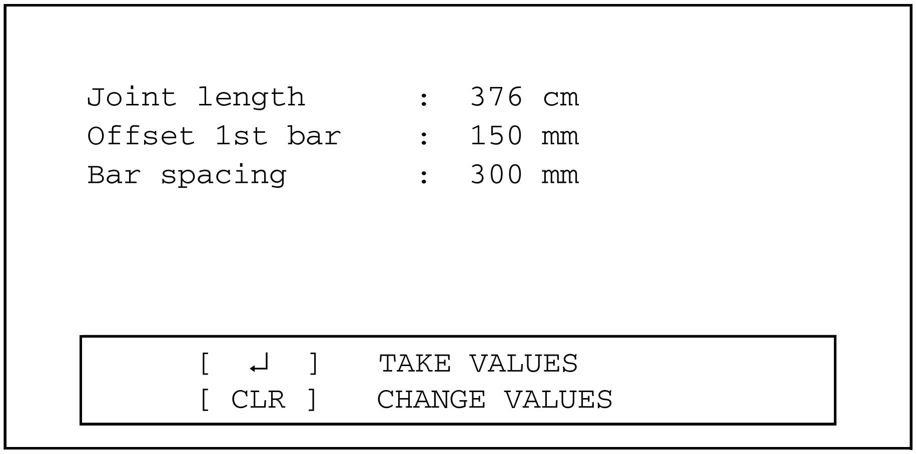


```
1ST LANE OF MEASUREMENT

[0] Outer Shoulder
[1] Lane 1
[2] Lane 2
[3] Lane 3
[4] Lane 4
[5] Inner Shoulder
```

Figure A20. Lane selection menu.

Each lane definition specifies the scan length (lane width) and bar spacing.

- Each lane definition specifies the joint length (lane width), offset of the first dowel bar from the edge of the lane, and bar spacing.
- The joint length defines the length over which the scan data are collected. The scanning process can be manually stopped at any time by pressing [0].
- The bar spacing input has no influence on the analysis results but defines the specified location of the dowel bars for the graphical output.

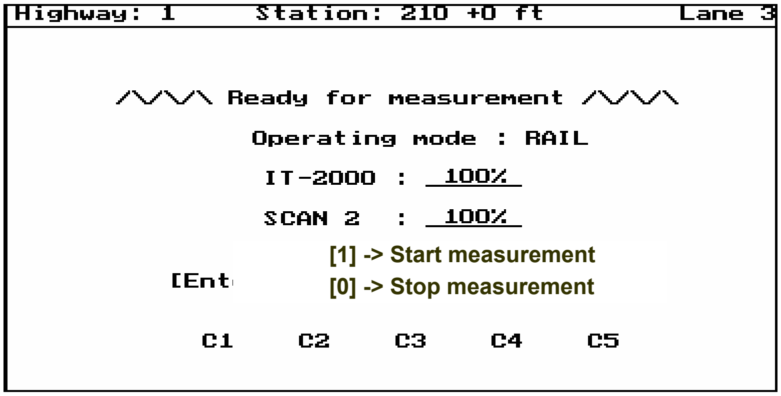


```
Joint length       :  376 cm
Offset 1st bar     :  150 mm
Bar spacing        :  300 mm


[  ↵  ]   TAKE VALUES
[ CLR ]   CHANGE VALUES
```

Figure A21. Lane description menu.

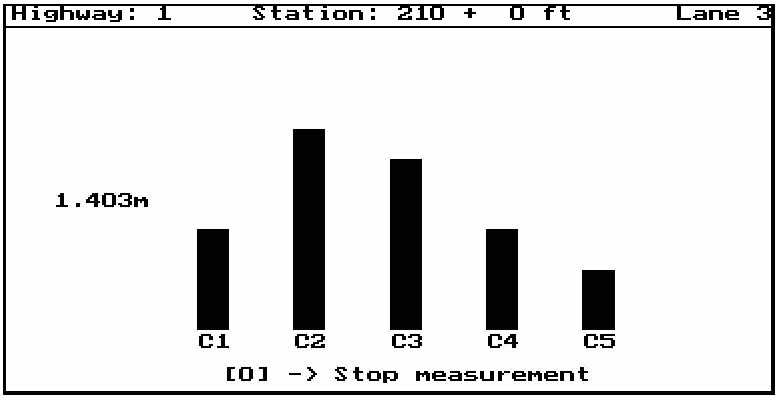
When the last input (bar spacing) is entered, MIT Scan-2 is ready to scan a joint. Before starting to measure, set the scan unit against the stopper as shown in Figure A22 to properly set the starting position.

