GROUND PENETRATING RADAR (GPR) ANALYSIS: *PHASE II FIELD EVALUATION*

FHWA/MT-11-002/8201-001

Final Report

prepared for
THE STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION

in cooperation with
THE U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

October 2011

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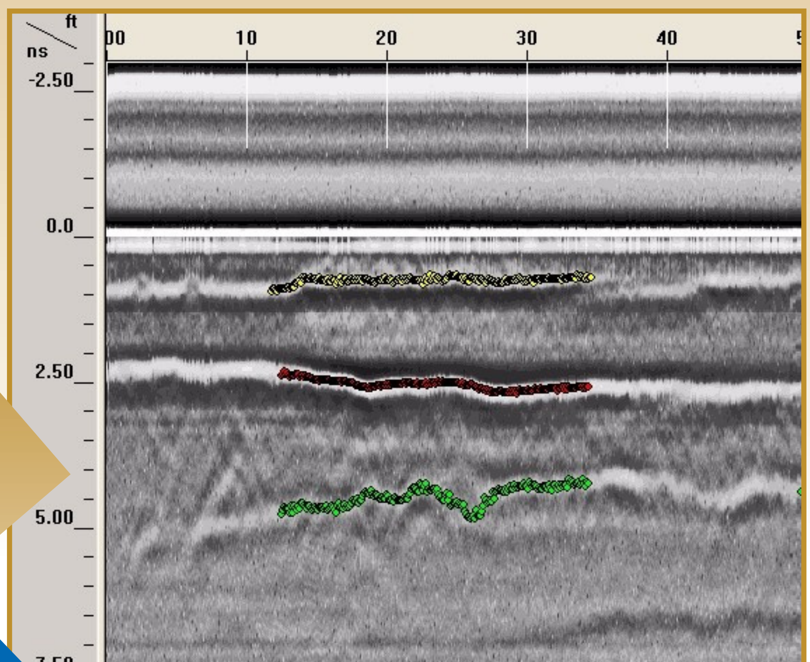

RESEARCH PROGRAMS

MDT

INFRASENSE, Inc.

Ground Penetrating Radar (GPR) Analysis: Phase II Field Evaluation

HWY-308813-RP

Final Report

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16. Abstract

The objective of this work was to evaluate the feasibility and value of expanding the MDT's Ground Penetrating Radar (GPR) program to pavement design and rehabilitation, and to network level evaluation. Phase I of this project concluded that in order to investigate the feasibility and value of these program expansions, a Phase II field evaluation project be designed and implemented to evaluate the accuracy of GPR pavement thickness data on Montana pavements, and to correlate these findings with the accuracy requirements of the individual applications. This field evaluation began with identifying 26 pavement test section of different composition and structure located throughout the diverse climatic regions of Montana. At each site, FWD and GPR data was collected, followed by coring and augering to determine the thickness of the pavement layer structure and base moisture content. This testing was carried out both in the spring of 2010 and in the fall of 2010 to capture seasonal variations. The GPR data was analyzed for thickness, and the GPR thickness data was evaluated for seasonal changes, and compared to core and plan data to investigate thickness accuracy and the effectiveness of calibration methods. Compared to cores, the average GPR bound layer thickness error was 10.3% vs. 15.2% using plan data. A GPR data checking method was developed using FWD and plan data to identify potential analysis layer analysis inconsistencies and suggest alternative interpretation. Implementation of this method reduced the GPR error to 7.6%. A sensitivity study was carried out to investigate the impact of having the more accurate GPR data. This study showed that, on average, the use of GPR reduced the pavement life prediction error by 62% when compared to using as-built plan data.

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1. INTRODUCTION

Since 2006, the Montana Department of Transportation (MDT) has utilized Ground Penetrating Radar (GPR) as a tool for evaluating pavement thickness and layer structure. MDT's implementation of GPR measurements in conjunction with its FWD data collection combines GPR layer thickness data with FWD data for more accurate characterization of pavement structural properties. The objective of the project presented in this report was to assist the MDT in expanding its implementation of GPR technology to a broader range of pavement engineering applications. In order to achieve this objective, it was necessary to understand:

(a) the types of layer structure information that GPR is capable of obtaining;

(b) the level of accuracy associated with this information under different pavement conditions, and expected levels of confidence;

(c) the use of this information in the selection and design of reconstruction and rehabilitation treatments; and

(d) the influence of the expected accuracy on the design and selection of reconstruction and rehabilitation treatments.

Montana's GPR equipment has been in use since 2006, and the state has gained some experience with the use of this technology. The MDT GPR system consists of a GSSI SIR-20 GPR system used in conjunction with a Model 4105 2.0 GHz horn antenna. Montana acquired its GPR equipment as part of a combined FWD/GPR system, and for the most part the GPR system has been used in conjunction with the FWD data collection. The GPR horn antenna is positioned in front of the vehicle, and the FWD is actuated from the rear of the vehicle. The MDT GPR system is shown in Figure 1.

Figure 1. MDT GPR/FWD vehicle (FWD deployed from the rear of the vehicle).

To address MDT's objective, this project has sought to integrate a detailed knowledge of the capabilities and limitations of GPR with the information needs of the MDT. This project has been carried out in two phases.

Phase I of the program included a review of literature and software dealing with pavement applications of GPR, a survey of state highway agency (SHA) use of GPR for pavement applications, a review of MDT's GPR program, and a review of MDT's pavement structures, environment, and pavement management, and rehabilitation practices. A detailed review of 45 documented studies showed that GPR pavement thickness measurements typically fall within 2-10% of core values for the bound layers. Most of these studies have used a 1.0 GHz horn antenna (vs. the 2.0 GHz antenna currently used by MDT). Accuracy of the unbound material is less precisely documented. The survey of SHA GPR practice supports the application of GPR for pavement thickness measurements—some agencies use GPR on a regular basis, while others use GPR on a project-specific basis.

Montana's pavement network is 97% AC, with mostly aggregate base but some areas with cement-treated base. Pavement renewal alternatives include maintenance activities (crack seal, crack seal and cover, and chip seal), minor rehabilitation activities (AC thin overlay, AC thin overlay engineered, and mill, fill, overlay), major rehabilitation activities (cold-in-place recycling and foamed asphalt), and reconstruction. Based on an evaluation of MDT's rehabilitation and reconstruction practices, it appeared that the GPR program can be expanded to provide useful information for the following applications: (a) calculation of structural number for pavement reconstruction and rehabilitation design; (b) insuring proper depth control for mill and fill rehabilitation, and cold in-place recycling; and (c) improved structural capacity calculation for network level evaluation. In order to investigate the feasibility and value of these program expansions, a Phase II field evaluation project was designed and implemented to evaluate the accuracy of GPR pavement thickness (and density) data on Montana pavements, and to correlate these findings with the accuracy requirements of the individual applications.

The objectives of the phase II program were to:

1. Determine, on a statistical basis, the accuracy that can be achieved using the MDT GPR system on typical Montana pavement types for the types of applications being considered.
2. Determine if the addition of a lower frequency antenna could provide accurate base thickness data.
3. Conduct a sensitivity study to evaluate the impact of the GPR data on rehabilitation design.

2. FIELD TESTING

2.1. Test Site Selection and Layout

A field data collection program was designed to generate the data required to support the objectives of this project. This program included GPR data collection, FWD data collection, coring, and auger sampling. The program included a group of 26 test sites, each of which was surveyed with GPR and FWD twice, once in the spring and once in the fall, in order to capture seasonal changes. Pavement thickness ground truth data was collected as part of the both spring and fall collection efforts. In order to investigate the influence of base moisture content on the GPR asphalt thickness measurements, base moisture content measurements were also made as part of the data collection efforts in both the spring and the fall.

Table 1 shows the list of 26 test sites selected by the MDT for this research. The sites were selected to provide a representative sample of pavement structure types and environmental conditions types found in Montana. At each of the sites, a 500-foot section of pavement was delineated for testing, and five ground truth core locations were selected per site. The site length and number of ground truth samples were selected to provide a representative sample of the pavement construction at each site. The site layout and ground truth core test locations are shown schematically in Figure 2. Note that FWD tests were carried out at each ground truth location prior to coring.

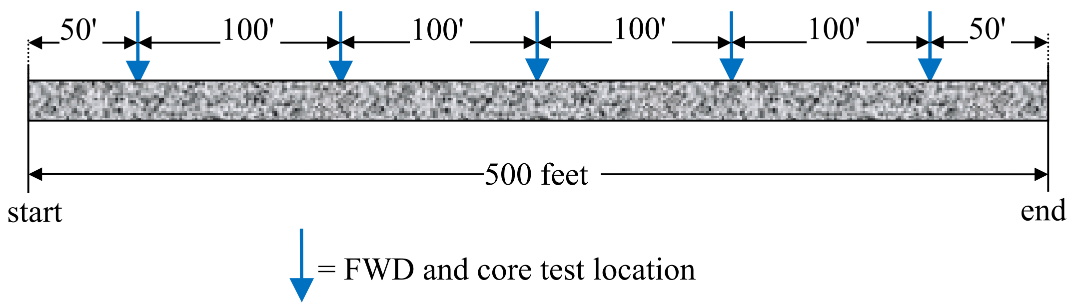


Figure 2. Layout of typical test section.

Figure 2 represents the typical layout for the testing carried out in the spring of 2010. For the testing carried out in the fall of 2010, coring and FWD testing was offset 10 feet up-station from the spring testing locations to avoid the disturbance to the pavement structure caused by the prior coring.

Two of these test sites, No.16 and No.22, served as GPR thickness calibration sites for this project. One core from each of these sites (core 1 at Site 16 and core 2 at Site 22) was used for calibration. These sites were chosen to represent the conditions in the eastern part of the state as well as the Helena area. For this project, these sites were used to provide an initial check of the accuracy of the GPR data analysis software, and to calibrate the processing procedures. Since this testing program provided documented layer thickness values at known locations for these sites, these sites can serve future calibration purposes as well.

Table 1. Test sites and as-built conditions.

Site No.	Site Name	Dir	As-Builts (thickness in inches)									
			PMS		BASE I		BASE II		BASE III		SUBBASE	
			Type	Thick	Type	Thick	Type	Thick	Type	Thick	Type	Thick
01	Dickey Lake – N	NB	PMBS	3.000	CTS	1.80	CBC	15.00				
02	Dickey Lake – S	SB	PMBS	3.000	CTS	1.80	CBC	15.00				
03	Perma Canyon	SB	PMBS	3.480	CTB	3.72	CAC	6.00				
04	Dixon	NB	PMBS	3.000	CTS	1.80	CAC	13.80			A-1-a	24.00
05	Condon	NB	PMBS	8.640	CTS	1.20	PULV	4.80	CAC	4.80		
06	Powell Co Line – N	SB	PMS	3.600	CAC	12.00						
07	Helmville – S	SB	PMS	3.600	CAC	12.00						
08	Helmville Jct – E	EB	PMBS	4.200	PULV/CAC	8.40	A-1-a (0)	7.32				
09	Beck Hill	EB	PMBS	4.320	PULV	8.16	CAC	33.12				
10	Silver City	NB	PMBS	4.920	CAC	6.96						
11	Jefferson City	NB	PMS	9.000	CAC	10.80						
12	Baum Road	WB	PMBS	4.680	CAC	20.52						
13	White Sulphur Springs	EB	PMBS	3.600	CTS	2.40	CAC	11.40				
14	Lothair	WB	PMBS	3.600	CTS	1.8	CAC	12.60			Special Borrow: A-2-4 (0)	24.00
15	Marias River	NB	PMS	4.560	CBC	4.56	PULV/CBC	9.60				
16	Vaughn	NB	PMBS	8.040	CAC	10.08					50% RAP / 50% Recycled Bas	21.12
17	Great Falls – E	NB	PMBS	6.000	PMBB	4.20	CAC	21.00				
18	Geyser	WB	PMBS	4.080	CTB	11.40	CAC	6.00				
19	Stanford	WB	PMSD	7.200	CTS	1.80	CBC	19.20				
20	Judith Gap	NB	PMBS	2.400	PMBB	12.00	CBC	5.40				
21	Lavina	WB	PMBS	2.760	CTB	15.24						
22	Melstone	WB	PMSD	3.864	CTS	1.80	CBC	19.68				
23	Dunmore Int. – S	EB	HOT REC	8.270	ATPB	3.94	CTS	23.62	Dig-Out Backfill	23.62		
24	Little Bighorn – N	EB	HOT REC	9.450	COLD MILL	2.36	PULV	6.69	CAC	18.15		
25	Busby – N	NB	PMS	4.800	CTS	1.80	CBC	11.40				
26	Busby – S	NB	PMS	4.800	CTS	1.80	CBC	11.40				

= shaded sites refer to auger locations

PULV = Pulverized Base
HOT REC = Hot Recycled
COLD MILL = Cold Milled
RAP = Recycled Asphalt Pavement

CTS = crushed top surfacing
CBC = crushed base course
CAC = crushed aggregate course
CTB = cement-treated base

ATPB = asphalt-treated permeable base
PMBB = plant mix bituminous base
PMBS = plant mix bituminous surface
PMSD = plant mix bituminous

2.2 GPR and FWD Data Collection Procedures

GPR and FWD data were collected by MDT personnel using the MDT 's equipment described in Section 1. The MDT model 4105, 2 GHz horn antenna was upgraded for noise reduction (NR) just prior to the initiation of the spring 2010 testing. The system was equipped with a DMI so that the rate of data collection (scans per foot) was controlled. The system was also equipped with a global positioning system (GPS), and GPS coordinates were collected along with the GPR data.

