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Field Demonstration of Magnetic Tomography Technology for Determination of Dowel Bar Position in Concrete Pavement

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16. Abstract

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Dowel alignment measurements were successfully performed on both mechanically inserted dowel bars and bars on dowel baskets. Although the verification with field coring showed reasonably accurate measurements, signal interference from uncut dowel baskets, the presence of foreign metal in nearby locations, and bars deeper than 8 in can result in unreliable quantitative results. The repeatability of the measurements for bars on dowel baskets showed general agreement with the data reported from FHWA. The device was found to be user-friendly, and its field operation was simple. Thus, there is a potential benefit from using the MIT Scan-2 as a quality assurance tool for detecting dowel bar misalignment in jointed plain concrete pavement in Virginia.

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FINAL REPORT

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and the University of Virginia since 1948)

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

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ABSTRACT

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INTRODUCTION

The performance of a jointed concrete pavement is greatly influenced by the load transfer efficiency between the consecutive slabs. One of the most widely used devices for load transfer in jointed concrete pavement is the use of dowel bars across the joint. However, proper functioning of these devices largely depends on the positioning and alignment of these bars.

Dowel bars are placed in the jointed concrete pavement at mid-depth, parallel with both the pavement surface and the direction of travel; the center of the dowel is right below the joint. Tayabji[1] presented five categories of dowel misalignment, as shown in Figure 1.

Yu et al.[2] discussed the impact of misalignment of dowel bars, which can have a significant influence on the performance of a jointed concrete pavement. It can lock a joint, resulting in spalling and cracking near the jointed area, or it may create looseness around dowel bars, which would reduce the load transfer efficiency. Improper embedment depth may also

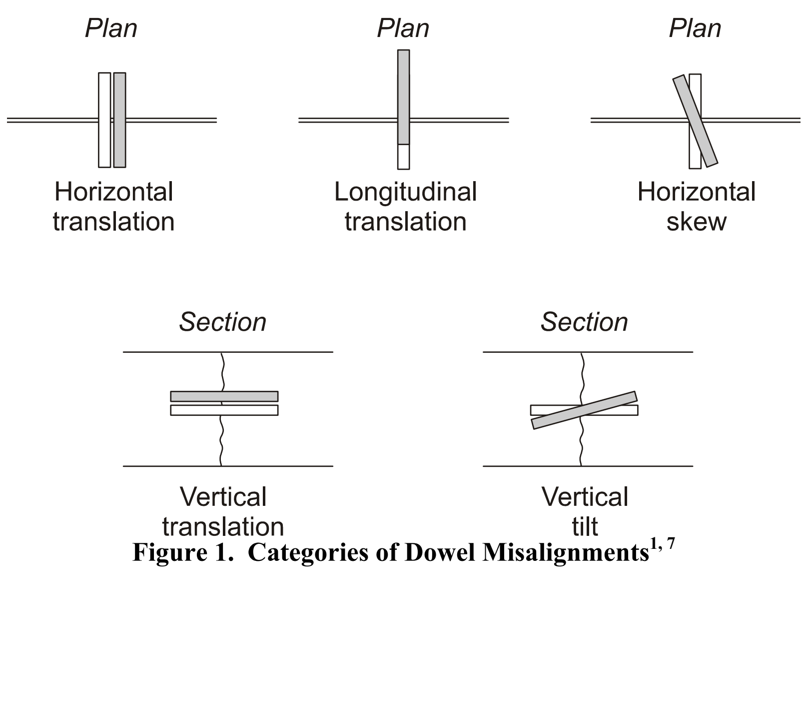

Figure 1. Categories of Dowel Misalignments[1, 7]

contribute to spalling and cracking. Although, no comprehensive evaluation of the effect of dowel misalignment on pavement life or joint life is available, some researchers[1,3] suggested that joint damage may occur for a misalignment of more than 25 mm (1 in). Therefore, proper placement of dowel bars is important to ensure good performance of jointed concrete pavement.

Several factors can lead to dowel misalignment, including plastic concrete properties (such as inconsistency and segregation); concrete placement practices (slip-forming versus fixed form, side delivery versus front delivery); construction quality control; handling, placement, and anchoring of dowel baskets; the type and adjustment of the dowel bar inserter (DBI) equipment; and operator skills.[1,4,5]

AASHTO has recommended the use of a falling weight deflectometer to measure load transfer efficiency across a joint, but such measurements will not reveal any information about misalignment. Magnetic tomography technology was used by a German company (Magnetic Imaging Tools [MIT] GmbH) to determine the location of the dowel bar in an existing pavement or even in fresh concrete. The MIT Scan-2, a state-of-the-art nondestructive device, uses this technology, which is based on the principles of pulse induction to locate the position of metal bars embedded in concrete.

The Virginia Department of Transportation (VDOT) Materials Division acquired the loan of an MIT Scan-2 for few months from the Concrete Pavement Technology Program (CPTP). This program is managed by the Federal Highway Administration (FHWA) through a partnership with state highway agencies, industry, and academia. CPTP is a national effort to improve the long-term performance and cost-effectiveness of concrete pavements. VDOT and the Virginia Transportation Research Council (VTRC) jointly evaluated the MIT Scan-2 and arranged for field demonstration. This report summarizes the demonstration and findings related to the technology.

PURPOSE AND SCOPE

The purpose of this study was to demonstrate and evaluate the use of magnetic tomography technology through use of the MIT Scan-2. The main objective was to measure the alignment of dowel bars in a selected number of jointed plain concrete pavements (JPCP) in Virginia and demonstrate the applicability of this new technology. The device was also used to evaluate the capability to measure the depth of longitudinal steel in continuously reinforced concrete pavement (CRCP).

METHODS

Demonstration Plan

The demonstration was planned in two phases. An initial training and a pilot demonstration were conducted in November 2005 for VDOT and VTRC personnel. After this training, VDOT performed a field determination of dowel bar location and orientation in a number of concrete pavements.

The Construction Technology Laboratories (CTL) group provided the initial training and pilot demonstration to respective demonstration team members from VDOT's Materials Division and VTRC. During this training the MIT Scan-2 was handed over to the Non-destructive Testing Section of VDOT's Materials Division. A small segment of roadway on westbound US 460 (Appomattox Bypass) in the Lynchburg District was selected for hands-on training on the use and field operation of the device. The Appomattox Bypass is a four-lane divided highway with JPCP. The demonstration and field training took about 2 hours. Figure 2 shows the hands-on training operation in Lynchburg. It was followed by a half-day presentation on the data analysis techniques at VDOT's Materials Division.

After training, field determination was planned to evaluate the technology. Five pavement sections were selected based on the traffic level/condition and concrete pavement type related to dowel placement techniques. Although the target was 100 joints per section, the number of joints scanned on different sections varied from 50 to 150. In addition to the scan for in-service pavements, the scanned data were analyzed in the laboratory (in office). A few joints in one section were scanned in triplicate to estimate the repeatability of the measurements. Field verification of actual bar location and orientation was also planned for few dowel bars in two projects through coring.

Traffic control and safety were also carefully coordinated for each project demonstration.

Figure 2. Hands-on Training in Lynchburg

Magnetic Tomography Technology and the MIT Scan-2[6]

Magnetic pulse-induction along with tomography is used to detect dowel bar location and orientation. The testing device emits a weak pulsating magnetic signal and measures the transient magnetic signal induced in the metal bar inside the concrete. Special receivers capable of measuring the response signals with high precision are used in the testing device. A large quantity of data collected within a very short period of exposure to ensure proper mathematical evaluation. Such data redundancy is necessary for evaluation of measurements taken under less than ideal circumstances (e.g., the presence of foreign metal such as tie bar, reflector, etc.). Tomography technology is used to evaluate the field measurements (signals) 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.

MIT developed the MIT Scan-2 for determination of dowel bar orientation in concrete pavement. The device uses magnetic tomography technology as a basis for finding dowel bar orientation. However, when multiple magnetic objects are present, only the overall effects of all objects within the detection range can be measured. Such an inability to separately detect the response signal of individual objects greatly complicates data analysis. The MIT Scan-2 uses other physical information about the object in question to overcome this limitation. Therefore, calibration and avoidance of interference by foreign metal play a significant role in the testing and data analysis. The use of the redundant data recorded from different positions of multiple sensors and novel filtering techniques are also helpful in data analysis and interpretation.