Figure A22. Properly positioned scan unit against the stopper for accurate determination of bar positions along the joint.



```
Highway: 1      Station: 210 +0 ft         Lane 3

     /\/\/\ Ready for measurement /\/\/\
            Operating mode : RAIL
             IT-2000  :  100%
             SCAN 2   :  100%
                  [1] -> Start measurement
   [Ent           [0] -> Stop measurement

       C1     C2     C3     C4     C5
```

Figure A23. MagnoNorm screen when the device is ready for a measurement.



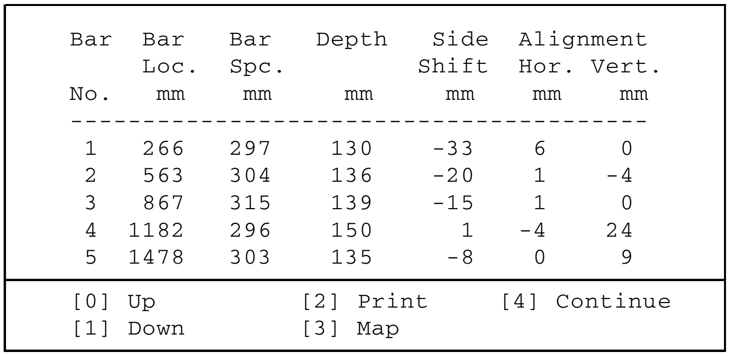
```
Highway: 1      Station: 210 +  0 ft       Lane 3

  1.403m

       C1     C2     C3     C4     C5
          [0] -> Stop measurement
```

Figure A24. The signal intensity at each sensor.

Figure A23 shows the screen displayed when the device is ready for measurement. During the measurement, MagnoNorm displays the signal strength detected by each of the five sensors (Figure A24).

- Before pressing [Enter] to begin measurements, set the scan unit against the stopper as shown in Figure A22 to set the correct starting position.
- Press [1] to start the measurements.
- Do not move the unit backward after pressing [1] to begin measurements.
- The measurement will stop automatically when the specified scan length (joint length) is reached.
- Stop the measurement at any time by pressing [0].

Upon completion of measurements, MagnoNorm displays a plot of the measured signal intensity along the joint just scanned. You can press any key to evaluate the data. The data analysis is automatic. The evaluation can take 2–3 minutes, depending on the length scanned. If MagnoNorm was able to evaluate the scan data, the results can be printed or viewed on the screen. Figure A25 shows the results screen for the coordinates print layout.



```
Bar   Bar    Bar    Depth    Side  Alignment
      Loc.   Spc.            Shift  Hor. Vert.
No.    mm     mm      mm      mm     mm     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

[0] Up           [2] Print      [4] Continue
[1] Down         [3] Map
```

Figure A25. Evaluation results screen.

- Press [0] to move up, and [1] to move down.
- Press [2] to print results.
- Press [3] to view a grey-scale map of the scan data.
- Press [4] to continue testing or exit this menu.