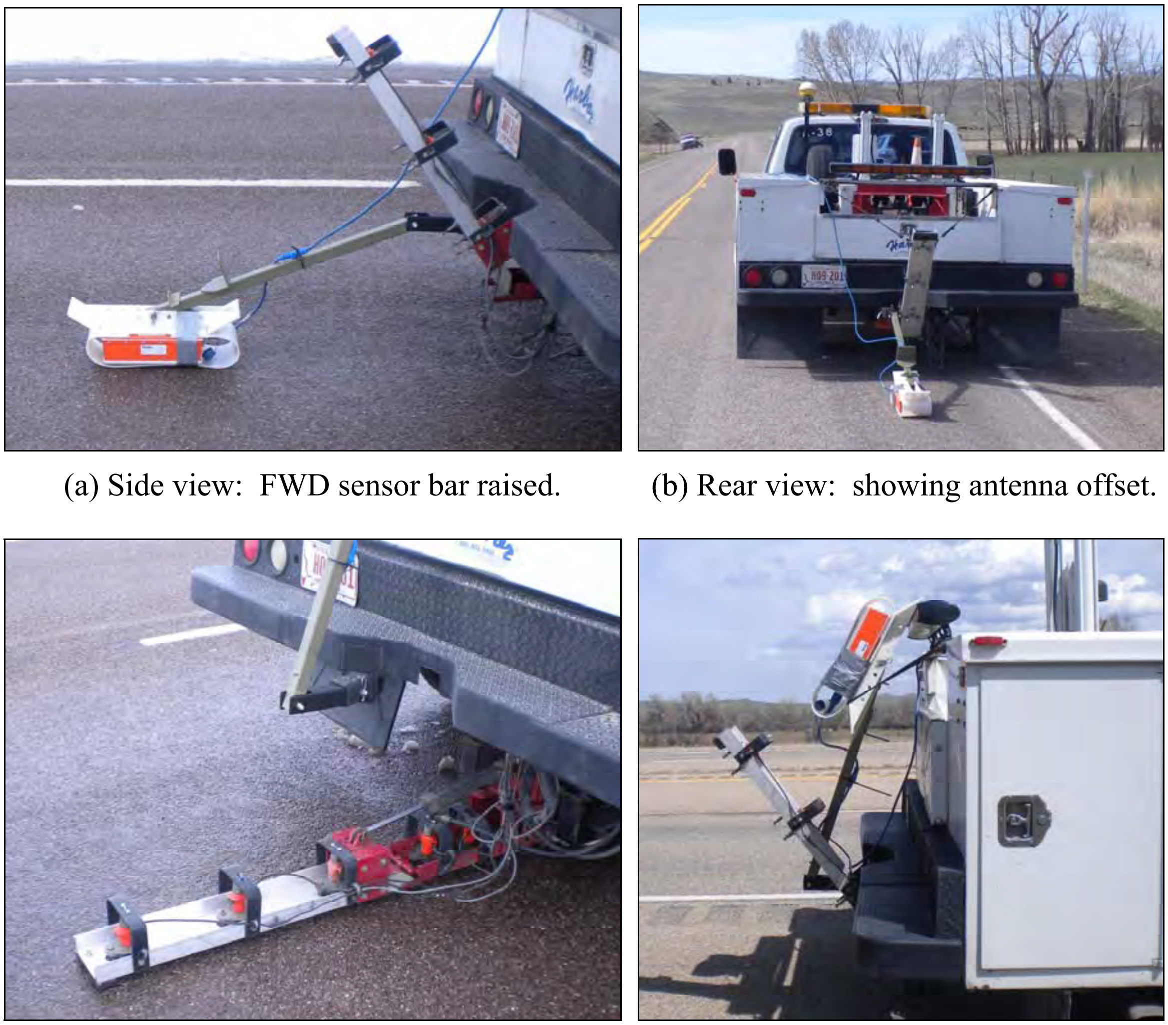
The 2 GHz horn antenna is typically capable of determining the thickness of bound layers and shallow unbound base layers. During the spring 2010 testing, GPR data collection included the use of a second, lower frequency 900 MHz antenna. The purpose of using this antenna was to investigate the ability of using GPR to determine the thickness of deeper base and unbound layers below the surface. The 900 MHz antenna was chosen because its depth range (up to 4 feet) and resolution were considered to be the most appropriate for the deeper pavement layer geometry.

The MDT's SIR-20 is a 2-channel system that supports two antennas, and software (RADAN) provided by the manufacturer (GSSI) provides a means for combining the two data channels into a single analysis. Since the 900 MHz antenna is "ground-coupled", it was deployed from the rear of the vehicle just offset from the FWD sensor bar, as shown in Figure 3a and 3b. The location near the sensor bar was chosen so that the offset of the 900 MHz antenna would be close to that of the 2 GHz antenna. The deployment used a hinged attachment, so that the antenna could be lifted out of the way for FWD testing and travel between sites, as shown in Figures 3c and 3d.

Note that since the 2 GHz horn antenna was deployed in the front of the vehicle, there is an offset between the 900 MHz data and the 2 GHz data. This offset was measured to be 29 feet.

The time range for the 2 GHz antenna was set to 12 nanoseconds (ns.), which is typical of MDT's normal operation. Accounting for the travel time in air, this provides approximately 8.5 ns. of travel time in the pavement, which translates to a maximum detectable depth of approximately 20 inches. The time range for the 900 MHz antenna was set to 25 ns., representing a maximum detectable depth of approximately 50 inches.

GPR data collection was carried out in two modes at each site: (1) FWD mode, where short (75-100 feet) sections of data were collected up to each FWD test location, and (2) continuous mode, where the data was collected continuously from the start to end of each site. Continuous mode represents how data will be collected for the anticipated project and network-level applications. For FWD mode, the data was collected at 10 scans/foot, which corresponds to MDT's typical setting for that mode of survey. For the continuous mode, data was collected twice—once at 5 scans per foot and once at 2 scans per foot. The 5 scan/foot setting provides more detail, but limits the speed of data collection (with 2 channels) to about 10 mph. The 2 scan/foot setting increases the allowable speed of data collection to 25 mph (with 2 channels) or 50 mph (for 1 channel). The latter is more desirable for other project and network-level data collection applications. Table 2 summarizes the data collection modes used and the features of each mode.



(a) Side view: FWD sensor bar raised. (b) Rear view: showing antenna offset.

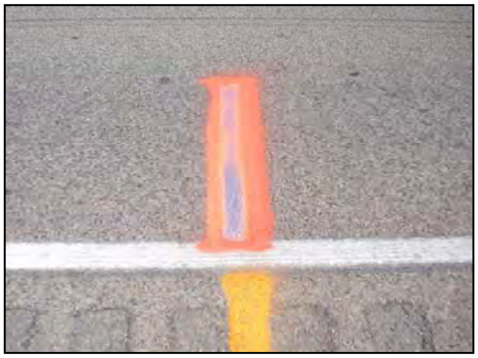
(c) Antenna raised for FWD testing. (d) Antenna and sensor bar raised for travel.

Figure 3. Deployment of the 900 MHz antenna.

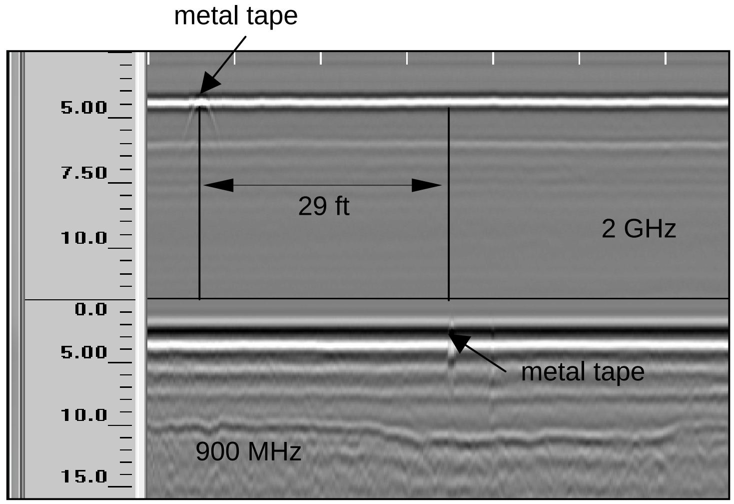
Table 2. Data collection modes at each site

Collection Mode	Scans/foot	Maximum Speed (mph)	Length of Each Scan (ft)
Continuous	2	50	550
Continuous	5	25	550
"FWD" Mode	10	12	70 -100

To ensure accurate registration of the start and end of each section, a metal tape was placed across the pavement at stations 0+00 and 5+00 feet (Figure 4a). This metal tape created a clear event in the GPR data that allowed for measuring distance from the start and end stations (see Figure 4b).



(a) Metal tape marker on pavement.



(b) Appearance of the metal tape mark in each data channel.

Figure 4. Marking the ends of each pavement section in the GPR data.

When the GPR data was collected in conjunction with FWD operation, the pavement at the load plate was painted to mark the location of the FWD test, so that cores at these locations could be registered directly with GPR data locations (Figure 5). The FWD load plate was 23.5 feet behind the 2 GHz horn antenna. As part of the data collection protocol, a metal plate calibration test was carried out at each site for the 2 GHz horn antenna. The metal plate was positioned under the antenna as shown in Figure 6, and the antenna was made to go up and down over the plate by jumping on the front vehicle bumper. Data was collected during the “bumper jump” test, which was later used for data processing.

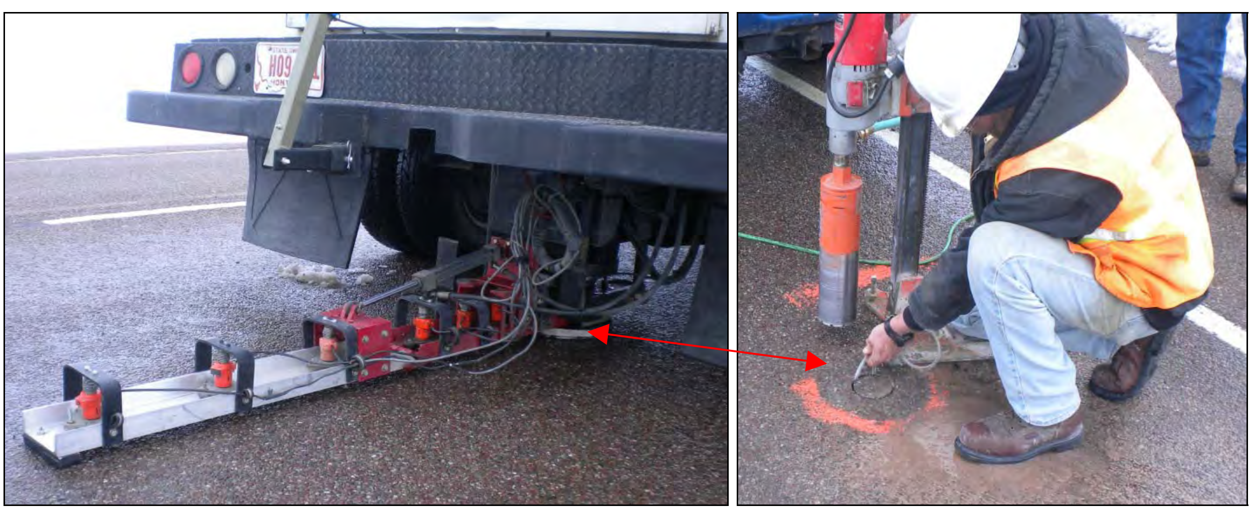


Figure 5. FWD load plate marked for subsequent coring.

Figure 6. Setup for metal plate calibration test

2.3. Ground-Truth Data Collection

A ground truth data collection program was designed to evaluate the accuracy of the GPR-based pavement thickness calculations, and to investigate the influence of base moisture on the GPR calculations. Testing was carried out in both the spring and fall to represent the anticipated wet and dry conditions respectively. The initial testing of each site was carried out in April of 2010 (spring) and included determination of bound pavement thickness, base moisture content, and unbound base layer thickness. The second round of testing at each site was carried out from mid-September to early October 2010 (fall) and included both pavement thickness and base moisture content measurements. Ground truth data collection, including coring and augering operations, traffic control, and base moisture evaluation, was carried out by Pioneer Technical Services of Helena, MT under subcontract to Infrasense.