The MIT Scan-2 is a portable device with plastic guide rails as shown in Figure 3. The large box is the main sensor unit. Attached on the top of the main unit is a small computer that runs testing, stores data and performs field data analysis. The guide rail facilitates precise movement of the unit along the test joint at a constant elevation. The device generates real-time

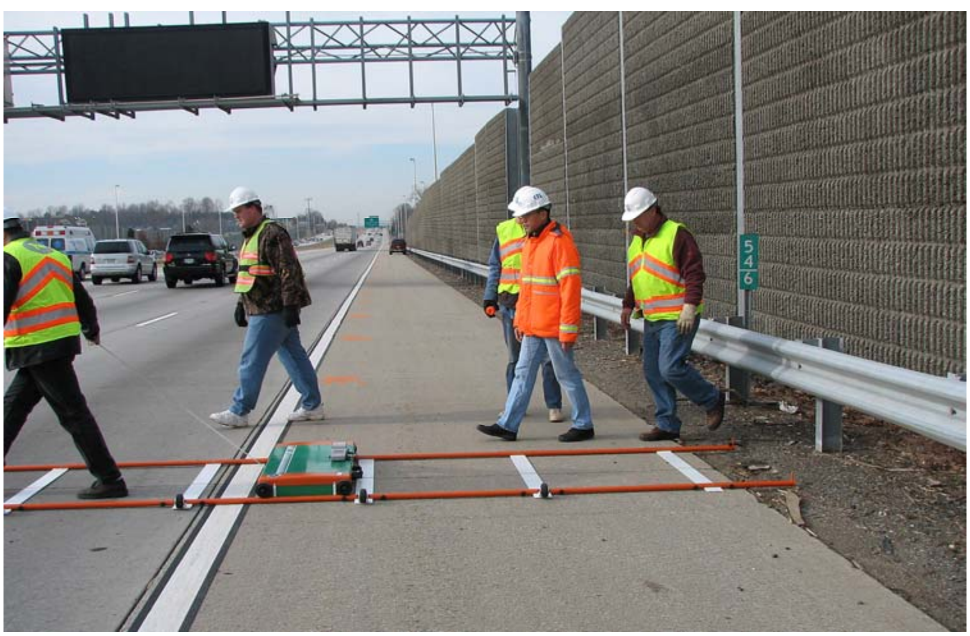

Figure 3. MIT Scan-2 with Track Rails

results in the field as it scans the joints. The operation is simple and efficient. It is claimed that more than 200 joints (about 2 min per joint) could be scanned in an 8-hour day and up to three lanes can be covered in one pass.

Each MIT Scan-2 is individually calibrated to each type of dowel 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 bar type is a required input during testing, and it is important to specify the correct bar type to obtain meaningful results. Both calibration and input requirements for bar types include following variables:

1. bar material (steel vs. stainless steel)
2. bar diameter
3. bar length
4. basket geometry
5. diameter of basket wire.

The cost of calibration for each type of bar or basket is about $1,000. The device came with factory calibrations for the following common U.S. bar types.

1. No. 5 tie bar, 16 mm (5/8 in)
2. 457 x 32 mm dowel bar (18 x 1 1/4 in)
3. 457 x 35 mm dowel bar (18 x 1 3/8 in)
4. 457 x 38 mm dowel bar (18 x 1 ½ in).

Although the research team had planned on using the device for dowels on a basket, there was no basket type-specific calibration available for the machine used for the demonstration. The lack of basket type-specific calibration might have influenced the accuracy of the results, but good results were obtained for baskets with cut shipping wire.

Project Selection

Five projects were selected for demonstration of the MIT Scan-2. The selection was based on different criteria that usually influence the dowel bar orientation in a concrete pavement. A dowel bar could be placed using a wire basket prior to the casting of concrete or it could be inserted using mechanical DBI during the casting. Three JPCP projects in Virginia, I-66, I-64, and US 460, were selected to represent both techniques of dowel construction. The selection of these three projects covered a wide range of traffic types. Two additional projects were selected to try the device in two special circumstances for which the device is neither designed nor supposed to be used. The first trial was a CRCP to determine the depth of longitudinal reinforcing steel on I-295 in the Richmond District. The second trial was a jointed reinforced concrete pavement (JRCP) on US 60 in James City County. The selected projects are summarized in Table 1.

Table 1. Projects for Demonstration

Highway	District	Location	Year Constructed	Pavement Type and Thickness (in)	Dowel Feature	Date Tested
I -64	Hampton Roads	Eastbound HOV lane in City of Chesapeake	1997	JPCP, 9.0	Basket	12/14/05
I-66	NOVA	Westbound between US 50 and VA 28 in Fairfax County	1995	JPCP, 11.0	Basket for shoulder and DBI[b] for main lanes	12/28/05
US 460	Lynchburg	Eastbound Appomattox Bypass between VA 26 and VA 24	1993-94	JPCP, 9.0	Basket	01/09/06
US 60	Hampton Roads	Eastbound at east county line of James City County	1948	JRCP, 9.0	Unknown	12/13/05
I-295	Richmond	Southbound south of US 60 in Henrico County	1987	CRCP, 9.0	Continuous longitudinal reinforcement with no transverse steel	12/20/05

[a]JPCP = Jointed plain concrete pavement; DBI = dowel bar inserter (mechanically inserted dowel), JRCP = jointed reinforced concrete pavement, CRCP = continuously reinforced concrete pavement.
1 in = 25.4 mm.

RESULTS AND DISCUSSION

Field Demonstration and Safety

A field demonstration was performed in all five project locations. VDOT engineers and managers were invited to observe the demonstration. Figure 3 shows the demonstration on I-66. Since all of the demonstration projects were on existing pavements, traffic control was a challenge. Although complete lane closure was preferred, rolling traffic control and limited lane closure were used successfully. There was no injury reported, and there was minor plastic track rail damage in one location.

The demonstration team preferred the following traffic control settings:

1. crash cushion in close proximity (7.5 to15 m [25 to 50 ft])
2. no bend or curve that obstructs the long view
3. at least partial traffic control over the passing lane.

Although it was possible to finish about 100 joints in half a day, the long walking distances and resetting of the rail for every joint was tedious. The pilot demonstration in the Lynchburg District seemed adequate for training purposes and subsequent operation during the full demonstration.

Data Interpretation and Analysis

Field Data Analysis

A computer program called MagnoNorm was internally used to analyze the field data in real time. Real-time test results were available in the field from the computer, the MIT IT-2000, attached to the machine. This text file provides information on the number of dowel bars, location of the bar with respect to the edge, depth of the bar, longitudinal side shift, horizontal misalignment, vertical misalignment, and bar spacing. The measurements are referenced at the center of the dowel bar. Some measurements could be either positive or negative depending on the convention used. A bar shifted further across the joint in the direction to the right of the scanning direction represents a positive side shift. Both vertical and horizontal misalignments are positive for clockwise rotation. A typical field result is shown in Figure 4.