MagnoNorm provides reliable results under the following conditions:

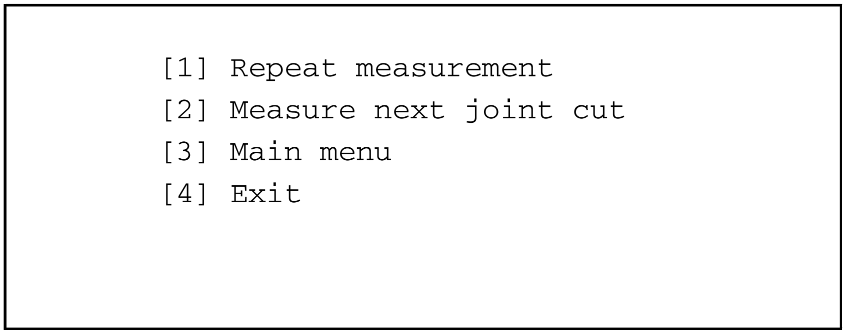
- Bar depth from 100 to 180 mm (4 to 7 in.)
- Horizontal misalignment less than 40 mm (1.5 in.)
- Vertical misalignment less than 40 mm (1.5 in.)
- Side shift less than 80 mm (3 in.)

The position errors listed above are well outside the typical specification limits. If desired, the laptop software MAGNOPROOF can be used to analyze the scan data more precisely.

CONTINUATION

The options available after each measurement are shown in Figure A26.

- Select [1] to repeat measurement. When this option is selected, the data from previous measurements are overwritten. The data from all repeat measurements are saved under the same file name that was created when the joint was first scanned.
- Select [2] to measure next joint. Select this option to measure successive joints in the same project. Different joints in the same project are differentiated by the joint number rather than the station number. The joint number is a sequential number that is automatically updated by MagnoNorm. The station number is used only to denote the location of the first joint, and the user is not prompted to enter the station number at each joint. The joint number is printed on evaluation results.
- Select [3] to go to the Main Menu. Use this option if a different lane needs to be measured.
- Select [4] to end testing and shut off IT2000.



```
[1] Repeat measurement
[2] Measure next joint cut
[3] Main menu
[4] Exit
```

Figure A26. Available options after each measurement.

APPENDIX B

Guidelines for Evaluating Dowel Alignment Using MIT Scan-2

Guidelines For Evaluating Dowel Alignment Using Mit Scan-2

INTRODUCTION

The placement accuracy of dowel bars can be evaluated very efficiently using MIT Scan-2. MIT Scan-2 is a state-of-the-art nondestructive testing (NDT) device that was developed specifically for detecting dowel bars placed in concrete pavements. The technology employed is magnetic tomography. Presented in the following are guidelines for using MIT Scan-2 to monitor construction quality of dowel alignment.

EFFECTIVENESS AND LIMITATIONS OF MIT SCAN-2

MIT Scan-2 is simple to operate, is efficient, and provides accurate, real-time results in the field. The device was intended for use on dowel bars placed using a dowel bar inserter (DBI), but it can also be used to scan bars placed in a basket, if the following conditions are met:

- The bars are epoxy-coated or painted to insulate the bars from the basket.
- The transport ties on the basket are cut.

If these conditions are met, good results can be obtained for dowel bars placed in baskets. Dowel baskets can be calibrated to obtain the same level of accuracy as bare bars.

MIT Scan-2 results are not affected by changing moisture conditions in the concrete, so the testing can be conducted at any concrete age, including over fresh concrete. The test results are also not affected by the presence of water on the pavement surface. The operating temperature range is – 5 ºC to 50 ºC (23 ºF to 122 ºF).

Accuracy

For inserted bars, MIT Scan-2 can provide an accuracy of ±5 mm (±0.20 in.) with 95 percent reliability on horizontal and vertical misalignment. The accuracy on the lateral bar position (side shift) is ±8 mm (0.16 in.), and that on depth is ±4 mm (0.08 in.). These measurement tolerances are valid for the following conditions:

- Dowel bar depth 150 ± 40 mm (4.3 to 7.5 in.)
- Horizontal and vertical misalignment less than +40 mm (1.6 in.)
- Lateral shift (side shift) less than +80 mm (+3.2 in.)

The measurement error is higher for more severely misaligned bars.

For dowel bars placed in a dowel basket, good approximate results can be obtained without any special consideration for the dowel basket. With basket-type-specific calibration, a similar level of accuracy can be obtained for dowels placed in baskets as bare bars.