At each of the 26 test sites, 4 inch-diameter wet-drilled cores were extracted, measured, and photographed on site (see Figure 7). Initially a dry-drilling method using air-cooling was explored and found to be unsuccessful. Heat generated by friction between the core barrel and asphalt pavement deformed the core sample. This reduced the accuracy of the pavement thickness measurements. Therefore the more standard water-cooling method was used.

Figure 7. Coring of asphalt pavement.

In order to mitigate the influence of drilling water on the base moisture content samples, a series of preventative measures were employed. During coring, as the drilling depth reached within an inch of the estimated pavement thickness, the water supply pressure was reduced to a minimum level. Following the extraction of each core, any water within the hole was immediately removed with a small vacuum. During the coring process; the bottom of each hole was carefully examined to ensure that all of the bound material was extracted. Each cored hole was patched to the finished surface using suitable materials.

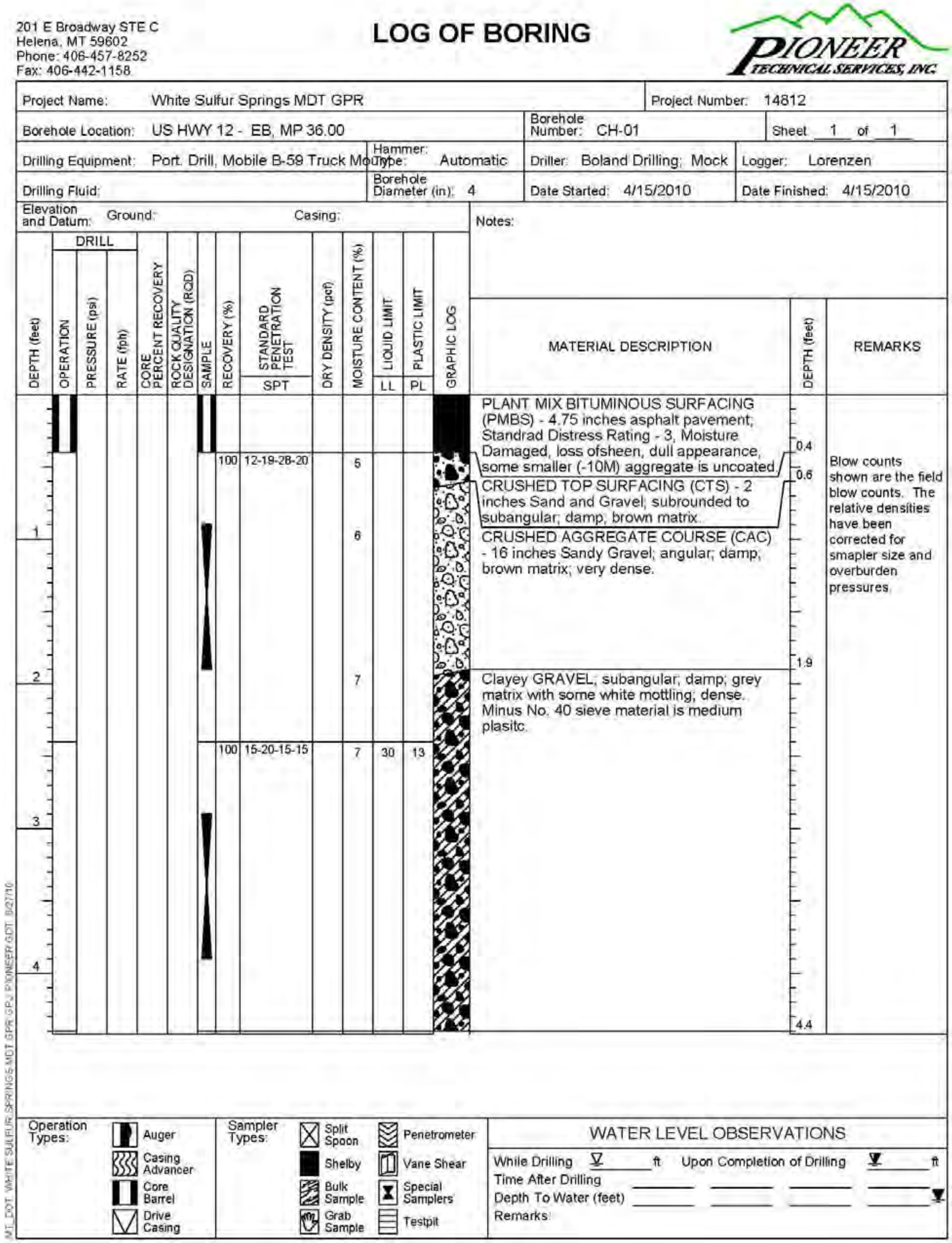
Following the coring, samples of the unbound base material were extracted using a 3 inch or 4 inch diameter hand auger for 23 sites in the spring and all 26 sites in the fall round of testing. Due to the anticipated difficulty in obtaining base thickness data with hand augering, a hydraulically operated truck mounted drill SPT sampler was used on three of the sites in the spring (No. 13, 16, and 18), to obtain split-spoon samples through the base and into the sub-base (see Figure 8). A visual soil classification based on the ASTM D2488 Standard was conducted on each split spoon sample. This testing method was limited to only three sites due to its relatively greater expense.

Figure 8. Hydraulic operated auger and resulting split-spoon sample.

The coring and augering operations at each site took place within two days of the GPR and FWD testing. This was done to minimize any changes in condition that might occur between the two sets of tests. In the spring, cores were taken at each of the locations shown in Figure 2. Locations tested in the fall were offset 10 feet up-station from the previous spring test locations to avoid the effects of the prior coring.

For the extraction of base samples at each core location, the first inch of unbound base material was discarded to ensure the moisture content samples were not contaminated with the water used for core barrel cooling during. A core log was provided for each of the five test locations at each site. A typical core measurement is shown in Figure 9 below and a typical core and boring log is shown in Figure 10.

Figure 9. Typical core measurement.



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LOG OF BORING

PIONEER TECHNICAL SERVICES, INC.

Project Name: White Sulfur Springs MDT GPR | Project Number: 14812

Borehole Location: US HWY 12 - EB, MP 36.00 | Borehole Number: CH-01 | Sheet 1 of 1

Drilling Equipment: Port. Drill, Mobile B-59 Truck Mount | Hammer Type: Automatic | Driller: Boland Drilling; Mock | Logger: Lorenzen

Drilling Fluid: | Borehole Diameter (in): 4 | Date Started: 4/15/2010 | Date Finished: 4/15/2010

Elevation and Datum: Ground: Casing: | Notes:

DEPTH (feet)	OPERATION	PRESSURE (psi)	RATE (fph)	CORE PERCENT RECOVERY	ROCK QUALITY DESIGNATION (RQD)	SAMPLE	RECOVERY (%)	STANDARD PENETRATION TEST SPT	DRY DENSITY (pcf)	MOISTURE CONTENT (%)	LIQUID LIMIT LL	PLASTIC LIMIT PL	GRAPHIC LOG	MATERIAL DESCRIPTION	DEPTH (feet)	REMARKS
														PLANT MIX BITUMINOUS SURFACING (PMBS) - 4.75 inches asphalt pavement; Standrad Distress Rating - 3, Moisture Damaged, loss ofsheen, dull appearance, some smaller (-10M) aggregate is uncoated.	0.4	
							100	12-19-28-20		5				CRUSHED TOP SURFACING (CTS) - 2 inches Sand and Gravel; subrounded to subangular; damp; brown matrix.	0.6	Blow counts shown are the field blow counts. The relative densities have been corrected for smapler size and overburden pressures.
1										6				CRUSHED AGGREGATE COURSE (CAC) - 16 inches Sandy Gravel; angular; damp; brown matrix; very dense.	1.9	
2										7				Clayey GRAVEL; subangular; damp; grey matrix with some white mottling; dense. Minus No. 40 sieve material is medium plasitc.		
							100	15-20-15-15		7	30	13				
3																
4															4.4	

Operation Types: Auger; Casing Advancer; Core Barrel; Drive Casing

Sampler Types: Split Spoon; Shelby; Bulk Sample; Grab Sample; Penetrometer; Vane Shear; Special Samplers; Testpit

WATER LEVEL OBSERVATIONS

While Drilling ____ ft Upon Completion of Drilling ____ ft
Time After Drilling
Depth To Water (feet)
Remarks:

MT_DOT WHITE SULFUR SPRINGS MDT GPR.GPJ PIONEER.GDT 8/27/10

Figure 10. Typical core and boring log.

Unbound base samples were collected and bagged in two inch intervals from an inch below the bottom of the bound material to the subgrade level or until the auger was refused (normally caused by large aggregate). The samples were transported to Pioneer's AASHTO/ASTM accredited materials testing laboratory in Helena to undergo moisture content testing.

A summary of the core thickness and base moisture results obtained in both the spring and fall testing is presented in Table 3. Since the coring locations in the fall were offset 10 feet from those in the spring, the small differences in the average thickness at each site that are observed in the table are to be expected. Note also that there is no significant change in base moisture content values from the spring to fall.

Table 3. Summary of average spring and fall asphalt thickness and moisture content.

Site No.	Site. Name	Average Spring Asphalt Thickness (in.)	Average Fall Asphalt Thickness (in.)	Asphalt Thickness Difference (in.)	Average Spring Moisture Content %	Average Fall Moisture Content %	Average Moisture Content Difference %
01	Dickey L. North	6.00	5.95	0.05	4.52	4.50	0.02
02	Dickey L. South	7.40	7.55	-0.15	5.02	4.40	0.62
03	Perma	3.20	3.40	-0.20	6.54	6.60	-0.06
04	Dixon	3.68	3.95	-0.28	3.48	3.20	0.28
05	Condon	7.40	7.65	-0.25	4.06	3.60	0.46
06	Powell Cty Line	4.85	4.95	-0.10	5.28	4.87	0.41
07	Helmville South	3.77	3.88	-0.10	7.66	6.50	1.16
08	Helmville East	4.70	4.75	-0.05	4.17	3.70	0.47
09	Beck Hill	4.55	4.55	0.00	3.45	3.60	-0.15
10	Silver City	5.65	5.55	0.10	2.93	2.80	0.13
11	Jefferson City	10.85	10.95	-0.10	4.57	3.70	0.87
12	Baum Road	5.40	5.45	-0.05	3.69	3.80	-0.11
13	White Sulph. Spr.	4.40	4.45	-0.05	5.62	4.90	0.72
14	Lothair	3.55	3.75	-0.20	3.97	2.80	1.17
15	Marias River	4.75	5.10	-0.35	3.54	2.70	0.84
16	Vaughn	8.40	8.70	-0.30	4.53	3.00	1.53
17	Great Falls East	8.15	8.50	-0.35	4.04	3.00	1.04
18	Geyser	4.00	4.10	-0.10	5.30	4.50	0.80
19	Stanford	5.15	5.10	0.05	3.97	4.00	-0.03
20	Judith Gap	2.35	2.60	-0.25	0.67	3.33	-2.66
21	Lavina	5.45	5.30	0.15	8.26	8.00	0.26
22	Melstone	3.83	3.95	-0.13	3.95	3.85	0.10
23	Dunmore Int.	10.28	10.35	-0.07	3.63	4.20	-0.57
24	Little Big Horn	10.20	12.00	-1.80	4.22	4.08	0.13
25	Busby North	5.03	5.00	0.03	3.02	2.87	0.15
26	Busby South	5.23	5.30	-0.08	4.03	3.07	0.96
Overall Averages				**-0.18**	**4.39**	**4.06**	**0.33**

3. DATA ANALYSIS AND EVALUATION

The data collected as described in Section 2 was evaluated to determine the accuracy of the GPR pavement thickness analysis and the variations obtained between data collected in the spring and fall. GPR data was analyzed using RADAN, the software provided by GSSI, the GPR equipment manufacturer. Aside from the two calibration cores referenced in section 2.1, the GPR data analysts had no access to the core data. The accuracy of the GPR layer thickness predictions was carried out independently by Nichols Consulting Engineers (NCE), under subcontract to Infrasense.

3.1. GPR Data Analysis

3.1.1. Overall Approach

The spring GPR data included both 2 GHz and 900 MHz data. Therefore, an effort was made to identify all observable pavement layers down to about 50 inches, which represents the maximum range for the 900 MHz antenna. For the fall data, only the 2 GHz data was available, and the focus was exclusively on the bound pavement structure.

The 2-channel spring GPR data was analyzed using a special 2-channel analysis feature provided by RADAN. Using this feature, the two data channels are aligned by correcting for the offset of the two antennas (29 feet), and the higher frequency and lower frequency data are combined into a single channel. In order to create the single channel data, the user specifies the depth at which the lower frequency data takes over from the high frequency data. A sample of this equivalent single channel data taken from Site 16 (Vaughn) is shown in Figure 11. The upper portion of the figure shows the data from the 2 GHz horn antenna, and the lower portion shows the data from the 900 MHz antenna. The depth scale at the left shows that the transition from the 2 GHz data to the 900 MHz data takes place at an approximate depth of 12 inches.