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email : mit@mit.tz-dd.de
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Date + Time          : 14/12/2005  10:55
File g:\05_12_14\14121055.hdf
-----------------------------------------------
Highway              : US 64
Direction            : E
Station No.          : 0 + 56
Joint                : 8
Lane                 : Lane 4
Bar type             : 454 x  38mm
Bar spacing          : 300 mm
Concrete thickness   : 230 mm
-----------------------------------------------
```

Bar No.	x-Location mm	Depth mm	Side Shift mm	Misalignm. hor. mm	Misalignm. vert. mm	Bar Space mm
1	86	139	2	10	5	86 D
2	395	142	5	10	2	309 D
3	705	141	3	12	6	310 D
4	1011	144	3	8	-1	306 D
5	1320	144	2	8	2	309 D
6	1622	145	2	10	-5	302 D
7	1903	142	0	-1	6	281 D
8	2210	144	-0	-3	1	307 D
9	2517	140	1	-2	14	307 D
10	2820	142	0	4	4	303 D
11	3130	142	2	1	7	310 D

Figure 4. Typical Field Text Output (for Joint 8 on I-64)

During the demonstration, field analysis results were obtained for most of the tested joints, but there were some cases where it was not possible, especially with a high level of signal interference or in cases where actual bar positions were significantly different from expected positions. There were several reasons for signal interference. The most prevalent observed during the demonstration were metal reflectors, tie bars, uncut shipping wire dowel baskets, and broken dowel insulations. In most cases of signal interference or excessive misalignment, the program results, if any, were unreliable. In this situation, the topographic map of the signal is useful in investigating the causes of interference and respective interpretation of data. The field computer program MagnoNorm is capable of providing such information in real time. An investigation[7] by FHWA found that field data analysis is accurate for the following conditions:

1. dowel depth 150 ± 40 mm (4.3 to 7.5 in)
2. horizontal or vertical misalignment of ±40 mm (1.6 in)
3. side shift of a maximum of 80 mm (3.2 in).

Laboratory Data Analysis

MagnoProof is another computer program developed by MIT to analyze the field measurement data at a later time in the office (laboratory), and it is supposed to provide results with a higher accuracy than with field analysis. Because of the use in an office environment, MagnoProof uses a higher computing power to optimize the bar positions in a situation where high signal interference or excessive misalignment is present. This program allows the user to correct some of the information used in the field such as dowel bar type and location information. Accordingly, it uses proper calibration factors to recalculate dowel bar positions. The biggest advantage of this program is a high-quality graphical output. It is easier to identify the areas of signal interference and excessive misalignment from this graphical output. The program also allows the user to select an evaluation area to interpret the results in the following complicated measurement situations:

1. excessive misalignment of one or more bars
2. influence of foreign metal objects in the evaluation zone
3. if the measurement starts or ends right above a dowel bar (partial scan of a bar).

Although the selection of evaluation area during the analysis provides a useful tool to interpret the data, it can easily create misleading information since it ignores the surrounding area without being able to separate the influences of signals from surrounding metals.

The measurements from the field demonstrations were later analyzed using MagnoProof with a corrected bar type as the information became available. Figure 5 is the graphical output from the demonstration on I-64 for Joint 8, the same joint as for the field output in Figure 4. The original output is in color, which makes it easier to visualize the locations of the bars. The contour map on the left shows the signal intensity for each dowel bar, and it obviously identifies the presence of a bar by the high intensity of signal. The second column shows the actual position of the dowel, the thick gray line, in plan view with respect to the expected position as marked by a box.

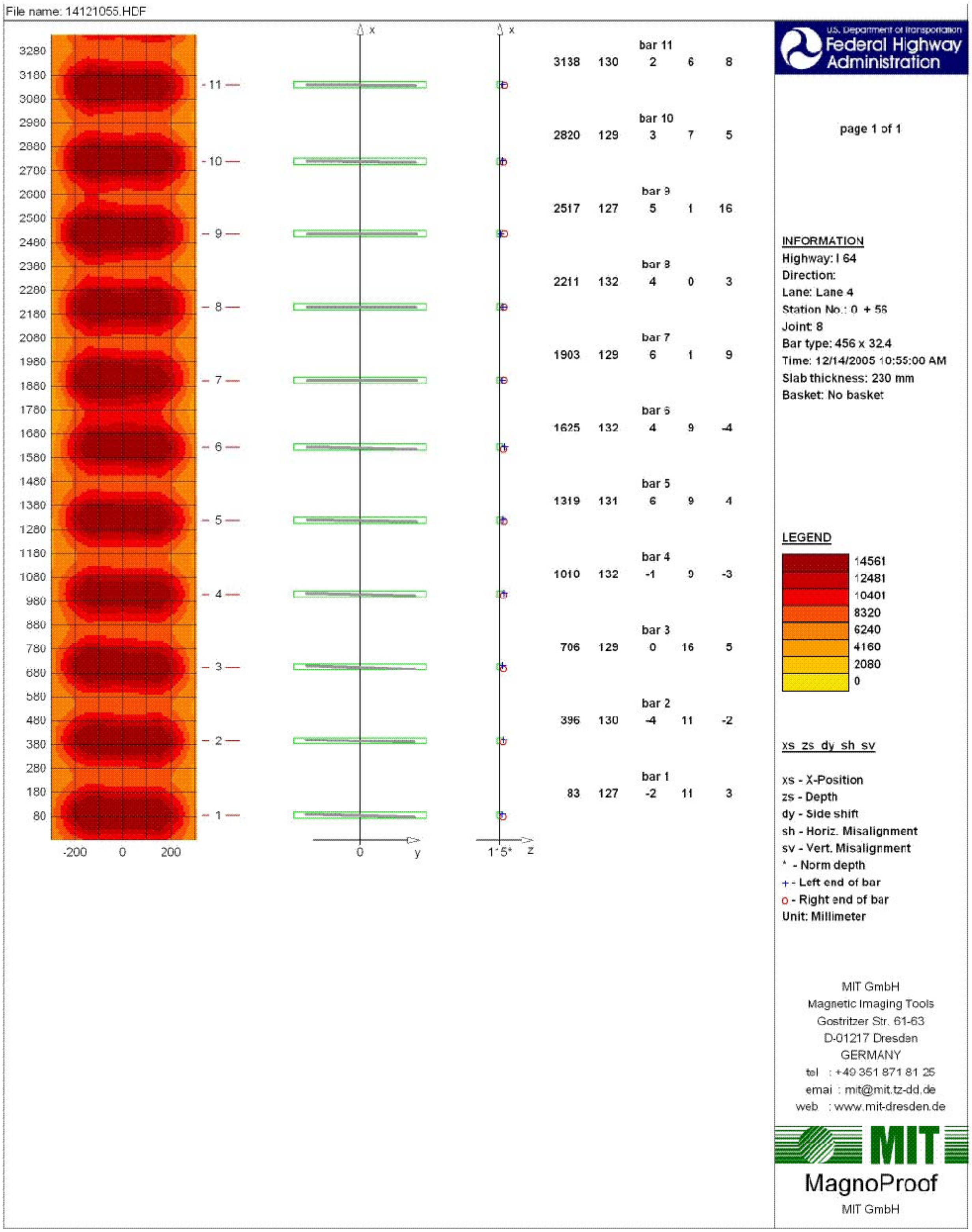

Figure 5. Typical Graphical Output from Laboratory Analysis of Joint 8 on I-64

The third column shows the elevation of the two ends of the bar with respect to the mid-depth of the slab. The text description of these measurements is included on the same output. For example, the following are the measurements for Bar 4:

1. X-position = 1010 mm (398 in) indicates that the location of Bar 4 is 1010 mm (398 in) from the start point of the scan (i.e., the edge of the pavement); it is the point where the actual bar intersects the transverse joint

2. Depth = 132 mm (5.2 in) from the concrete surface

3. Side shift = –1 mm (0.04 in), middle of the dowel bar is 1 mm (0.04 in) left of the transverse joint (positive value indicates the shift is on the right of the joint)

4. Horizontal misalignment = 9 mm (0.35 in) means Bar 4 is skewed 9 mm (0.35 in) from one end to the other in a plan view (clockwise is positive)

5. Vertical misalignment = –3 mm (0.12 in), elevation of right end is 3 mm (0.12 in) higher than left end (positive would indicate right end is lower than the left).

During the analysis of the data from the field demonstration of projects on I-64, I-66, and US 460, several difficulties were encountered. Most of these difficulties were the direct results of signal interference and excessive misalignment, as mentioned previously. Although such difficulties are acknowledged by FHWA and/ or MIT, some of the actual situations are discussed here.

Results from I-64