The presence of metal objects such as tie bars, nails, reflectors, or other objects within the detection range of the Scan-2 can affect the results, effectively invalidating the results for the affected bars. Such objects are usually easy to detect on the graphical output of the Windows-based software accompanying MIT Scan-2 (MagnoProof). When scan results indicate significant misalignments, a close inspection using MagnoProof is highly recommended to verify that the results are not affected by the presence of extraneous metal objects.

Productivity

After setup, testing takes 1 minute or less per joint, depending on the number of lanes tested. Up to three lanes can be scanned together in a single pass, and testing multiple lanes together does not significantly slow the rate of testing. The device setup takes about 20 minutes, but marking out the test area with joint numbers can take an hour or longer, depending on the length of the section to be tested. To ensure that the test data are accurately correlated to the correct joint, marking joint numbers on the pavement is highly recommended.

Peak productivity is about 100 joints per hour when testing a single lane, but this rate of testing is difficult to sustain throughout a workday. For planning purposes, a good estimate of average daily productivity is about 70 joints per hour for single lanes (assuming a crew of 2) and moderately less (e.g., 60 joints per hour) for 2 lanes on continuous testing. If the test areas are scattered, the time required to move from one location to another (which may involve disassembling and reassembling the rail) should be taken into consideration in planning.

The battery life of the sensor unit may be a factor limiting daily productivity. The device is designed for a minimum of 8 hours of continuous testing on one charge, and under most conditions this is easily achieved. On single-lane testing, up to 12 hours of continuous testing may be possible on one charge. However, the battery life may be greatly reduced (e.g., 30 to 40 percent reduction) when testing under low temperatures (e.g., 30°F [2°C] or lower).

Limitations

The principal limitation of MIT Scan-2 is that the presence of foreign metal affects the results. Although the presence of such metal objects is easily detected, the loss of information for the affected bars is a limitation. The most problematic of such objects is tie bars in close proximity to the joint being evaluated. The inability to obtain accurate results for dowel bars influenced by tie bars is a limitation of MIT Scan-2. However, the fact that a tie bar is within the influence region of the scanned joint may already be an indication of a problem, because most States require tie bars to be placed at least 500 mm (20 in.) away from the joints.

FREQUENCY OF TESTING

For evaluating the quality of dowel alignment in a pavement section, testing a random sample of 50 consecutive joints is recommended. Depending on the consistency of the testing results and quality of construction, the rate of testing may be on per day's paving, per mile, or per section of project basis.

For construction using a DBI, any systematic problems due to equipment adjustment could be determined from a fewer number of joints (e.g., 20 joints); however, the portland cement concrete (PCC) mix has a significant effect on the alignment of inserted dowel bars. Testing over the full 50-joint sample is recommended to capture the effects of any batch-to-batch variations in PCC mix consistency, and to detect any problems resulting from segregation.

On projects constructed using dowel baskets, problems with dowel misalignment are usually the result of inadequate anchoring of the baskets (i.e., inadequate number or size of anchoring pins). Inadequate anchoring causes the baskets to burst open, deform, or move during paving, which in turn, causes severe dowel misalignment. If the anchoring procedure is grossly inadequate, the problem will be prevalent and readily apparent in even a relatively small sample. Even if adequate anchoring is specified, occasional problems may arise due to poor work quality. The baskets are also subject to damage during construction. These types of problems are more random and less frequent. To ensure that a representative sample of random problems is captured in the test results, testing 50 consecutive joints is recommended.

FIELD TESTING

The details of the operation of MIT Scan-2 are provided in Appendix A, MIT Scan-2 Operations Guide. Following is a summary of the key steps:

- Preparation—fully charge the battery on the sensor unit and the onboard computer. A full charge provides up to 8 hours of testing.
- Setup
  - Connect the onboard computer and the sensor unit.
  - Switch on both the sensor unit and the onboard computer. Check the memory status to ensure that both units have adequate power for the amount of testing planned. The sensor unit requires 5 minutes to warm up. If measurements are taken while the unit is not warmed up, additional errors may be introduced. The readiness of the unit can be verified by setting up and then testing the same joint three times without moving the rail. If the unit is properly warmed up, the maximum difference in measurements for any dowel should be 2 mm (0.08 in.) or less.
  - Assemble the rail system.