This combined data is analyzed by picking the layer boundaries using the RADAN program. The program then calculates the layer depths from the picked data. The depth calculation in the 2 GHz data is based on a dielectric calculation that uses the metal plate calibration test. No such calibration is possible for the 900 MHz data, so the analysis of this data assumes a uniform dielectric equal to that of the lowest layer in the 2 GHz data. Figure 12 shows how the data in Figure 11 was picked. Note that the estimated layer thicknesses shown in Figure 12 match closely with the plan data for this site shown in Table 1.

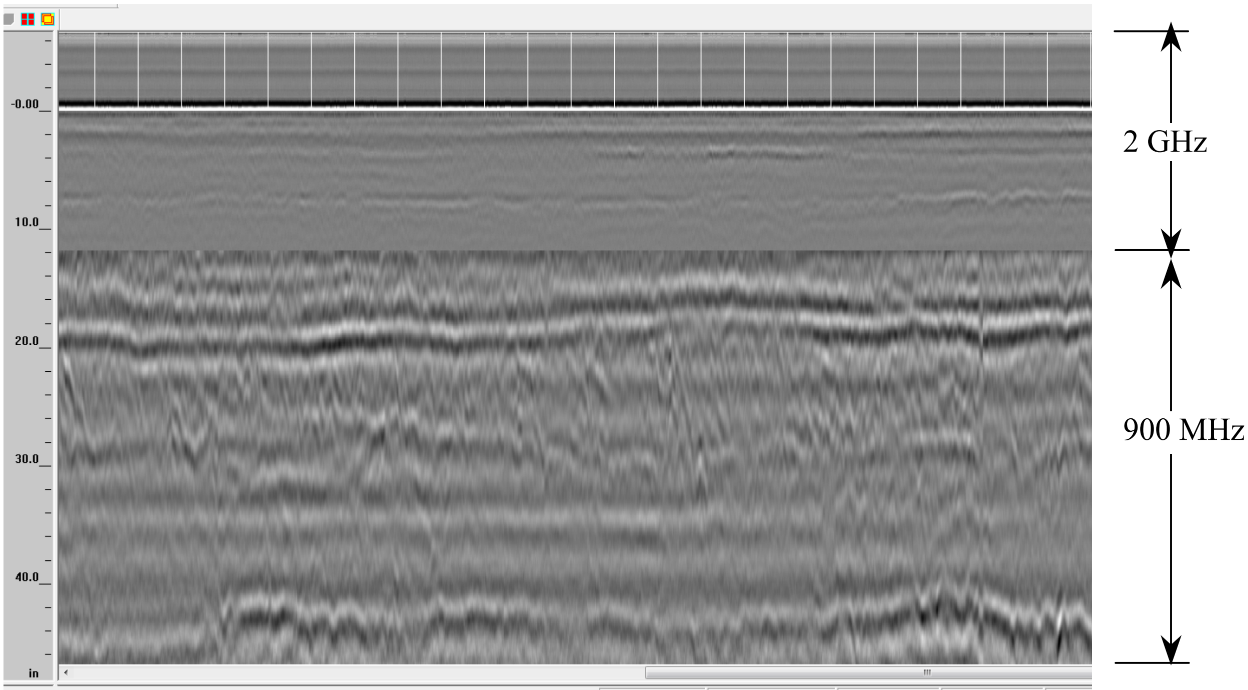


Figure 11. Combined two-channel GPR data (Site 16).

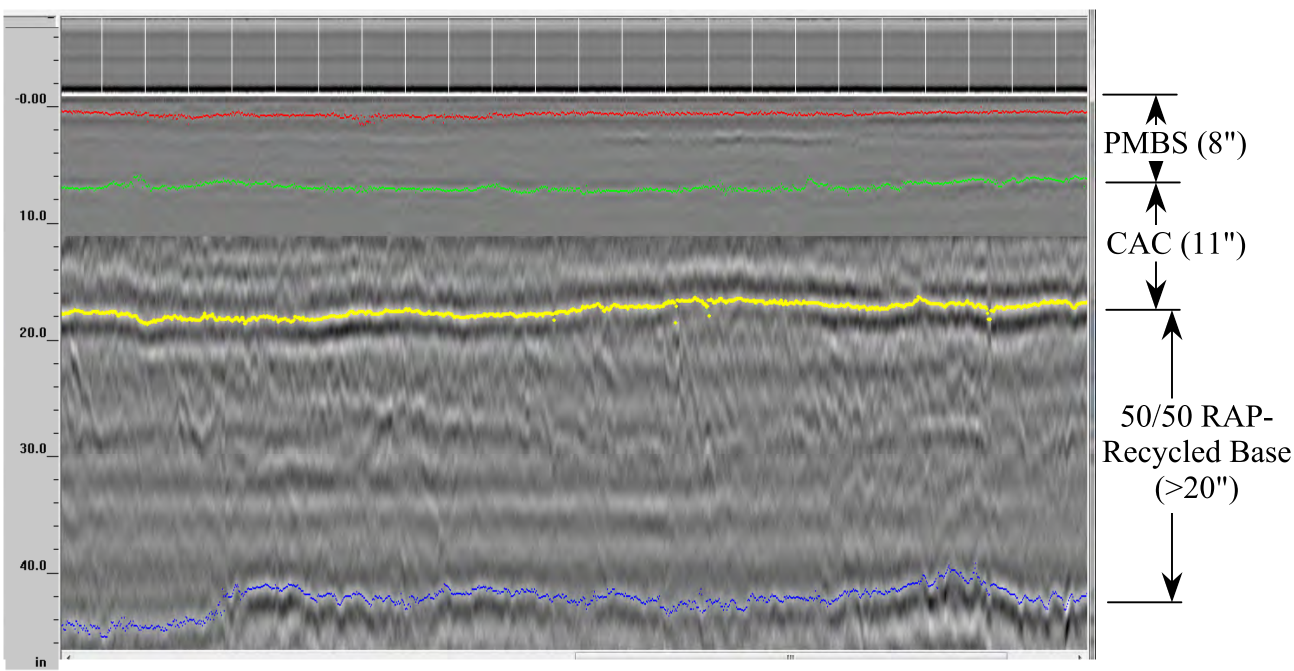


Figure 12. Layer analysis of the two-channel data (Site 16).

3.1.2. Comparison of Spring vs. Fall GPR Data

The GPR results for data collected in the spring vs. the fall were evaluated. Since the fall data only includes the 2 GHz antenna, this analysis focused on the layers that were detectable with that antenna. The comparison is shown in Table 4. The analysis is based on the data collected at 5 scans per foot, and the average and standard deviation values are based analyzing every scan over each 500 foot long site. The blank cells in the table indicate layers that were not detectable in the GPR data. Note that Site 16 was surveyed twice. During the first survey there were wet surface conditions, so the survey was repeated later when the surface conditions were dry.

Table 4 shows that, with a few exceptions, the calculated layer depths are very similar from spring to fall. On average, the difference between the bound layer thickness between spring and fall data sets is 0.20 inches, and the difference between base layer depths between spring and fall data sets is 0.39 inches. One notable exception is Site 2, where the differences were 1.25 inches and 1.39 inches, respectively.

3.1.3. Comparison of Data Collected at 2 and 5 Scans per Foot

Data over the full length of each site was collected twice - once at 5 scans per foot and once at 2 scans per foot. Data for each of the five FWD test locations was collected at 10 scans per foot, which is MDT's standard data collection protocol with FWD testing. In the interest of determining an appropriate data density for future applications, the 2 and 5 scan per foot data were analyzed and the results compared to determine if there was any significant difference. The results are shown in Table 5 below.

At each site, the average thickness was calculated for each of the two files and the averages were compared. For the 5 scan per foot data, the average over 500 feet is based on the results for 2500 scans, while the average for the 2 scan per foot data is based on 1000 scans. The results show very little difference. The average difference is 0.07 inches for the thickness of the asphalt layer and -0.02 inches for the depth to the bottom of the first base layer.

3.1.4. Comparison of GPR vs. Core Data

The GPR data was analyzed at each core location, and the resulting layer depth results were compared to data obtained by cores. There were five core locations per site, providing ground truth data at 130 locations. Other than data from two calibration cores, the coring data from the remaining 128 test locations was not available to the GPR analysis. The comparison of the GPR data to the core data was carried out independently, so the GPR analysis was essentially “blind”.

The GPR data at the core locations was obtained by analyzing the entirety of each site, collected at 5 scans per foot, and then selecting the resulting layer depths at the core locations. The GPR value reported at each core location represents the average 10 scans, located +/- 0.5 feet on either side of the core location. Two types of GPR analysis were conducted at each site - one using the “custom” plate calibration, and one using the “global” plate calibration. In the “custom” plate analysis for a given site, the data was calibrated using a plate reflection file collected at that site at the time that the layer thickness data was collected. In the “global” plate analysis, a single plate calibration file was used for all 26 sites.

Table 4. Comparison of layer depth results obtained from spring vs. fall data.

Site No.	Name	Average Asphalt Depth (in) GPR Spring Avg.	St. Dev.	GPR Fall Avg.	St. Dev.	Difference	Depth to Bottom of Base I (in.) GPR Spring Avg.	St. Dev.	GPR Fall Avg.	St. Dev.	Difference
01	Dickey Lake - NB	6.09	1.05	5.84	1.09	0.25	–	–	–	–	–
02	Dickey Lake - SB	4.61	1.15	3.36	0.40	1.25	6.20	0.72	4.81	1.06	1.39
03	Perma Canyon - SB	3.43	0.28	3.10	0.26	0.33	8.03	0.73	7.09	0.66	0.94
04	Dixon - NB	1.74	0.28	1.79	0.26	-0.06	5.88	0.83	5.74	0.83	0.14
05	Condon - NB	7.85	0.30	7.70	0.31	0.15	10.96	0.79	10.41	0.62	0.55
06	Powell Co Line - SB	3.97	0.44	3.81	0.43	0.16	10.50	0.96	10.09	1.32	0.41
07	Helmville South - SB	3.55	0.26	3.50	0.28	0.05	9.53	1.48	11.26	1.51	-1.73
08	Helmville Jct East - EB	4.24	0.30	4.26	0.32	-0.02	17.00	1.76	–	–	–
09	Beck Hill - EB	4.83	0.44	4.73	0.44	0.11	11.94	0.83	11.87	0.83	0.07
10	Silver City - NB	5.15	9.66	4.95	0.36	0.20	9.66	0.60	9.18	0.65	0.48
11	Jefferson City - NB	11.12	0.51	11.96	0.48	-0.85	20.75	2.02	–	–	–
12	Baum Road - WB	5.55	0.45	5.35	0.40	0.20	23.30	1.06	–	–	–
13	White Sulphur Springs	4.07	0.34	4.04	0.32	0.04	7.74	0.45	7.78	0.52	-0.03
14	Lothair - WB	3.64	0.43	3.59	0.33	0.05	16.74	1.40	–	–	–
15	Marias River - NB	4.64	0.50	4.57	0.46	0.07	9.01	0.67	8.59	0.66	0.42
16	Vaughn (dry) - NB	9.30	0.38	8.66	0.49	0.64	21.62	0.87	–	–	–
17	Great Falls East - NB	8.30	0.54	7.64	0.44	0.66	11.92	1.79	11.34	1.69	0.59
18	Geyser - WB	4.23	0.34	4.06	0.29	0.17	14.48	0.99	13.52	0.65	0.96
19	Stanford - WB	5.10	0.39	5.09	0.42	0.01	9.60	0.65	9.80	0.80	-0.20
20	Judith Gap - NB	2.93	0.13	2.76	0.17	0.17	15.12	0.82	14.17	0.74	0.95
21	Lavina - WB	6.06	0.45	5.76	0.42	0.30	13.80	1.00	13.11	0.96	0.69
22	Melstone - WB	3.92	0.36	3.85	0.36	0.07	7.41	0.55	7.42	0.59	-0.01
23	Dunmore Int. South - EB	10.28	0.39	9.46	0.46	0.82	14.13	0.40	13.05	0.51	1.08
24	Little Bighorn North - EB	7.73	1.32	7.42	1.43	0.31	–	–	–	–	–
25	Busby North - NB	4.81	0.39	4.99	0.35	-0.18	–	–	–	–	–
26	Busby South - NB	5.42	0.31	5.10	0.33	0.32	8.24	0.38	7.82	0.43	0.42

Note: –- = not applicable

Table 5. Comparison of results using 5 scans per foot vs. 2 scans per foot.