The dowels on I-64, as mentioned earlier, were placed on wire baskets. From the well-defined contour map, it seemed that shipping wires for the dowel baskets were cut before paving for all joints. During the field measurement, the wrong-size dowel bar (38 mm, 1.50 in) was used as an input on the MIT Scan-2, but it was later corrected (32 mm, 1.25 in) for laboratory analysis. This correction resulted in a significantly shallower (about 10 mm) depth for all bars, as shown in Figure 6. Another interesting observation in Figure 6 is the influence of a foreign metal on Bar 4. Although the signal contour map is clearly showing the presence of a foreign metal near Bar 4, there is no evidence in the field results (output). A total of 82 joints were scanned on I-64, and only 2 joints (Joints 58 and 80) did not produce meaningful results: 97.6 percent of joints provided useful information. Although Joint 58 gave a printout (text file) in the field showing the presence of only a few bars, further analysis with MagnoProof was inconclusive. A device error was suspected for both of these cases.

Results from I-66

Scanning on I-66 was one of the most difficult operations in terms of both traffic control and data analysis. Difficulties were encountered in analyzing data in both the field and the office for several reasons. It was possible to scan up to only 57 joints; then, the machine started malfunctioning. For the first 20 joints, only the outer travel lane was scanned, but for the

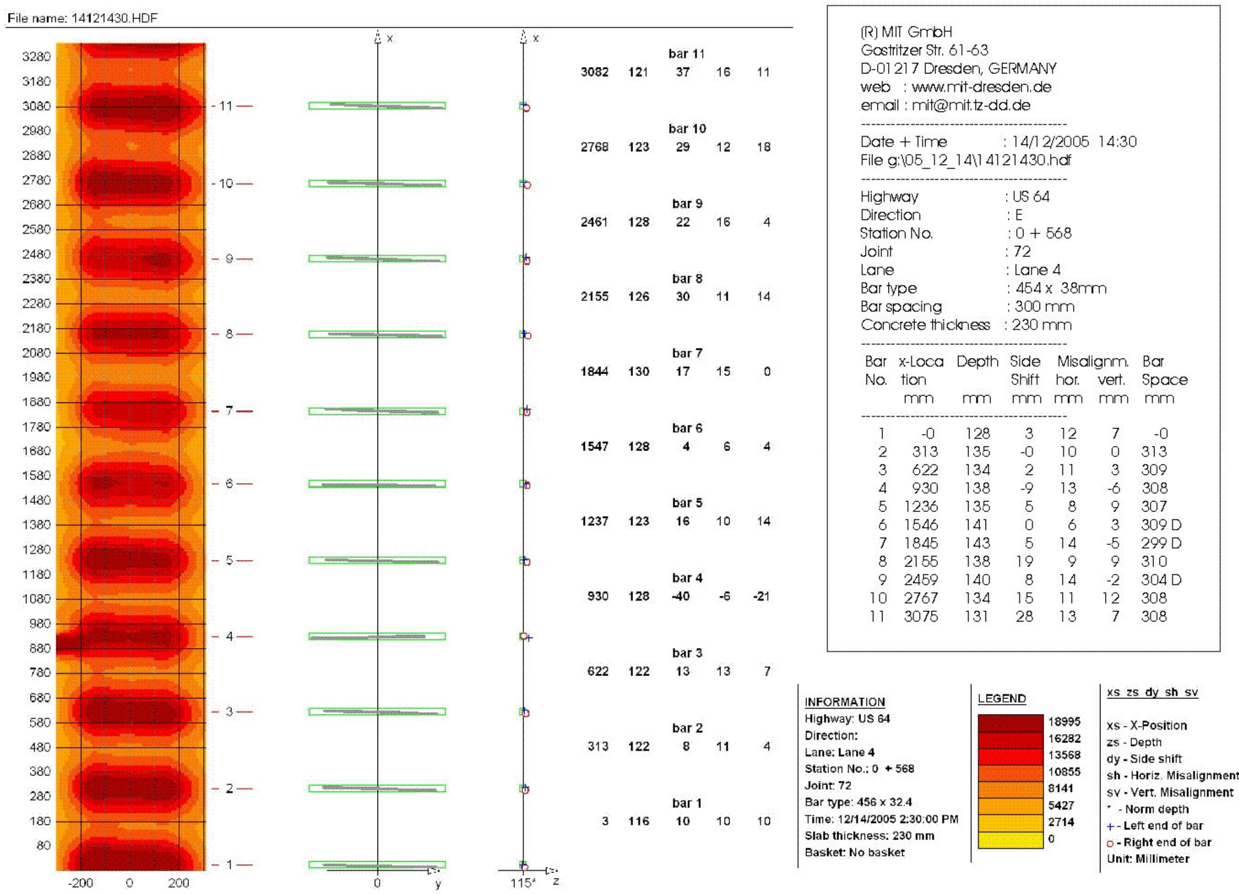

Figure 6. Comparison of Field and Laboratory Data Analysis (Joint 72 on I-64)

remainder of the joints, both the shoulder and travel lane were scanned together in one pass. This created an unusual circumstance for the MIT Scan-2. The dowel basket was used in the shoulder lane, whereas bars in the travel lane were inserted mechanically using a DBI. Despite this situation, MagnoNorm was able to complete the data analysis for all but 5 of the joints. It was also not possible to complete data analysis using MagnoProof for any of these 5 joints. MagnoProof was also unable to complete the data analysis for 15 more joints. Of all the problem joints on I-66, only 3 were from the first 20 joints scanned, in only the travel lane. Some of the reasons for the inability to analyze the data are discussed here.

Joint 54 on I-66 had an exposed dowel bar near the left wheel path of the travel (outermost) lane. During the scan, MagnoNorm was unable to complete the analysis and no field results were obtained. Therefore, MagnoProof was used to analyze the data, and the bar locations were found as shown in Figure 7. There were 11 bars, and all of them show excessive misalignment. The exposed dowel is identified as Bar 10 with the "splotch" between 2880 and 2960 (blue in color) on the exposed side. The depths for all bars were shallow and vary from 75 to 125 mm (3.0 to 4.9 in). The side shifts were also excessive, with a range of 69 to 155 mm (2.7 to 6.1 in). Again, both the vertical and horizontal misalignments were excessive, with a value as high as 87 mm (3.4 in). So there were obvious reasons for the device not being able to accomplish data analysis in the field. Although MagnoProof, with the higher computing power, was able to provide a qualitative picture of the dowel bar locations, the results might still be

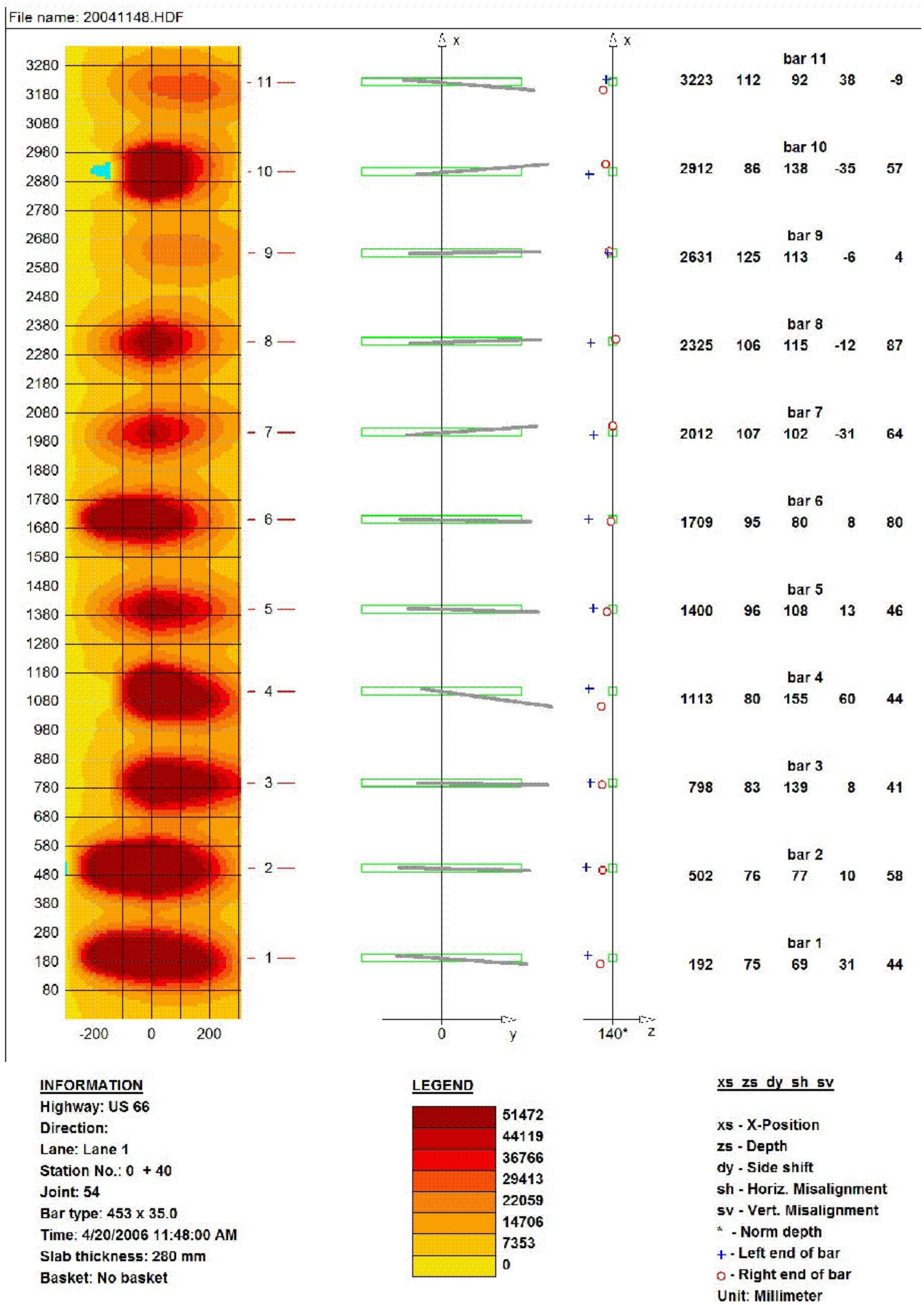

Figure 7. Results from Joint 54 on I-66

unreliable. It is important to note that dowels were mechanically inserted for this section of highway. Field verification was planned for this location and is discussed later in the report.

Another joint (Joint 16) on I-66 had dowel bars too deep into the concrete. An example of the field output, shown in Figure 8, was obtained for this joint, and all 11 bars in the outmost travel lane were found to be deeper than 200 mm (8 in). These bars were also mechanically inserted using the DBI. Further analysis with MagnoProof revealed similar depths but showed a significant instability of the results leading to a completely different output with each successive run of the program. For many occurrences, it was not even possible to complete the analysis because of floating point over flow error; in one run, it showed only a few bars. Results are presented in Figure 9 from one successful run. Again, all bars except one are deeper than 200 mm (8 in). The data from this joint were unreliable and did not allow analysis because of the depth of the bars.

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Date + Time : 28/12/2005 10:14
File g:\05_12_28\D2810141.hdf

Highway : IS 66
Direction : W
Station No. : 0 + 75
Joint : 16
Lane : Lane 1
Bar type : 453 x 35mm
Bar spacing : 150 mm
Concrete thickness : 225 mm

Bar No.	x-Location mm	Depth mm	Side Shift mm	Misalignm. hor. mm	Misalignm. vert. mm	Bar Space mm
1	51	232	33	-35	20	51 DH
2	410	238	32	-30	16	359 DSHV
3	726	240	40	34	30	316 DSHV
4	1029	240	40	14	30	302 DV
5	1336	240	50	3	50	307 DV
6	1645	231	33	14	22	309 D
7	1950	226	39	8	26	305 DV
8	2254	221	45	16	27	304 DV
9	2558	218	49	12	40	304 DV
10	2866	215	34	19	18	307 D
11	3182	209	42	13	51	316 DV

Figure 8. Field Data Analysis Results for Joint 16 on I-66

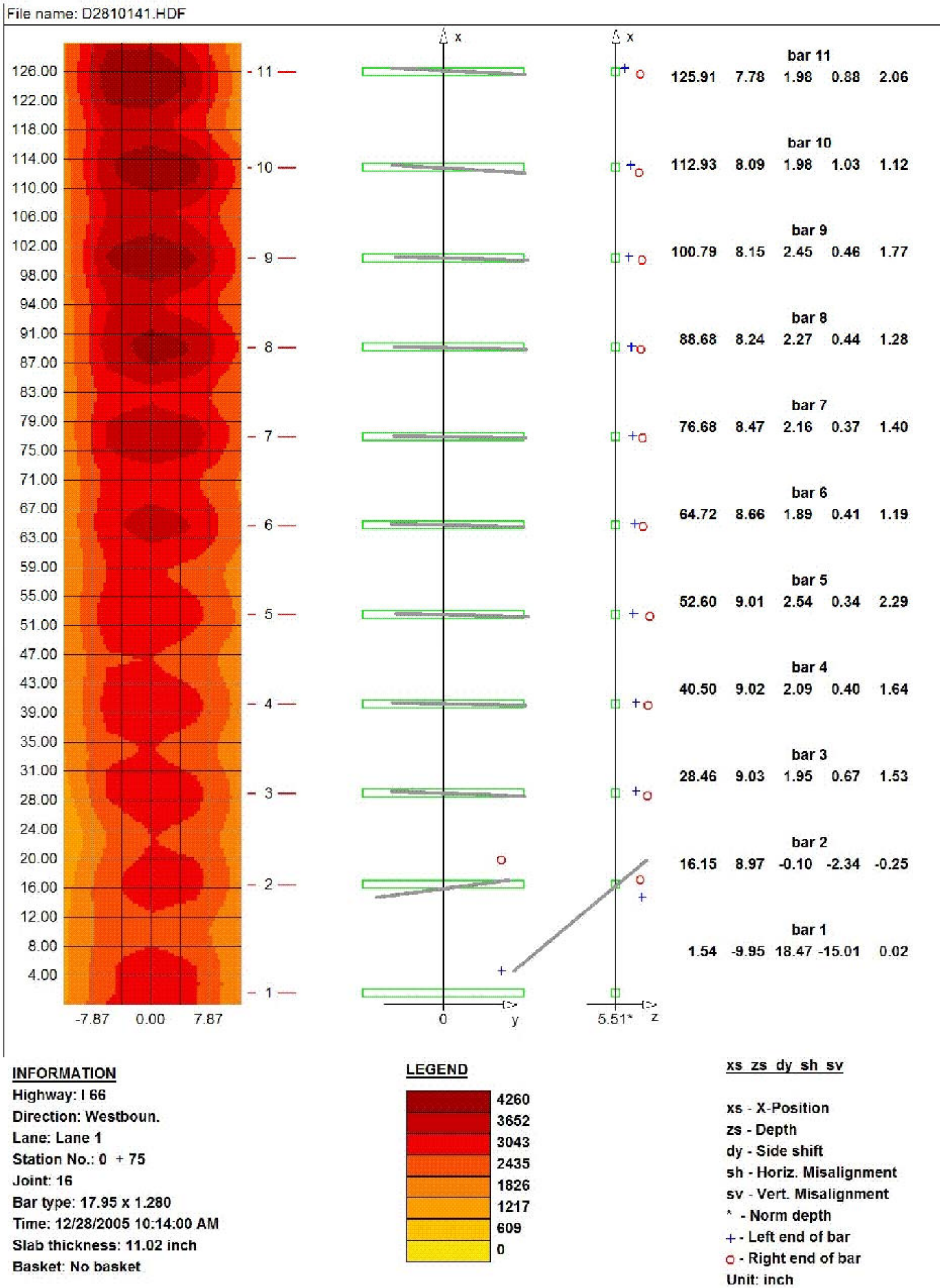

Figure 9. Laboratory Data Analysis Results for Joint 16 on I-66

As discussed previously, signal interference and excessive misalignment might have been the main reasons for the difficulties in data analysis. Possible explanations based on the comparison of text results from the field and the graphical output from MagnoProof include:

1. There was a strong magnetic signal loop surrounding several bars in the shoulder where dowels were on a basket. One such loop is shown in Figure 10 for Joint 37. Either the shipping wire was not cut or the epoxy insulation on the dowel itself might have been broken/abraded. When bars are too shallow and closely spaced, similar loops may be shown.