Before testing begins, number and mark the joints sequentially to keep track of those being tested. In the field, joint numbers are a simpler way to keep track than station numbers. To speed up the marking process, a paint mark (a dot) may be placed every 5th joint and the joint number on every 10th joint. During marking, any station numbers or mileposts found in the area should be recorded in the field notes. By recording the begin station and the station number for any joints located close to the station numbers stamped on the pavement, the station number for all joints can be determined. MIT Scan-2 automatically keeps track of both joint and station numbers.

As with any field survey, maintaining good field notes is important. The following information should be recorded at the beginning of each pavement section tested:

- Route number and direction
- Begin station and milepost
- Lane number(s)
- Direction
  - Direction of scanning (e.g., from outside shoulder to centerline joint)
  - Direction of survey
- Time of scanning the first joint—MIT Scan-2 uses the date and time as the data file name. The record of the date and time of testing provides additional reference information for the pavement section tested.

During testing, the presence of any metal objects in the scan area that can interfere with MIT Scan-2 results should be recorded in the field notes. Examples of such objects include reflectors and drainage inlet covers.

DATA ANALYSIS AND EVALUATION

The MIT Scan-2 results can be used directly to check for compliance with specification requirements. Dowel placement tolerances are typically specified in terms of the following:

- Horizontal and vertical misalignment—Typical tolerances range from 5 mm (0.18 in.) to 14 mm (0.56 in.) for both horizontal and vertical misalignment for 457-mm (18-in.) dowel bars. The most common standard is 10 mm (0.375 in.).
- Lateral displacement (side shift)—Typical tolerances range from 25 to 50 mm (1 to 2 in.); 50 mm (2 in.) is the most common.
- Depth deviation—Typical specifications call for the bars to be placed within 25 mm (1 in.) of the slab middepth.

The evaluation can be based on either field results (produced by MagnoNorm) or the results obtained using the Windows-based software (MagnoProof) accompanying MIT Scan-2. The field results are accurate for the following conditions:

- Mean dowel depth 150 ± 40 mm (4.3 to 7.5 in.)
- Horizontal and vertical misalignment ±20 mm (0.8 in.)
- Maximum lateral position error (side shift) <±50 mm (2 in.)

For other conditions, MagnoProof can be used to conduct a more comprehensive analysis. MagnoProof incorporates a more robust solution algorithm and allows more manual control of the analysis process to provide more accurate results. The presence of foreign metal is easily identified on the signal intensity plot provided on the MagnoProof screen. As mentioned earlier, MagnoProof analysis is highly recommended for any joints showing significant misalignment in the field results to ensure that results are not affected by the presence of foreign metal.

Limitations of Existing Standards

Most agencies have fairly strict tolerances on dowel placement accuracy, but those standards are based on limited laboratory and field data. In some cases, the manufacturing tolerances for dowel baskets are adopted directly as the dowel placement tolerance. The actual dowel bar alignment needed to ensure good pavement performance is largely unknown.

A recent study showed that many well-performing pavement sections contain at least a few joints that are potentially locked due to dowel misalignment (Yu 2005). Projects with a significant number of misaligned bars performed well without showing any signs of distress after 8 or more years of service under heavy traffic. The following conclusions were drawn based on the field observations:

- In a joint that is already locked, additional misaligned bars have no further adverse effect.
- On short jointed concrete pavements, the presence of a few occasional locked joints is not likely to have a significant adverse impact on pavement performance, as long as the locked joints are separated by working joints.

The above observations suggest that a joint-by-joint evaluation may be more appropriate for the evaluation of dowel alignment from a pavement performance perspective. Further research is also needed to establish the critical level of misalignment, considering all relevant factors.

General Quality of Dowel Alignment

The general quality of dowel bar alignment may be evaluated in terms of the percentage of bars at various levels of misalignment, as shown in Figure B1. The effects of horizontal and vertical misalignment are combined in this figure simply by taking the maximum value of misalignment for each bar, either horizontal or vertical. Another approach to combining the effects of horizontal and vertical alignment is to use the resultant misalignment, but the dowel placement tolerances are defined in terms of horizontal and vertical misalignment, and there are no standards for the resultant misalignment.