Site No.	Average Asphalt Depth (in.)			Depth to Bottom of Base I		
	5 scans per ft	2 scans per ft	Difference	5 scans per ft	2 scans per ft	Difference
01	5.84	5.79	0.05	–	–	–
02	3.36	3.36	0.00	4.81	4.74	0.07
03	3.10	3.10	0.00	7.09	7.05	0.04
04	1.79	1.80	-0.01	5.74	5.73	0.01
05	7.70	7.68	0.02	10.41	10.74	–0.33
06	3.81	3.79	0.02	10.09	9.89	0.20
07	3.50	3.57	-0.07	11.26	11.55	–0.29
08	4.26	4.25	0.01	–	–	–
09	4.73	4.73	0.00	11.87	11.80	0.07
10	4.95	5.01	-0.06	9.18	9.33	–0.15
11	11.96	11.03	0.93	–	–	–
12	5.35	5.22	0.13	–	–	–
13	4.04	4.06	-0.02	7.78	7.75	0.03
14	3.59	3.63	-0.04	–	–	–
15	4.57	4.27	0.30	8.59	8.43	0.16
16	8.66	8.40	0.26	–	–	–
17	7.64	7.68	-0.04	11.34	11.16	0.18
18	4.06	3.98	0.08	13.52	14.01	–0.49
19	5.09	5.09	0.00	9.80	9.71	0.09
20	2.76	2.77	-0.01	14.17	14.16	0.01
21	5.76	5.64	0.12	13.11	12.91	0.20
22	3.85	3.87	-0.02	7.42	7.59	–0.17
23	9.46	9.44	0.02	13.05	13.07	–0.02
24	7.42	7.29	0.13	–	–	–
25	4.99	5.00	-0.01	–	–	–
26	5.10	5.07	0.03	7.82	7.76	0.06

Note: – = not applicable

Table 6 shows the GPR vs. Core data for the spring global plate analysis. The table shows the depths to the bottom of the asphalt, the first base layer, and the second base layer taken from the plans, from the GPR data, and from the coring and augering. Note that the augering was generally able to determine the depth of the first base layer, but was only able to obtain the depth of the second base layer at 8 sites. At 3 of these sites, this second base depth data was obtained using a split spoon driven by a large boring rig.

The core and GPR data for each site is the average of the values at the 5 core locations. The error percentages shown is the absolute value of the difference between the core data and the plan or GPR data divided by the core data. The GPR error in inches is the absolute value of the difference between the GPR data and the core data.

Table 6. GPR data vs. core – spring 2010 using global plate.

Site No.	Average Asphalt Depth (in)						Depth to Bottom of Base I (in.)					Depth to Bottom of Base II (in.)				
	Plan	Core	GPR	Plan Error %	GPR Error In.	GPR Error %	Plan	Core	GPR	Plan Error %	GPR Error %	Plan	Core	GPR	Plan Error %	GPR Error %
01	3.00	6.00	6.78	50.0%	0.78	13.0%	4.80	7.80				19.80		22.06		
02	3.00	7.40	3.70	59.5%	3.70	50.0%	4.80	8.98	5.22	46.5%	41.6%	19.80		22.40		
03	3.48	3.20	3.62	8.7%	0.42	13.1%	7.20	7.50	8.24	4.0%	13.2%	13.20	17.75	18.58	25.6%	4.7%
04	3.00	3.83	1.92	21.6%	1.91	49.8%	4.80	4.99	6.40	3.8%	27.8%	18.60		20.50		
05	8.64	8.30	8.74	4.1%	0.44	5.3%	9.84	9.66	12.26	1.9%	27.0%	14.64	15.96	20.82	8.3%	30.5%
06	3.60	3.93	4.08	8.3%	0.16	3.9%	15.60	15.00	11.42	4.0%	33.3%					
07	3.60	3.80	3.98	5.3%	0.18	4.7%	15.60	9.10	10.90	71.4%	20.5%					
08	4.20	4.70	4.84	10.6%	0.14	3.0%	12.60	13.50	18.74	6.7%	30.4%					
09	4.32	4.55	4.84	5.1%	0.29	6.4%	12.48	13.75	12.10	9.2%	12.7%	45.60		18.36		
10	4.92	5.65	4.92	12.9%	0.73	12.9%	11.88	13.56	9.44	12.4%	31.5%					
11	9.00	10.95	12.42	17.8%	1.47	13.4%	19.80		23.48							
12	4.68	5.40	5.74	13.3%	0.34	6.3%	25.20	26.75	25.60	5.8%	13.6%					
13	3.60	4.40	4.08	18.2%	0.32	7.3%	6.00	6.40	7.80	6.3%	21.9%	17.40	22.80	22.16	23.7%	1.9%
14	3.60	3.55	4.04	1.4%	0.49	13.8%	16.20		19.12							
15	4.56	4.75	4.80	4.0%	0.05	1.1%	9.12	9.31	9.26	2.0%	4.3%	18.72		21.68		
16–wet	8.04	8.40	7.60	4.3%	0.80	9.5%	18.12	18.00	17.78	0.7%	3.2%	39.24	43.44	40.41	9.7%	7.0%
16–dry	8.04	8.40	8.28	4.3%	0.12	1.4%	18.12	18.00	19.88	0.7%	10.4%	39.24	43.44	46.15	9.7%	6.2%
17	6.00	8.15	8.14	26.4%	0.01	0.1%	10.20	16.00	11.72	36.3%	29.1%	31.20		20.74		
18	4.08	4.00	4.04	2.0%	0.04	1.0%	15.48	15.30	14.02	1.2%	8.3%	21.48	21.12	21.70	1.7%	2.7%
19	7.20	5.15	5.12	39.8%	0.03	0.6%	9.00	6.95	9.78	29.5%	40.8%	28.20		33.38		33.5%
20	2.40	2.35	2.74	2.1%	0.39	16.6%	14.40	11.70	14.12	23.1%	27.1%	19.80		27.70		
21	2.76	5.45	5.82	49.4%	0.37	6.8%	18.00	19.50	19.86	7.7%	2.1%					
22	3.86	3.83	4.10	1.0%	0.27	7.2%	5.66	5.83	7.42	2.8%	27.6%	25.34		35.62		
23	8.27	10.28	10.24	19.5%	0.04	0.3%	12.21	14.70	14.02	16.9%	7.4%	35.83	40.00	36.64	10.4%	8.4%
24	9.45	10.20	7.56	7.4%	2.64	25.9%	11.81	11.55	9.26	2.3%	20.0%	18.50		18.62		
25	4.80	5.03	4.92	4.5%	0.11	2.1%	6.60	6.83		3.3%		18.00		18.98		
26	4.80	5.23	5.24	8.1%	0.02	0.3%	6.60	7.03	7.74	6.0%	10.2%	18.00	18.20	18.20	1.1%	0.0%

Note: blank cells = data not available

The Table 6 results show that the GPR error in asphalt thickness calculation was less than 8% for 15 of the sites, and greater than 20% for three of the sites. Sites where the errors are large are where the feature in the GPR data representing the bottom of the asphalt layer was either not clear, and/or not properly identified.

Comparisons similar to that shown in Table 6 were made for the spring data using the "custom" plate, and for the fall data. A summary of results are shown in Table 7. The table shows that the use of the custom plate produces a slight improvement in the accuracy, but may not be significant enough to warrant the extra time and exposure in the field. The table shows that the GPR data is more accurate than the plan data for asphalt thickness. For base data, the results are mixed. Plan data appears to be more accurate than GPR data for the first base layer, while GPR data appears to be more accurate for the second base layer. Note that depth data from coring for the second base layer is only available for 8 of the 26 sites.

Table 7. Summary of comparisons between GPR, plan, and core data.

Data Collection	Calibration Plate	Asphalt Thickness Error (%)		Base I Depth Error (%)		Base II Depth Error (%)	
		Plan	GPR	Plan	GPR	Plan	GPR
Spring	Custom	15.2%	9.7%	12.7%	18.3%	11.6%	8.4%
Spring	Global	15.2%	10.3%	12.7%	18.7%	11.6%	10.5%
Fall	Custom	16.9%	11.0%	6.9%*	14.7%*	n.a.	n.a.

n.a. = not available   *Base data available from only 7 sites

3.2. Analysis of FWD Data

FWD data was collected at each core location as part of the GPR data collection effort. The FWD data has been analyzed for two purposes: (1) to see whether FWD measurements could be used to check the accuracy of GPR data and to suggest an alternate interpretation, and (2) to conduct a sensitivity analysis to study the impact of layer thickness error on overlay design.

FWD testing was conducted using MDT's JILS FWD testing equipment. The FWD data collected included deflections at nine sensors (spaced at 0, 8, 12, 18, 24, 36, 48, 60, and 72 inches from center of the loading plate) and using four drops at different load levels (approximately 5,700, 9,000, 11,800, and 15,800 pounds). The data analysis included the first seven sensors (0, 8, 12, 18, 24, 36, and 48 inches) in order to stay consistent with MDT's procedure. Additionally, the data analysis only gives consideration to deflections measured at the 9,000 pound load level. The FWD data used in this analysis was collected between April 14 and May 5 of 2010.

With reference to error checking, the most significant errors in the GPR data analysis occur when there are multiple layer boundaries in the GPR data and it is not clear to the analyst which boundary represents the bottom of the asphalt. Since layer thickness is an input into the FWD backcalculation process, it is possible that this process might yield some useful information when incorrect layer thickness data is used. With reference to the sensitivity analysis, the overlay design process uses the backcalculated moduli as input.

To accomplish the error checking, it was necessary to develop indicator values that could be compared to thickness error values for trend analysis. The GPR thicknesses together with the FWD measurements could be backcalculated to determine some of these indicators, such as the moduli of each layer and backcalculation error (between the measured and calculated deflection basin). These and other indicators included:

- Backcalculated moduli of the surface layer.
- Backcalculation error (output from the program).
- Backcalculated moduli of each layer normalized to pavement temperature.
- Area values normalized by the thickness of the surface layer.
- Error of backcalculated subgrade modulus from predicted subgrade modulus.
- Estimated structural number of the pavement normalized by area values.

A review and evaluation of these potential indicators is described below.

3.2.1. Backcalculation Methods

The program used to perform backcalculation in this analysis was MODULUS 5.1 developed by the Texas Department of Transportation. MODULUS was chosen for this analysis because this program was used to develop MDT's *Automated Deflection Analysis Procedure (ADAP) User's Manual* (PCS/LAW, 1996), which is used to calculate the subgrade modulus for MDT's reconstruction and rehabilitation design.

MODULUS produces backcalculated layer moduli, backcalculation error, and depth to bedrock through an iterative process. The process uses a deflection data file and manual inputs of FWD plate radius, sensor spacing, sensor weight factor (left blank), layer thicknesses, modulus ranges (minimum and maximum) per layer, Poisson's ratio per layer, and a subgrade seed (most probable) modulus (Table 8). Although the raw deflection data file included deflections from seven sensors (radial distances of 0, 8, 12, 18, 24, 36, and 48 inches) at four different load levels, only the outputs from the 9,000 pound load were considered for error checking analysis. Backcalculation was performed using the "Full Analysis" method in MODULUS, which has no built-in feature for temperature correction. The program assumes pavement temperature was considered when selecting the modulus range of the surface layer.

Table 8: MODULUS inputs and outputs.

INPUTS	OUTPUTS
• Deflection data file • FWD plate radius • Sensor spacing • Sensor weight factor (left blank) • Layer thicknesses • Modulus ranges per layer • Poisson's ratio per layer • Subgrade seed (most probable) modulus	• Layer moduli • Backcalculation error • Depth to bedrock

The first step in the backcalculation process was to combine layers with similar material types. The layer types provided by as-built plans were categorized as plant-mix surfacing, recycled surfacing, asphalt treated base, asphalt treated permeable base, cement treated base, crushed top surfacing, crushed aggregate course, pulverized material, special borrow, backfill, and subgrade. MODULUS allows an input of no more than four layers (including subgrade) in a backcalculation analysis. Additionally, the program's user manual denotes that although a four-layer analysis may show less backcalculation error than a three-layer analysis, the results may not be realistic. Therefore, adjacent layers with similar material types were combined to minimize the number of layers in the analysis. The layer types were combined into seven groups: (1) surface layer, (2) asphalt treated base, (3) cement treated base, (4) unbound base, (5) pulverized, (6) special borrow and (7) subgrade. Table 9 shows how layer types were grouped into analysis material types.

Backcalculation of the dataset was performed twice using two methods for selecting subgrade seed values, modulus ranges, and Poisson's ratios per layer:

- Wide modulus range method
- ADAP user's manual based method

Wide Modulus Range Method

The basis for this method is to establish the critical boundaries of possible layer moduli and allow the MODULUS program to iterate through the established range. Modulus ranges and Poisson's ratios for the layer varied depending on the material type. Surface layers and bound (treated) bases have a modulus range from 100 ksi to 3,000 ksi and Poisson's ratio of 0.35. Unbound bases have a modulus range from 10 ksi to 75 ksi and Poisson's ratio of 0.4. Pulverized material bases have a modulus range from 20 ksi to 100 ksi and Poisson's ratio of 0.4. Special borrow bases have a modulus range from 10 ksi to 60 ksi and Poisson's ration of 0.4. Lastly, subgrades have a Poisson's ratio of 0.45 and seed values vary depending on the AASHTO soil classification as shown in Table 10. These values were based on tables from the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (ARA, 2004), and the *Review of the Long-Term Pavement Performance Backcalculation Results* (ARA, 2006).

Table 9. Layer material type grouping.