2. The dowel bars near the left wheel path of the outer travel lane are too deep and have excessive side shift. Although it was possible to scan most joints successfully, this trend was evident for many joints.

3. The end bars were only partially scanned.

4. Foreign metal was present in one or two cases.

5. For one joint, one dowel bar was exposed and several others were severely misaligned along with being at a low depth (<100 mm, < 4 in).

6. For one joint, (Joint 16), all the bars were deeper than 200 mm (8 in).

In addition, signal looping was evident in 13 joints in the shoulder. Although data analysis was possible for all of them, the results were unstable (changing values) with every run of the program, especially near the loop.

Results for US Route 460

Approximately 150 joints were scanned on US 460, but not a single text file was produced for this project. There were no apparent reasons for this other than the equipment was not set up to obtain field analysis results. Although it was possible to analyze most of the joints using MagnoProof later in the office, more than 50 percent of the joints (81 joints) showed signal interference in one way or another. In most cases, it was suspected that the dowel basket shipping wire was not cut or the epoxy coating of the bar was broken/abraded. In other cases, foreign metal such as a reflector or tie bar was present. Despite signal interference, only 3 joints had problems with a floating point overflow and did not allow completion of the analysis. MagnoProof was able to complete the analysis for rest of the problem joints, but the results were unstable and had a high standard deviation for all three sensors. Field verification was also planned for this project and is discussed later.

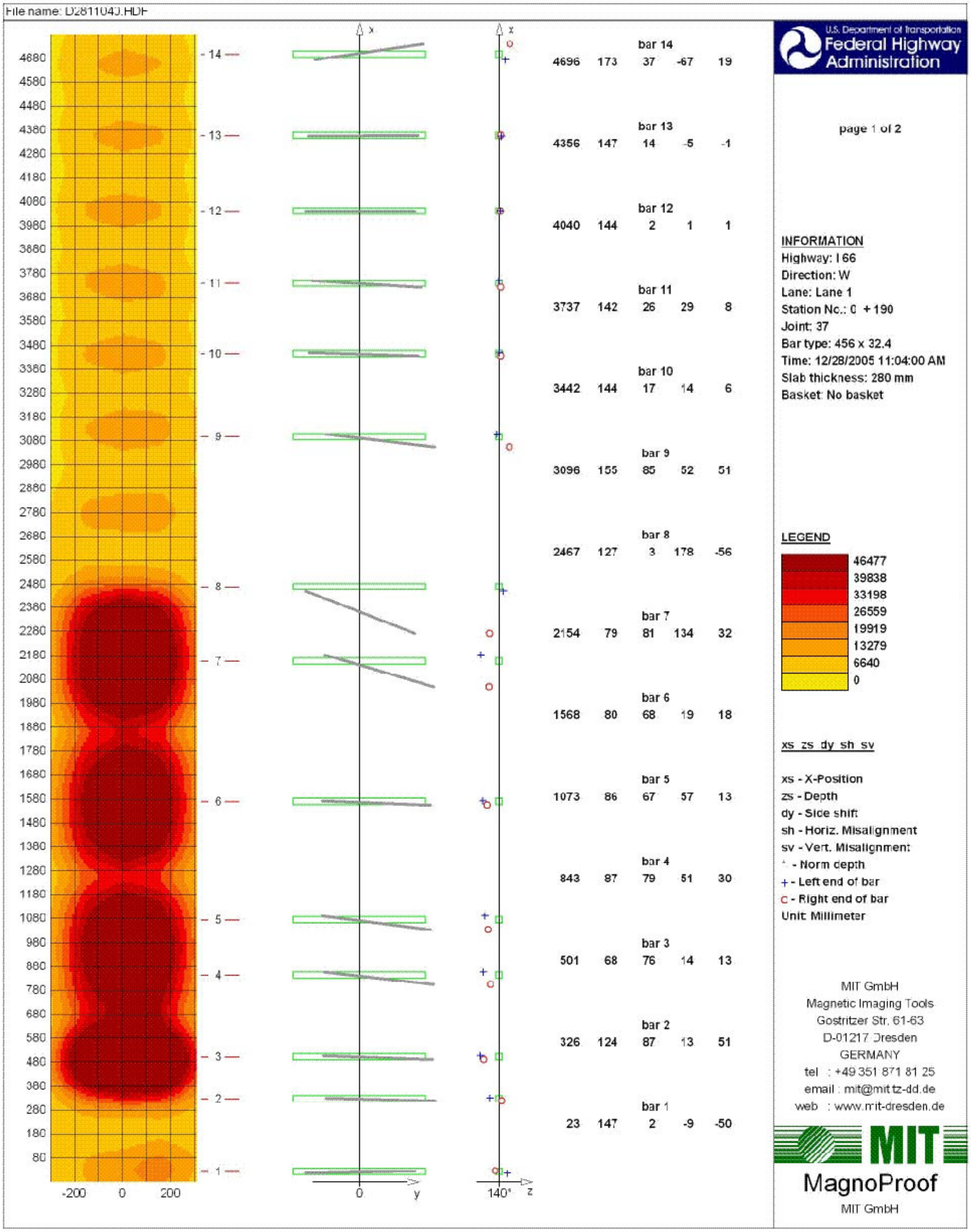

Figure 10. Signal Looping for Joint 37 on I-66

Field Verification

A field verification of the actual dowel bar locations through coring was planned for a few dowel bars after the initial analysis of the results. The Northern Virginia and Lynchburg districts volunteered to core their respective projects on I-66 and US 460. This provided the opportunity to verify dowels locations for both types of construction: DBI and dowels on basket. Three bars were selected on US 460 at joint locations 18, 37, and 72 on the travel lane, one bar from each joint. On the other hand, six bars were selected on I-66, three from the shoulder with the dowels on basket and three from the travel lane with the DBI. Table 2 summarizes the location of the nine bars selected for coring.

It was planned to core the two ends of dowel bar to physically locate its position. Although we had scanned results from earlier tests, a fresh scan was performed right before coring to confirm the location of target bar. The dowel bar location was marked on the pavement based on this scan results before actual coring as shown in Figure 11 for Joint 21 on I-66. The coring operation on I-66 near Joint 54 on the travel lane is shown in Figure 12. The concrete pavement was cored about half an in into the dowel bar in order to confirm the location and facilitate the subsequent measurements. The pulled out core and dowel bar inside the bore hole is shown in Figure 13 for Joint 43 on I-66. The measurements of depth and end locations were taken in the field to verify scanned results of bar location. Dowel bar orientations were recreated in the laboratory from such measurements and actual cores. The dowel bar orientation in Figure 14 was recreated in the laboratory for bar 9 of Joint 21 on I-66 travel lane. An actual dowel bar of the same size as in the field was used to recreate the bar orientation.

Four sets of results are available for each dowel bar and are presented in Tables 3, 4, and 5 for US 460, the I-66 travel lane, and the I-66 shoulder, respectively. The deviations presented represent the difference between laboratory-recreated measures and MagnoProof results from in-office analysis. Both results are thought to be more reliable in their category.

Of these nine bars, only one bar did not have any signal interference: Bar 9 of Joint 21 on the I-66 travel lane (Table 4). The location of this bar was about 12.5 mm (0.5 in) off the actual location. The distance measurements in the field might have contributed to this error. All other parameters were within 10 mm (0.4 in), with a range of 1.0 to 9.5 mm (0.04 to 0.37 in).

Table 2. Dowel Bar Locations for Field Coring

Project	Lane	Joint No.	Bar No.[a]	Remarks
I-66 Westbound	Travel (DBI)	21	9	Drilled through dowel bar
		43	7	
		54	10	One core because of exposed edge
	Shoulder (Basket)	21	7	
		42	3	
		54	2	
US 460 Eastbound	Travel (Basket)	18	10	
		37	6	
		72	2	

[a]Bars were numbered from the right edge.

Figure 11. Field Marking of Dowel Bar Near Joint 21 on I-66

Figure 12. Field Coring Operation Near Joint 54 on I-66

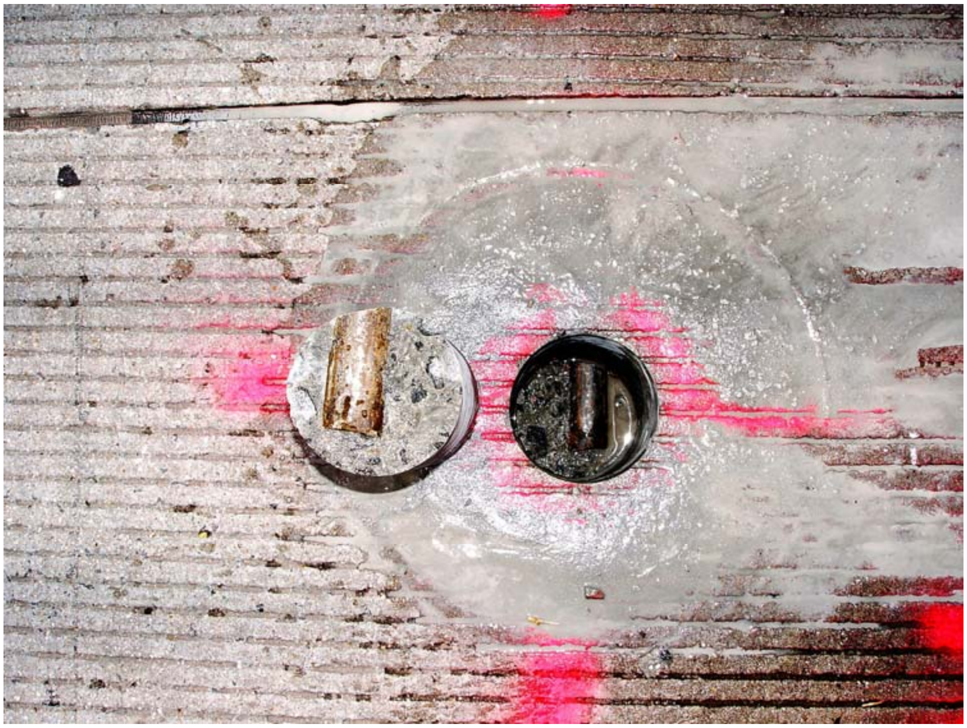

Figure 13. Field Core and Dowel Bar Near Joint 43 on I-66

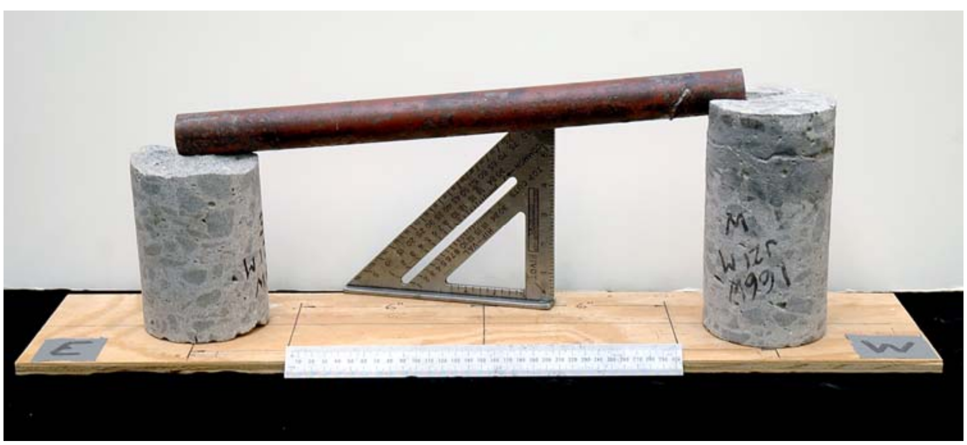

Figure 14. Laboratory Recreation of Dowel Bar Orientation for Dowel 9 of Joint 21 on I-66

Table 3. Actual Dowel Bar Orientation Compared to Scanned Measurements on US 460

Joint/Bar	Measurements (mm)	Scanned Results in Field	Actual Field Measurements	Laboratory-Recreated Measurements	Scanned Results in Office Analysis	Deviations mm	Remarks (comments)
Joint:18 Dowel: 10	X-location	2853.0	2879.0	2879.5	2852.0	27.5	Presence of reflector at beginning
	Depth	109.0	92.5	109.5	109.0	0.5	
	Side Shift	-1.0	11.0 (?)	2.5	-1.0	3.5	
	Horizontal Misalignment	-5.0	N/A	-4.5	-7.0	2.5	