Figure B1 shows that the frequency distribution plot could be used to compare the quality of dowel alignment of different projects. Both the magnitude and number of misaligned bars affect proper functioning of pavement joints. The bars that are more severely misaligned (e.g., more than 20 mm [0.79 in.]) are much more critical than bars that are more moderately misaligned (e.g., 10 < d < 15 mm [0.39 < d < 0.59 in]). In the example given in Figure B1, the dowel alignment of IN1 is better than IN2, both in terms of total percentage of misaligned bars and the percentage of bars with more severe misalignment.

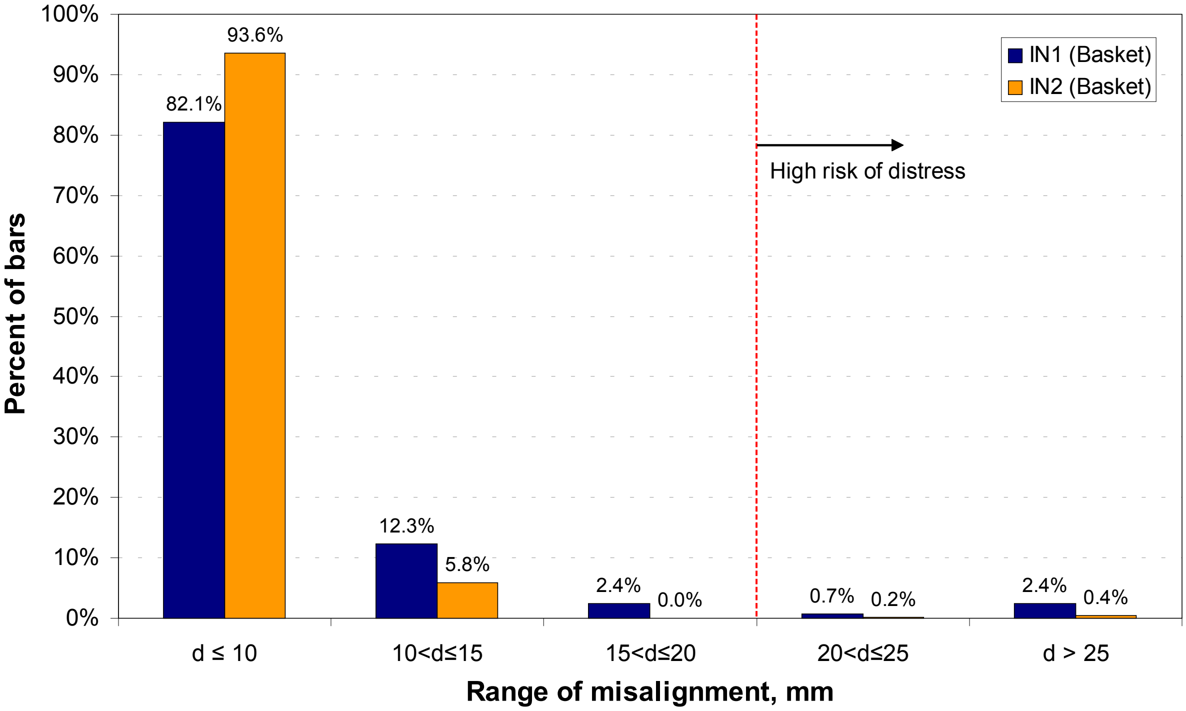


Figure B1. Example distribution of dowel misalignment (maximum horizontal or vertical) by range of misalignment (Yu 2005).

Joint-by-Joint Evaluation

Although the distribution of dowel misalignments shown in Figure B1 reflects the general quality of dowel alignment, it does not describe how the misaligned bars are distributed within a project, which may be important to pavement performance. For example, 10 badly misaligned bars in 1 joint affect the performance of that single joint, but the same number of badly misaligned bars evenly distributed over 10 joints (i.e., 1 bad bar per joint) affects the performance of 10 joints. From a pavement performance perspective, the latter case is much more critical.