CORING MATERIAL TYPE	ANALYSIS MATERIAL TYPE
Plant-mix surfacing	Surface AC layer
Hot recycled surfacing	
Asphalt treated base	Asphalt treated base
Asphalt treated permeable base	
Cement treated base	Cement treated base
Crushed top surfacing	Unbound base
Crushed base course	
Crushed aggregate course	
Pulverized material	Pulverized material
RAP/Recycled base	
Special borrow	Special borrow (combine with subgrade when applicable)
Backfill	
Subgrade	Subgrade

Table 10. Subgrade seed moduli.

AASHTO SOIL CLASSIFICATION	SUBGRADE SEED MODULUS
A-1-a	36
A-2-4	28
A-2-6	22
A-4	20
A-6	13
A-7	6
Assume A-2-4 if unknown	28

ADAP User's Manual Based Values

The ADAP User's Manual provides a detailed array of rules for performing backcalculations. The main intention of ADAP in providing backcalculation rules is to reduce user variability and maintain consistency, productivity, and simplicity. The rules defined in the ADAP manual were used as a foundation to replicate the same intentions in this analysis. For this reason, some assumptions or modifications were made to further simplify the rules to fit the specific dataset for this analysis.

Modulus ranges for the surface layer were calculated from a three part equation. The first part computes the deflection constant, X (Equation 1a). The second part was an MDT regression equation used to estimate the surface layer's seed modulus (Equation 1b). The regression constants (B, Y, and Z) are dependent on the surface layer thickness as shown in Table 11. The third part used the computed seed modulus to calculate the minimum and maximum values of the modulus range (Equation 1c).

$$X = 1/((D1 \times 4) - (((D1 + D2) \times 4 + (D2 + D3) \times 2 + (D3 + D4) \times 6 + (D4 + D5) \times 6 + (D5 + D6) \times 6)/12))$$

Equation 1a

Where,

X = deflection constant,
$D1$ = deflection at 0 inches,
$D2$ = deflection at 8 inches,
$D3$ = deflection at 12 inches,
$D4$ = deflection at 24 inches,
$D5$ = deflection at 36 inches, and
$D6$ = deflection at 48 inches

$$E_{AC} = X \times B \times Y + Z$$

Equation 1b

Where,

E_{AC} = surface layer seed modulus
X = deflection constant,
B = regression constant,
Y = regression constant, and
Z = regression constant,

Table 11. Regression constants for estimated surface layer seed modulus.

SURFACE LAYER THICKNESS (IN)	B	Y	Z
0 TO 3.0	2,200,000	0.975094	54,988
3.1 TO 8.0	2,200,000	0.735901	63,114
8.1 TO 10	1,750,000	0.599332	111,147
10.1 or more	1,750,000	0.821073	10,872

$$\begin{matrix} \textit{Surface layer} \\ \textit{modulu srange} \end{matrix} = \begin{Bmatrix} (E_{AC})_{\min} = 0.25 \times E_{AC} \\ (E_{AC})_{\max} = 3.00 \times E_{AC} \end{Bmatrix}$$

Equation 1c

Where,

$(E_{AC})_{\min}$ = minimum surface layer modulus, and

$(E_{AC})_{\max}$ = maximum surface layer modulus

The modulus range and Poisson's ratios for base or subbase material types is defined in Table 12.

Table 12. Poisson's ratios modulus range per base/subbase material type.

BASE/SUBBASE MATERIAL TYPE	POISSON'S RATIO	MODULUS RANGE	
		MINIMUM	MAXIMUM
Cement treated base	0.25	50	1500
Asphalt treated base	0.35	Same as surface layer	
Pulverized material	0.40	10	150
Unbound base			
Special borrow			
A-1-a			

The subgrade seed value was calculated using th e Boussineq one-layer equation (Equation 2a). A set of subgrade modulus values was calculated per the deflections of the last six FWD sensors (radial distances of 8, 12, 18, 24, 36, 48 inches). Of which the lowest value of the set was used as the subgrade seed modulus in the backcalculation (Equation 2b).

$$E(comp) = \frac{P \times (1 - u^2)}{\pi \times def \times r}$$

Equation 2a

Where,

$E(comp)$ = pavement composite modulus,

P = load applied on loading plate (lb),

u = Poisson's ratio of subgrade,

def = measured deflection at give radial distance r from center of load plate, and

r = radial distance for deflection in question

$$E_{SG} = \min E(comp)$$

Equation 2b

Where,

E_{SG} = subgrade seed modulus, and

$E(comp)$ = pavement composite modulus

3.2.2. Limitations of Backcalculation Methods

The objective of using the wide modulus range method was to allow the MODULUS program a wide amount of freedom in backcalculating the modulus of the surface layer. With this larger modulus range, locations with incorrect thicknesses are more likely to produce unreasonable surface layer moduli, which could be used as indicators in a QC process to flag layer thicknesses that require further investigation.

Note that the wide modulus range may be useful for the checking of the GPR thickness data, but it is not appropriate for other purposes. Intentionally allowing an unreasonable surface layer modulus forces the subsurface layer moduli to adjust to fit the measured deflection basin. Unfortunately, all or most of the resulting moduli may not be reasonable, and may be unusable for pavement design purposes. As such, the wide modulus range method was only used in the GPR QC check development and not used in the pavement design sensitivity analysis. Also, allowing too much freedom lets the program backcalculate a deflection basin that matches well with the FWD measured basin regardless of how unreasonable the backcalculated modulus values may be. In other words, it is possible to have low backcalculation errors using incorrect thicknesses because the program can calculate a deflection basin with a good fit using unreasonable layer moduli.

The purpose of using narrower modulus ranges in the ADAP-based method was to restrict the backcalculated modulus of the surface AC layer to reasonable values based on MDT's experience, and thus to serve as a basis for overlay design.

Some of the FWD deflection basins were observed to show questionable deflection trends, of which only the most obvious were omitted from further analysis. FWD deflection basins for four locations in Site 16 (wet) and one location in Site 18 were considered questionable and omitted from analysis.

Examples of these suspect deflection basins are shown in Figure 13 below. As can be seen in the deflection basin on the left, the sensor at 8 inches from the load produced lower deflections than the next 2 sensors (at 12 and 18 inches from the load). Similarly, in both graphs, the sensor at 36 inches from the load produced a lower deflection that the senor at 48 and 60 inches from the load. It is expected that deflections should decrease as the sensor is moved away from the load.

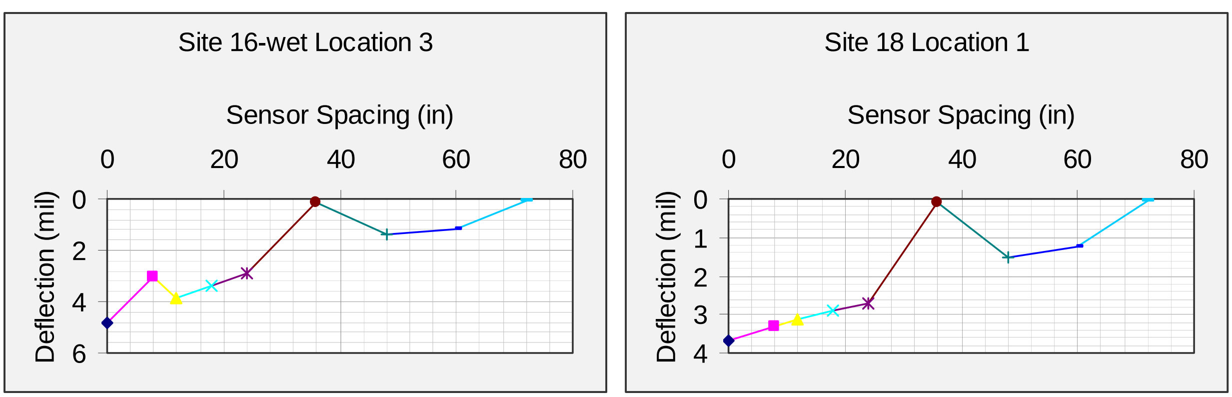


Figure 13. Questionable deflection basins omitted from further analysis.

Furthermore, in order to avoid variability, the engineering judgment of the user was eliminated using very mechanical backcalculation procedures. The primary intention in developing back-calculation methods is to maintain consistency throughout the dataset. Making adjustments to the data on a site-by-site basis is undesirable for comparisons used in the sensitivity analysis.

3.3. GPR Data Quality Control Investigation

The purpose of the QC analysis was to identify trends from correlating layer thickness error to other indicators of error. The resulting trends could then be used to establish criteria for flagging questionable data that requires additional investigation. The ability to differentiate questionable layer thicknesses from reasonable layer thicknesses would help identify locations where further investigation was needed. This investigation could range from revisiting the GPR data at a particular site and revising the analysis, to taking cores at the site in question.

Backcalculation Results for Wide Modulus Range Method

Figure 14 plots the backcalculated surface layer modulus using the wide modulus range method, with the absolute GPR thickness error. Each point on the plot represents the data for one test location. Although no apparent trend can be observed in the graph, one can see that there are a number of locations with high GPR error that also have surface moduli values at the 3000 ksi limit. The boundary limit of 3000 ksi was chosen to account for the possibility of very stiff AC surface layers. However, surface layer moduli greater than 1500 ksi could be considered questionable. None of the locations met the lower boundary limit of 100 ksi. These questionable moduli should be subject to further investigation. Had the modulus range been inputted at 100 to 1500 ksi, then every location with thickness error greater than 28 percent would have hit a boundary limit. The problem with lowering the boundary limit is that a significant number of locations with low GPR error would also hit the boundary limit.

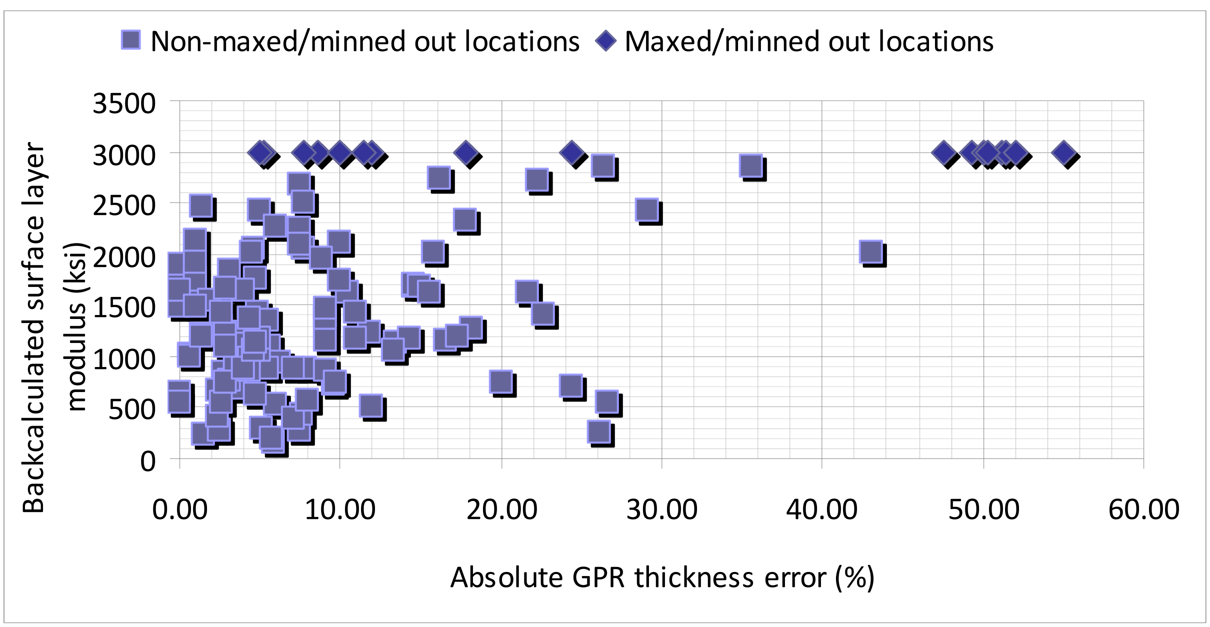


Figure 14. Trend analysis of backcalculated surface layer modulus using wide modulus range method.

MODULUS does not have a temperature correction feature for its full analysis backcalculation option. In order to normalize the backcalculated modulus, an adjustment factor was applied to the backcalculated modulus using the WSDOT relationship equation for Class B asphalt concrete (Equation 3a). This method for temperature correction is also present in MDT's ADAP manual. The adjustment factor is the ratio between the estimated AC moduli at a reference temperature (75°F) and the pavement temperature at the time of FWD testing (Equation 3b). The normalized modulus is equated from multiplying the backcalculated modulus by adjustment factor (Equation 3c).

$$\log E_{AC} = 6.4721 - 1.47362 \times 10^{-4} \times (T_P)^2$$

Equation 3a

Where,

E_{AC} = estimated modulus of the AC surface layer, and

T_P = temperature of the pavement

$$TAF = \frac{(E_{AC})_{75°F}}{(E_{AC})_{T_P}}$$

Equation 3b

Where,

TAF = temperature adjustment factor,

$(E_{AC})_{75°F}$ = estimated modulus of the AC surface layer at a pavement temperature of 75°F, and

$(E_{AC})_{T_P}$ = estimated modulus of the AC surface layer at the pavement temperature during FWD testing

$$(E_{AC})_{norm} = TAF \times (E_{AC})_{backcalc}$$

Equation 3c

Where,

$(E_{AC})_{norm}$ = normalized AC modulus,

TAF = temperature adjustment factor, and

$(E_{AC})_{backcalc}$ = backcalculated AC modulus

Figure 15 shows the data from Figure 14 after temperature normalization. Temperature normalization does not appear to produce a trend. In comparison to the non-normalized moduli, it appeared that temperature normalization had reduced the surface layer moduli at most locations. This is because most of the locations were tested at pavement temperatures less than 75°F. Site 23 was the exception, as it was tested at a pavement temperature of approximately 93°F. This caused the backcalculated moduli at Site 23 to increase from about 1200 ksi to 3300 ksi.