	Vertical Misalignment	-7.0	-5.0	-7.0	-7.0	0.0	
Joint: 37 Dowel: 6	X-location	1647.0	1659.5	1659.0	1639.0	20.0	Unreliable results due to uncut basket throughout joint
	Depth	76.0	99.0	103.0	84.0	19.0	
	Side Shift	-39.0	-16.0	-11.0	-38.0	27.0	
	Horizontal Misalignment	-3.0	N/A	-6.0	-4.0	2.0	
	Vertical Misalignment	-6.0	-2.0	0.0	-7.0	7.0	
Joint: 72 Dowel: 2	X-location	454.0	462.0	459.0	455.0	4.0	Foreign metal influenced result near first and second bars
	Depth	130.0	126.0	123.0	139.0	16.0	
	Side Shift	8.0	29.0	23.5	5.0	18.5	
	Horizontal Misalignment	-13.0	N/A	-13.5	-17.0	3.5	
	Vertical Misalignment	-3.0	-2.0	0.0	-7.0	7.0	

Table 4. Actual Dowel Bar Orientation Compared to Scanned Measurements on I-66 Travel Lane

Joint/Bar	Measurements (mm)	Scanned Results in Field[a]	Actual Field Measurements	Laboratory-Recreated Measurements	Scanned Results in Office Analysis	Deviations (mm)	Remarks (comments)
Joint: 21 Dowel: 9	X-location	2660.0	N/A[b]	2647.5	2660.0	12.5	Perfect joint for scanning machine
	Depth	169.0	N/A[b]	174.0	180.0	6.0	
	Side Shift	-13.0	N/A[b]	-18.5	-9.0	9.5	
	Horizontal Misalignment	-13.0	N/A[b]	-15.0	-14.0	1.0	
	Vertical Misalignment	37.0	N/A[b]	39.0	43.0	4.0	
Joint: 43 Dowel: 7	X-location	2011.0	1994.0	1993.5	2012.0	18.5	Last few bars too deep, greater than 200 mm. This influenced results.
	Depth	161.0	149.0	167.5	172.0	4.5	
	Side Shift	-29.0	-32.0	-36.0	-21.0	15.0	
	Horizontal Misalignment	7.0	2.0	0.0	5.0	5.0	
	Vertical Misalignment	2.0	0.0	0.5	6.0	5.5	
Joint: 54 Dowel: 10	X-location	N/A[c]	2928.0	2928.0	2912.0	16.0	Exposed bar at one end and excessive misalignments resulted in unreliable results.
	Depth	N/A[c]	92.5	82.5	86.0	3.5	
	Side Shift	N/A[c]	N/A	161.0	143.0	18.0	
	Horizontal Misalignment	N/A[c]	-4.0		-37.0		
	Vertical Misalignment	N/A[c]	150.0	165.0	56.0	109.0	

[a]Incorrect bar size was used in the field (32 mm instead of 35 mm).
[b]Drilled through the bar, so no measurements could be taken.
[c]Device could not complete field analysis because of exposed bar.

Table 5. Actual Dowel Bar Orientation Compared to Scanned Measurements on I-66 Shoulder.

Joint/Bar	Measurements (mm)	Scanned Results in Field [a]	Actual Field Measurements	Laboratory-Recreated Measurements	Scanned Results in Office Analysis	Deviations (mm)	Remarks (comments)
Joint: 21 Dowel: 7	X-location	2310.0	2291.0	2292.5	2331.0	38.5	Dowel 7 was in middle of signal loop due to uncut basket.
	Depth	87.0	132.5	132.5	99.0	33.5	
	Side Shift	44.0	16.5	16.0	43.0	27	
	Horizontal Misalignment	5.0	4.0	4.5	3.0	1.5	
	Vertical Misalignment	9.0	-4.0	-9.0	10.0	19.0	
Joint: 42 Dowel: 3	X-location	768.0	752.5	757.0	767.0	10.0	Signal loop due to uncut basket is away from Dowel 3, so results are reasonable.
	Depth	149.0	154.0	155.5	159.0	3.5	
	Side Shift	4.0	3.0	-1.5	3.0	4.5	
	Horizontal Misalignment	1.0	3.0	-1.5	-1.0	0.5	
	Vertical Misalignment	2.0	3.0	-1.0	0.0	1.0	
Joint: 54 Dowel: 2	X-location	475.0	464.5	461.0	476.0	15.0	Signal loop due to uncut basket is away from Dowel 3, so results are reasonable.
	Depth	131.0	135.0	136.5	140.0	3.5	
	Side Shift	-15.0	-10.0	-12.0	-12.0	0.0	
	Horizontal Misalignment	10.0	5.0	3.0	7.0	4.0	
	Vertical Misalignment	-13.0	-5.0	-11.0	-14.0	3.0	

[a] Incorrect bar size was used in the field (32 mm instead of 35 mm).

No deviation was more than 40 mm (1.6 in), except the vertical misalignment for Bar 10 of Joint 54 on I-66. This bar has an exposed (visible) end at the joint, excessive side shift, and excessive vertical misalignment, which are all good reasons for unreliable results. An exposed dowel bar should be alarming to the engineer without the need for a scanning device.

The measurements on Bar 10 of Joint 18 on US 460 had very close agreement (within 5 mm or 0.2 in) for all parameters except x-location (27.5 mm or 1.1 in). The influence of the reflector was confined at the beginning of the scan near the second bar and did not influence Bar 10 significantly. Similarly, the influence of foreign metal near Dowel 2 of Joint 72 on US 460 was not very great, and the observed deviations were within 20 mm (0.8 in). The deviation for Bar 7 of Joint 43 on I-66 was also within 20 mm (0.8 in), and a few bars toward the end of the joint that were 8 in deep might have influenced the results. All other bars (37/6 on US 460, 21/7 on I-66, 42/3 on I-66, and 54/2 on I-66) were influenced by signal loops, which might have been created by either an uncut basket or broken/abraded insulation of the dowel bar. Bar 7 of Joint 21 and Bar 6 of Joint 37 were in the middle of the loop and showed a deviation as high as 39 mm (1.5 in), indicating a high level of unreliability of the result. The other two bars (Bar 3 of Joint 42 and Bar 2 of Joint 54) were outside the signal loop area and had a low deviation of within 5 mm (0.2 in) for all parameter except the x-locations of 10 and 15 mm (0.4 and 0.6 in) for the respective joints.

According to an FHWA study,[6] the MIT Scan-2 provides an accuracy of ±5 mm (0.2 in) with 95 percent reliability on horizontal and vertical misalignments as long as no foreign metal object is present within about 1 m (3.3 ft) of bars being scanned and the maximum misalignment is within 40 mm (1.6 in). The accuracy on the lateral bar position (side shift) is ±8 mm (0.3 in) for a maximum side shift of 80 mm (3.1 in). Similarly, the tolerance for depth is ±4 mm (0.16 in) with the range of dowel bar depth between 110 and 190 mm (4.3 and 7.5 in). These observations are somewhat comparable to those in the current study.

Repeatability of Measurements