The Joint Score and Rolling Average Joint Score introduced in the recent report (Yu 2005) could be used to perform a joint-by-joint evaluation. The Joint Score is a measure of the combined effects of misaligned dowel bars at a joint. Joint Score is determined by adding 1 to the sum of the product of the weights (given in Table B1) and the number of bars in each misalignment category. For example, if a joint has four misaligned bars in the range 15 to 20 mm (0.6 to 0.8 in.), the joint score is 9; if a joint has one misaligned bar in the range 15 to 20 mm (0.6 to 0.8 in.) and one bar in the 25- to 38-mm (1- to 1.5-in.) range, the score is 8. Further research is needed to refine and verify Joint Score, but the weighting factors listed in Figure B1 may be used as an interim measure.

Table B1. Weighting Factors Used to Determine Joint Score

Range of Misalignment, mm	Weight
$10 < d \leq 15$	0
$15 < d \leq 20$	2
$20 < d \leq 25$	4
$25 < d \leq 38$	5
$38 < d$	10

The Joint Score has the following meaning:

- Joint Score $s < 5$ indicates very low risk of joint locking
- Joint Score $5 < s < 10$ indicates low risk of joint locking
- Joint Score $10 < s < 15$ indicates moderate risk of joint locking
- Joint Score $15 < s$ indicates high risk of joint locking

In general, a Joint Score of 10 or higher indicates a significant potential for joint locking.

Field experience indicates that a few randomly distributed locked joints do not adversely affect pavement performance (Yu 2005). However, consecutive locked joints are not desirable. The risk of joint problems due to clusters of locked joints can be identified by determining the Running Average Joint Scores as follows:

- Cap Joint Scores—If a joint has a score greater than 10, assign a Joint Score of 10; otherwise, use the actual Joint Score.
- Determine Running Average Joint Score—The Running Average Joint Score is the maximum of the average of the capped Joint Scores for two joints ahead and two joints behind the current joint. A value of 10 indicates 2 or more consecutive locked joints and a high risk of developing distress due to poor dowel alignment.

Example plots for Joint Score and Running Average Joint Score are shown in Figures B2 and B3. In this example, the project has four joints with high potential for joint locking (Joint Score > 10), but there are no clusters of potentially locked joints. The Running Average Joint Score is less than 10 for all joints in this project (Figure B3).