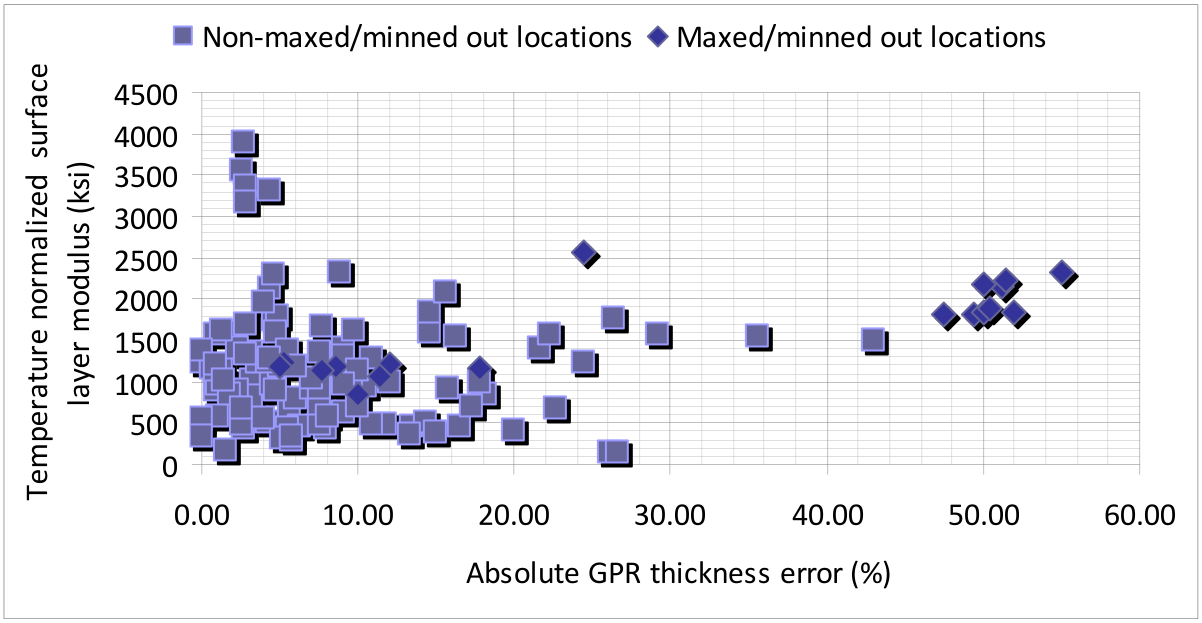


Figure 15. Trend analysis of backcalculated surface layer modulus (using wide modulus range method) normalized by temperature.

Figure 16 shows the absolute error of the sensor output from the backcalculation. As discussed earlier, the amount of freedom the wide modulus range method gives the program allows it to backcalculate deflection bowls with low errors. For this analysis, most of the locations had a backcalculation error value between 0% and 3%. The majority of locations with high absolute error values were from three particular sites (Site 4, Site 7, and Site 9). Note that while a number of data points with high GPR error also have high backcalculation error, there are also points where high backcalculation error corresponds to low GPR error.

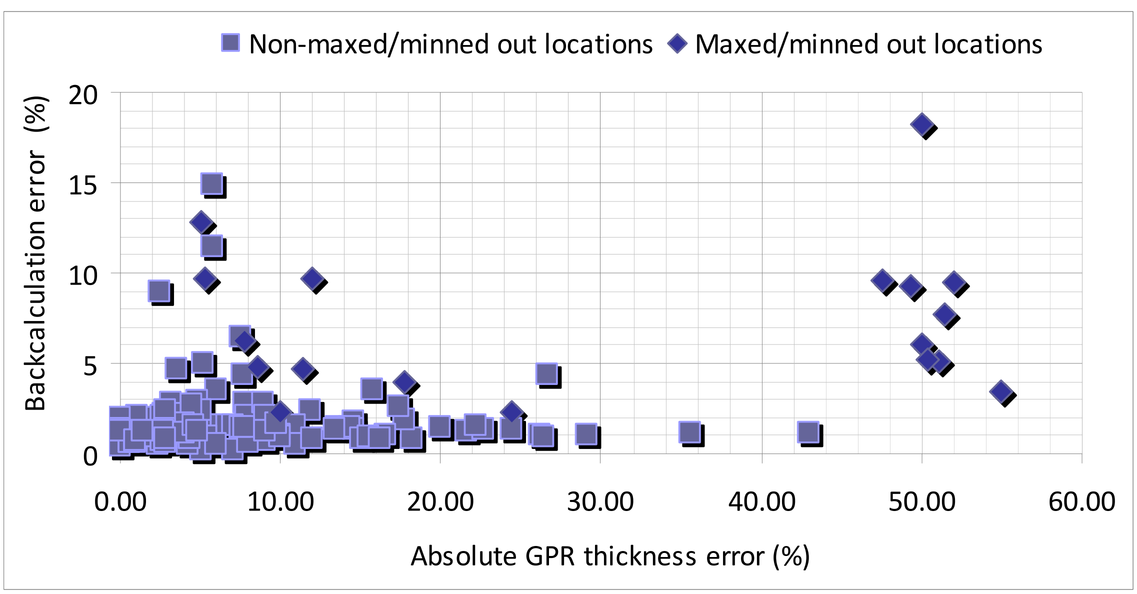


Figure 16. Absolute error of the sensor output from the backcalculation.

Backcalculation Results for ADAP User's Manual Based Values

Figure 17 plots the backcalculated surface layer modulus with the absolute GPR thickness error. No trend was expected since the moduli of all layers were restricted to constraints that were considered reasonable. The majority of locations that met boundary limits had surface layer moduli between 300 and 600 ksi. Compared to the wide modulus range method, there were a higher percentage of locations that met the boundary limit. Figure 17 suggests that meeting the boundary limit using this method is not a valid indication of when a site requires further investigation. Temperature normalization was also carried out on this data, but this did not lead to any improvement related to error checking.

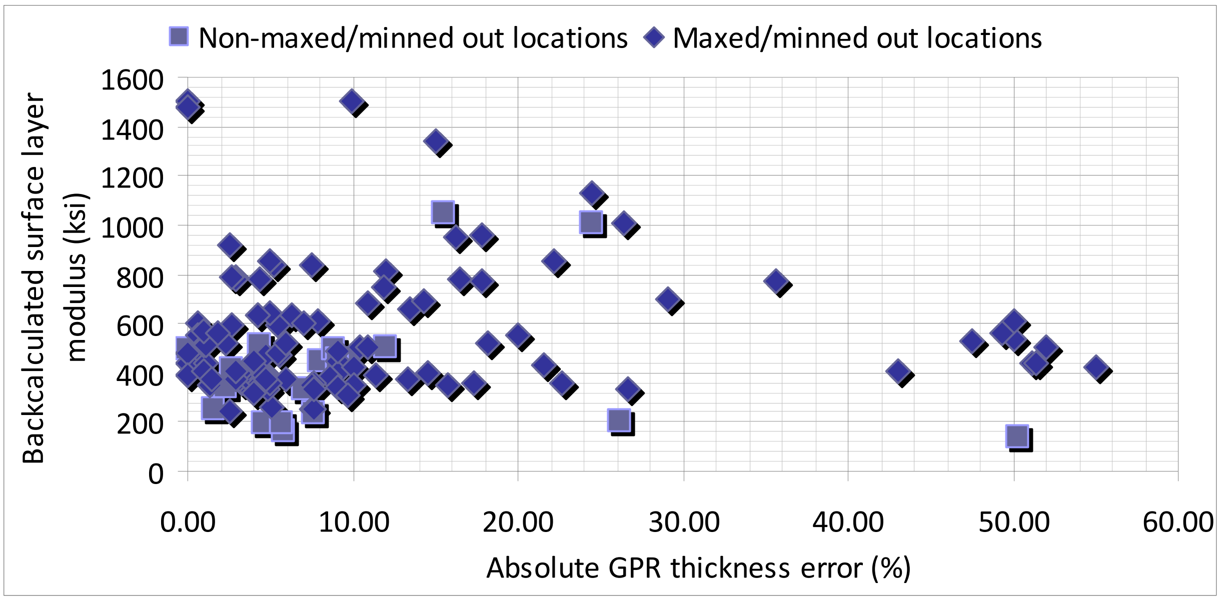


Figure 17. Trend analysis of backcalculated surface layer modulus using ADAP-based method.

Figure 18 plots the backcalculation error with the absolute GPR thickness error. The ADAP-based method restricted backcalculated moduli to reasonable ranges. It was expected that backcalculated error would be much more dependent on accuracy of layer thicknesses. However, Figure 18 shows that no trend is evident. The only observation that could be made was that layer thickness errors of greater than 30% did not produce backcalculation errors of less than 5%.

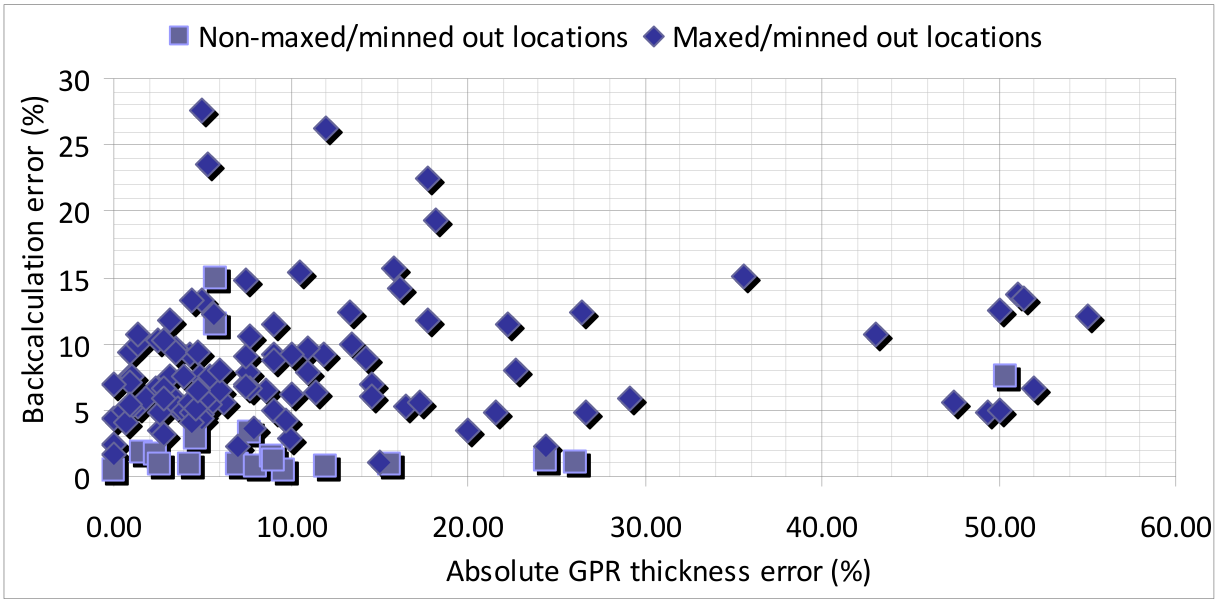


Figure 18. Trend analysis of backcalculation error using the ADAP-based method.

Similar trend analyses have been carried out considering backcalculated subgrade MODULUS and area values, neither of which led to any noteworthy result. The analysis results were also differentiated by base type (bound or unbound), with no revealing trends.

Comparison of MODULUS and EVERCALC

The lack of trends in the QC analyses described above could possible by attributed to the nature of the backcalculation program. To explore this issue, the surface layer moduli and backcalculation errors produced with the MODULUS program were compared to similar results obtained using EVERCALC, developed by WSDOT. Locations from four sites (Sites 1, 2, 9, and 17) with variable layer thickness error were selected for this comparison. Layer thicknesses from the GPR dataset were used for all layers (bound and unbound).

Figure 19 indicates the backcalculated surface layer moduli using either program are close to each other. In Figure 20, the backcalculation error for EVERCALC appears to be much larger than that for MODULUS, but there is no trend with increasing layer thickness error.