The repeatability of the measurements was assessed during the demonstration on I-64 in the Hampton Roads District. As mentioned earlier, a dowel basket was used for this JPCP. Three replicate measurements were taken for the first nine joints. After finishing the first set of measurements for the first nine joints, the same crew came back and performed a second set of replicate measurements for the joints. They then started back at the first joint and measured the dowel orientation for a third time. Each joint had 11 dowel bars. None of these joints showed any signal interference from any foreign metal or uncut shipping wire baskets.

A statistical analysis was performed of the collected data, and the results are presented in Table 6. The maximum differences among three measurements for each of the (total 99) bars were calculated; those for 95 are shown in Column 2 of Table 6. The third column shows the arithmetic average of the standard deviations for 99 bars. The standard deviation for each bar was calculated based on three replicate measurements. In addition to the arithmetic average of the standard deviation, a pooled average was calculated and is presented in Column 4. Although the experiment was not designed to calculate the precision statement of the MIT Scan-2, a good estimate based on the pooled standard deviation could be determined. The values in column 5 were calculated as d2s limits (2√2* standard deviation), similar to the precision statement calculations described in ASTM Practice C670.[8] Therefore, the expected difference between two measurements by the same operator at two different settings in the same day are estimated to be 7.9, 1.2, 4.8, 5.7, and 1.4 mm (0.3, 0.05, 0.19, 0.22, and 0.06 in) for x-location, depth, side shift, horizontal misalignment and vertical misalignment, respectively. According to the FHWA study, the estimated overall standard deviation of measurement error is 3 mm (0.12 in), and MIT claims that the variation of repeat measurement is within ±2.0 mm (0.08 in) for measurements with same setting.[6] The dowel bars for the FHWA study were without any basket, whereas this study considered dowels on baskets, which might have added variability but were real measurements in the field.

Since the actual orientations of the bars were not available, it was not possible to estimate any bias in the experiment. The depth and vertical misalignment measurements showed the highest repeatability and lowest variability. The location (x-location) measurements showed the highest variability, and they could easily have been influenced by the reference settings at the beginning of the scan. This observation is supported by the similar difference among the replicate measurements of all bars in a particular joint. Here, *reference setting* means the physical setup of the machine at the start point. The time delay between the start of the computer on the machine and the physical pull of the machine might have also influenced the reference setting.

Joint Performance and Dowel Misalignment

Dowel misalignment may compromise joint performance in terms of loss of load transfer efficiency and premature development of faulting. Pavement damage such as spalling and cracking may also develop because of misalignment. As discussed previously, the MIT Scan-2 can measure dowel orientation with a reasonable degree of accuracy.

Yu[6] developed a joint scoring system to use with MIT Scan-2 results. The joint score reflects the risk of joint locking; the higher the joint score, the higher the risk. The score is a measure of the combined effects of all misaligned dowel bars at a joint. It is determined as a sum of the product of the number of bars at each level of misalignment and the respective weighting factor. There are several weighting factors for different levels of misalignments. Yu also described the idea of using a frequency distribution plot in terms of the percentage of bars in a project at various levels of misalignment to evaluate the overall quality of the dowel bar alignment.

Extended Use of the Technology

As described earlier, the MIT Scan-2 was used on two special projects on US 60 in James City County and I-295 in the Richmond District. I-295 is a CRCP with no transverse steel; the researchers thought finding the depth of reinforcement might be possible. The MIT Scan-2 was used to perform 100 scans at 5-m (or 15-ft) intervals. The calibration for a No. 5 tie bar was used for field data analysis. But there were only a few scans where it was possible to complete the data analysis in the field. Laboratory analysis of the data did not yield any meaningful

Table 6. Repeatability Analysis for I-64 Measurements

Measured Parameter (3 replicate measures on 99 bars)[a]	Maximum Observed Difference (mm) (95% of the time)	Average SD (mm)	Pooled Average SD (mm)	Expected Maximum Difference Between 2 Measurements (mm) at 95% Confidence Level[b]
X-location	8.80	2.46	2.78	7.9
Depth	1.24	0.37	0.41	1.2
Side Shift	5.75	1.35	1.70	4.8
Horizontal Misalignment	6.88	1.64	2.02	5.7
Vertical Misalignment	1.84	0.39	0.50	1.4

[a]Number of joints measured = 9; number of bars per joint = 11; total number of bars with 3 replicate measurements = 99.

[b]These numbers represent the values similar to the d2s limits described in ASTM Practice C670.

results. Although no transverse steel was present, the longitudinal steel bars were too close to each other and to the surface. The reason for the irregular spacing of the reinforcing steel was the use of a feed-tube system to place the steel in the fresh concrete during construction. The bar spacing was about 150 mm (6 in), and the depth was supposed to be about 100 to 125 mm (4 to 5 in). It was obvious from visual observation that in some places, the depth was even shallower than 4 in. Therefore, the enormous signal interference did not allow for meaningful results. The data were later evaluated by MIT. After a careful evaluation of the data, MIT is hopeful that such use could be explored with proper calibration.