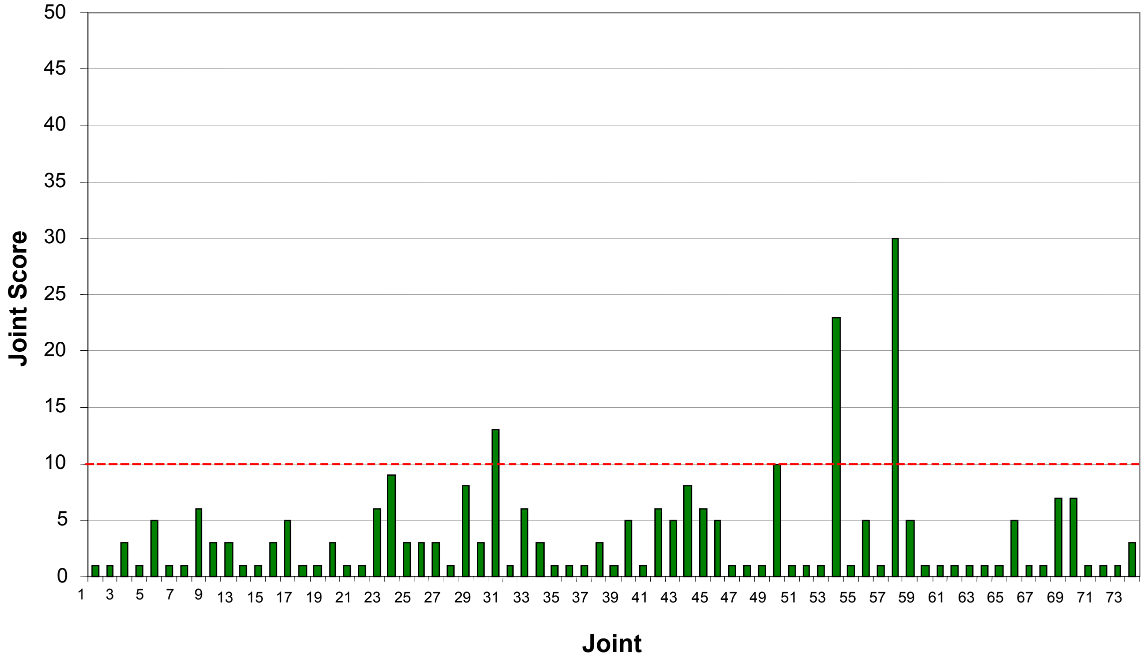


Figure B2. Example Joint Score plot. A score greater than 10 indicates a high potential for joint locking (Yu 2005).

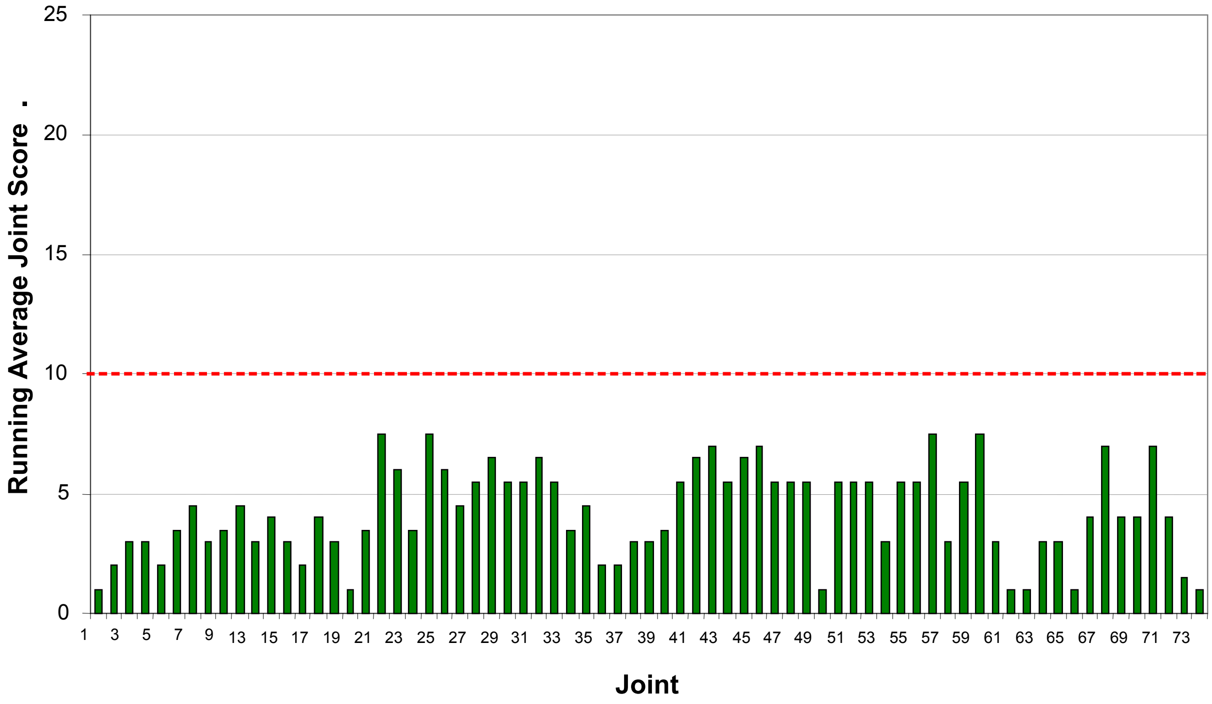


Figure B3. Running Average Joint Score plot corresponding to Figure B2, indicating low risk of any performance problems due to potentially locked joints (Yu 2005).

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