The pavement on US 60 is JRCP with wire mesh reinforcement. As expected, the signal interference was so high because of the reinforcement that none of the scanned data could be analyzed. Later it was found that there were no dowels used for any of the joints on this pavement except for a few repaired joints. Again, the interference from the reinforcement did not allow analysis of these joints.

CONCLUSIONS

- *The MIT Scan-2 successfully scanned both basket and DBI dowel bars using bare bar calibration.*

- *The MIT Scan-2 yielded fairly accurate measurements for joints without any interference, and the deviation from the actual orientation was less than 10 mm (0.4 in).* Dowel bars were successfully located. Although the data are quantitatively unreliable for situations where signal interference is possible, a qualitative observation is possible in most cases, at least for the part of the unaffected joint. The real challenge is to find a situation without much signal interference in the field.

- *The repeatability of the measurement by the MIT Scan-2 was very good, with an overall maximum difference of 8 mm (0.3 in) between two replicate measurements.* The maximum difference between two replicate measurements was as low as 2 mm for depth and vertical misalignment measurements. The overall maximum standard deviation of 2.78 mm (0.11 in) is comparable with the FHWA standard deviation of 3 mm (0.12 in).

- *The MIT Scan-2 is very user-friendly.* Although data analysis is more involved, actual field operation is simple and easy to learn. The challenges for field operation are traffic control and the tedious processes of manual setup of the device for every joint.

- *Most complications in the data analysis are due to signal interferences for several reasons, including the following:*

  — signal loop
  — dowels deeper than 200 mm (8 in)
  — exposed dowel bar
  — presence of tie bar or any other foreign metal nearby
  — excessive misalignment in general

— apparent depth of dowels shallower than 100 mm (4 in) in the field results.

- *The close spacing and shallow depth of the reinforcing steel in continuously reinforced concrete pavement made using the MIT Scan-2 to determine the depth of longitudinal reinforcement impossible.*

- *The interference from the reinforcing steel in jointed concrete pavement made using the MIT Scan-2 impossible in such situations.*

RECOMMENDATIONS

1. *VDOT's Asset Management Division or the district pavement management sections should include the collected data and analysis in the respective project data base for future consideration during evaluation and rehabilitation.*

2. *VDOT's Materials Division should consider the MIT Scan-2 a viable technology for construction quality control.* For VDOT to be able to use this technology, the signal interference needs to be minimized. One way to minimize the interference is to establish a practice of cutting the shipping wire for the dowel basket.

3. *VDOT's Materials Division should use this technology in conjunction with other technologies such as the falling weight deflectometer, ground-penetrating radar, and video logging to allow a complete evaluation on the project level and forensic analysis.*

4. *VTRC should conduct further research to establish acceptance criteria for dowel bar misalignment based on measurements using magnetic tomography technology.* The ongoing research in NCHRP Project 10-69, "Guidelines for Dowel Alignment in Concrete Pavements," would greatly complement this demonstration and could lead to VDOT establishing a new specification.

BENEFITS AND COSTS ASSESSMENT

The value of the MIT Scan-2 is in its non-destructive approach and its ability to work on recently placed and hardened JPCP. As a quality assurance tool for new JPCP construction or evaluation for rehabilitation, it can accurately pin point the degree of misalignment. The potential (projected) cost/benefit of using such technology can be demonstrated in the following example, based on traditional experiences with JPCP.

For 1 lane-mile (5,280 ft, 1.61 km), assuming a joint spacing of 15 ft (4.57 m), the number of joints is 352 per mile. If it is assumed that 5 percent of the joints (18 joints) have severe misalignments that were not detected, these joints will eventually be replaced because of locking, spalling, and lack of load transfer efficiency between the jointed concrete slabs. The minimum replaced area of concrete per joint is recommended to be 6 ft by 12 ft (1.83 m by 3.66 m), resulting in 8 yd^2 (6.69 m^2) of concrete placement, leading to a total replacement of 144 yd^2/mile. The cost of joint replacement is estimated at \$300/yd^2, giving a total of \$43,200 per lane-mile. Considering that 50 percent of VDOT's total jointed concrete pavement is estimated at about 300 lane-miles of JPCP, this represents a savings of \$13 million for the entire JPCP system during its service life. If the analysis is repeated assuming only 2.5 percent joint deterioration, the cost savings can be estimated at \$6.5 million for the entire JPCP system. Based on these assumptions, the potential savings can be clearly realized from implementing this new technology. This does not include the user cost, which may also be significant. In addition, capturing the misaligned dowel bars during construction would obligate the contractor to bear the repair cost. Experience has also shown that when VDOT has a quality assurance technology, the contractor's performance improves tremendously, since VDOT can identify the problem early on during construction. This leads to a savings in both time and money.

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