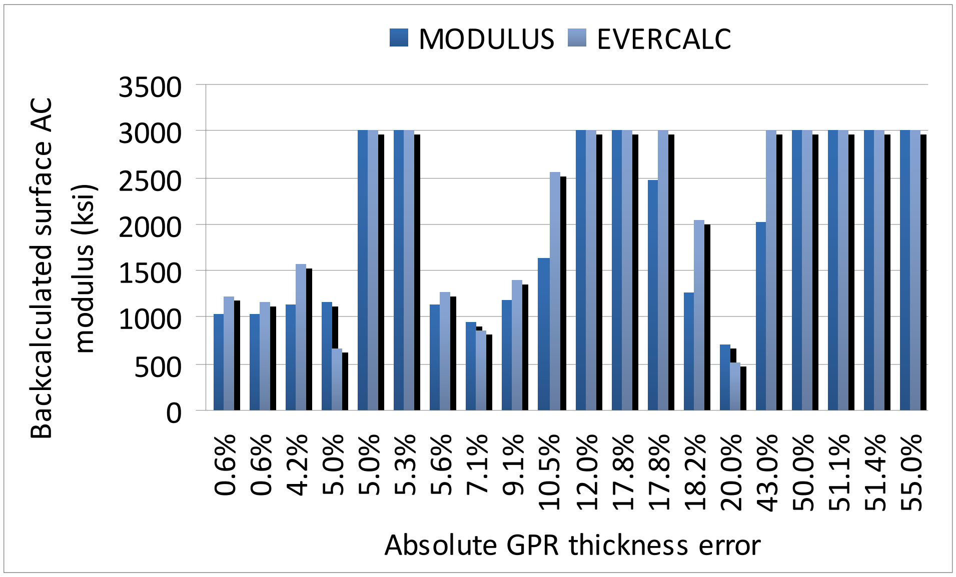


Figure 19. Backcalculated surface layer moduli (wide modulus range method) using MODULUS and EVERCALC for Sites 1, 2, 9, and 17.

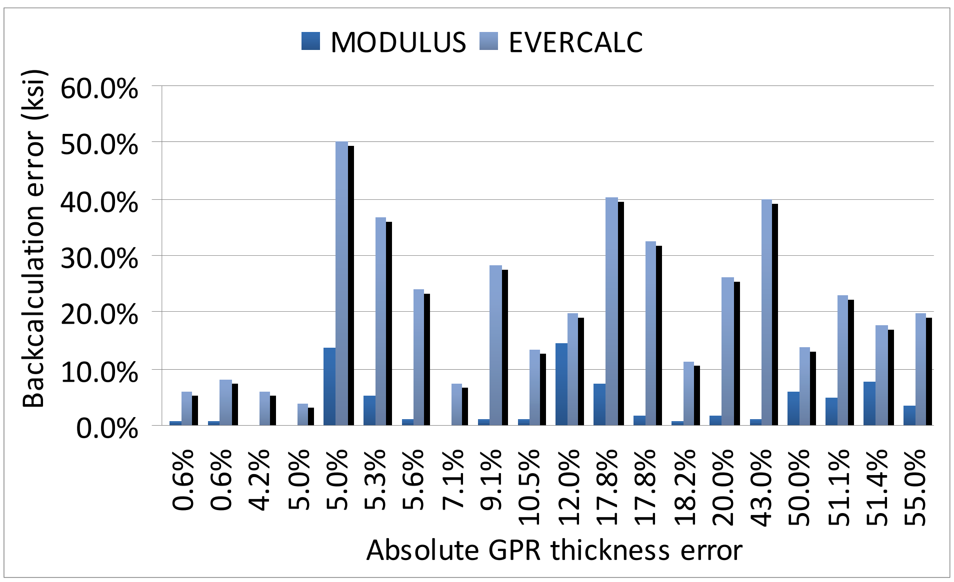


Figure 20. Backcalculation error (wide modulus range method) using MODULUS and EVERCALC for Sites 1, 2, 9, and 17.

3.4. Data Checking Method and Result

Based on the above analysis, a data checking method for GPR asphalt thickness was proposed and tested. The purpose of the method is to determine if the GPR data should be reviewed and possible re-analyzed or re-interpreted. The checking method is based on three indicators – the backcalculated asphalt modulus using the wide range method; the backcalculation error using the wide range method, and the difference between the GPR value and the as-built data. The as-built deviation was added to complete the checking procedure. While it is expected that actual thicknesses will deviate from as-built data, it is reasonable to observe this deviation and to consider it as a factor in deciding whether or not to review the GPR data analysis.

A threshold value is required for each of the three indicators described above. After some trial and error with different thresholds, the following thresholds were established:

- Asphalt Modulus: 2500 ksi
- Backcalculation Error: 3.0%
- Deviation from as-built: 1.0 inches

Table 13 shows the result of the error check for the global plate data collected in the spring. The columns labeled "Check Test" represent the check criteria described above. An "x" entered under the test means that the threshold has been exceeded for that particular criterion. If, for a given site, more than one check criterion has been exceeded (i.e., it has two or more x's), then the recommendation is to check the GPR data.

Based on applying this checking procedure, four sites were identified for checking. Note that all of these four sites had errors (GPR vs. core) of greater than 11% and three had the highest percent errors of the 26 sites. This indicates that the checking procedure has successfully identified the highest errors.

The next step in the checking process is to review the GPR data at each of the sites indicated and see if there is an alternative analysis or interpretation that would remove that site from the checked list.

Table 13. Results of error checking.

Site No.	Average Asphalt Depth (in)				Check Criteria			Check Test			Check
								E (ksi) >	GPR-Plan (in.) >	Abs Error (%)* >	
	Plan	GPR	Core	GPR Error	E (ksi) >	Abs Err (%)	GPR-Plan	2500	1.00	3%	
01	3.00	6.78	6.00	13.0%	1185.8	1.2%	3.78		x		OK
02	3.00	3.70	7.40	50.0%	2803.8	4.8%	0.70	x		x	check
03	3.48	3.62	3.20	13.1%	987.8	2.3%	0.14				OK
04	3.00	1.92	3.83	49.8%	3000.0	8.3%	-1.08	x	x	x	check
05	8.64	8.74	8.30	5.3%	972.6	1.4%	0.10				OK
06	3.60	4.08	3.93	3.9%	951.0	2.2%	0.48				OK
07	3.60	3.98	3.80	4.7%	257.8	10.2%	0.38			x	OK
08	4.20	4.84	4.70	3.0%	741.8	2.2%	0.64				OK
09	4.32	4.84	4.55	6.4%	2891.8	8.6%	0.52	x		x	check
10	4.92	4.92	5.65	12.9%	1434.2	1.6%	0.00				OK
11	9.00	12.42	10.95	13.4%	1160.6	1.6%	3.42		x		OK
12	4.68	5.74	5.40	6.3%	1540.6	0.8%	1.06		x		OK
13	3.60	4.08	4.40	7.3%	2232.6	1.6%	0.48				OK
14	3.60	4.04	3.55	13.8%	2374.2	4.3%	0.44			x	OK
15	4.56	4.80	4.75	1.1%	1626.4	1.5%	0.24				OK
16-wet	8.04	7.60	8.40	9.5%	1293.0	66.2%	-0.44			x	OK
16-dry	8.04	8.28	8.40	1.4%	535.2	1.2%	0.24				OK
17	6.00	8.14	8.15	0.1%	1062.4	0.4%	2.14		x		OK
18	4.08	4.04	4.00	1.0%	1605.6	23.3%	-0.04			x	OK
19	7.20	5.12	5.15	0.6%	1930.8	0.7%	-2.08		x		OK
20	2.40	2.74	2.35	16.6%	870.2	1.0%	0.34				OK
21	2.76	5.82	5.45	6.8%	479.4	1.0%	3.06		x		OK
22	3.86	4.10	3.83	7.2%	2072.0	1.2%	0.24				OK
23	8.27	10.24	10.28	0.3%	1251.2	1.7%	1.97		x		OK
24	9.45	7.56	10.20	25.9%	2569.0	1.1%	-1.89	x	x		check
25	4.80	4.92	5.03	2.1%	858.0	1.2%	0.12				OK
26	4.80	5.24	5.23	0.3%	1422.2	1.1%	0.44				OK

x = criteria criterion is exceeded
shaded cells = sites whose GPR data is to be checked
* Abs Error (%) = backcalculation error discussed earlier

The analysis described above suggests that checking be carried out at sites 2, 4, 9, and 24. Note that three of these four sites had the highest GPR error, so the check was successful at highlighting significant errors. Since all four of the identified sites had asphalt moduli that exceeded the threshold, the analyst was instructed to review the GPR data at these four sites and see if an alternative interpretation leading to a thicker AC layer was possible, and, if so, to provide the alternative thickness data. The results of this review are shown in Table 14.

Table 14. Results of review of checked sites

Site	Location	AC Thickness (in.) Plan	Initial GPR	Alternative GPR 1st	2nd	3rd	Notes
2	01	3.0	3.3	4.0	5.9	7.5	Layer structure unclear in the GPR data at this site; alternative AC thickness needs to be selected.
	02		3.5	4.5	6.0	7.7	
	03		3.4	4.2	5.9	7.7	
	04		3.6	4.6	6.7	8.7	
	05		4.7	5.3	7.5	9.1	
4	01	3.0	2.1	3.3	5.0	7.5	Layer structure unclear in the GPR data at this site; alternative AC thickness needs to be selected.
	02		1.9	3.2	5.2	7.1	
	03		2	3.5	5.6	7.4	
	04		1.8	2.8	4.8	5.9	
	05		1.8	3.1	4.8	6.4	
9	01	4.32	5.3	none	none	none	Layer structure is clear in the GPR data.
	02		5.3	none	none	none	
	03		4.4	none	none	none	
	04		5	none	none	none	
	05		4.2	none	none	none	
24	01	9.45	8.8	10.5	none	none	Alternative GPR 1 was initially thought to include PULV layer; Since the bottom of this layer is clear in the GPR data it represents an appropriate alternative.
	02		9.2	12.0	none	none	
	03		6.6	7.8	none	none	
	04		7.0	8.4	none	none	
	05		6.2	7.6	none	none	

Table 14 shows two different scenarios. For Site 9, the original analysis was clear and no alternative was proposed. For Sites 2, 4, and 24, alternative AC thickness values are proposed. These alternatives are evaluated by recalculating the modulus and absolute error using the alternative to see if the resulting values no longer exceed the thresholds. For Site 24, use of the alternative thickness yields E_{avg} and Abs Error (backcalculation error) values that eliminate it as a site to be checked, so the original thickness will be replaced with the alternative (9.25 inches average). Site 2 and Site 4 were processed, as with Site 24, starting with the first alternative thickness and progressing to the second and third alternative until a point was reached where the site was eliminated as a site to be checked. The alternate layer thickness that produced this result then replaces the original value. In the case of Sites 2 and 4, the resulting AC thickness values are:

- Site 2: 6.4 inches average thickness (2nd alternative)
- Site 4: 5.1 inches average thickness (2nd alternative)

Table 15 shows the results of Table 12 after updating the data from Sites 2, 4, and 24. Note that after the update only Site 9 remains as a check site. Since the GPR data at that site shows no alternate GPR layers, no further adjustment is made.

Table 15. Updated data after error checking.

Site No.	Average Asphalt Depth (in)				Check Criteria			Check Test			
								E (ksi) >	GPR-Plan (in.) >	Abs Error (%) >	
	Plan	GPR	Core	GPR Error	E (ksi) >	Abs Err (%)	GPR-Plan	2500	1.00	3%	Check
01	3.00	6.78	6.00	13.0%	1185.8	1.2%	3.78		x		OK
02	3.00	6.40	7.40	13.5%	1044.6	1.9%	3.40		x		OK
03	3.48	3.62	3.20	13.1%	987.8	2.3%	0.14				OK
04	3.00	5.09	3.83	33.0%	905.0	1.1%	2.09		x		OK
05	8.64	8.74	8.30	5.3%	972.6	1.4%	0.10				OK
06	3.60	4.08	3.93	3.9%	951.0	2.2%	0.48				OK
07	3.60	3.98	3.80	4.7%	257.8	10.2%	0.38			x	OK
08	4.20	4.84	4.70	3.0%	741.8	2.2%	0.64				OK
09	4.32	4.84	4.55	6.4%	2891.8	8.6%	0.52	x		x	check
10	4.92	4.92	5.65	12.9%	1434.2	1.6%	0.00				OK
11	9.00	12.42	10.95	13.4%	1160.6	1.6%	3.42		x		OK
12	4.68	5.74	5.40	6.3%	1540.6	0.8%	1.06		x		OK
13	3.60	4.08	4.40	7.3%	2232.6	1.6%	0.48				OK
14	3.60	4.04	3.55	13.8%	2374.2	4.3%	0.44			x	OK
15	4.56	4.80	4.75	1.1%	1626.4	1.5%	0.24				OK
16-wet	8.04	7.60	8.40	9.5%	1293.0	66.2%	-0.44			x	OK
16-dry	8.04	8.28	8.40	1.4%	535.2	1.2%	0.24				OK
17	6.00	8.14	8.15	0.1%	1062.4	0.4%	2.14		x		OK
18	4.08	4.04	4.00	1.0%	1605.6	23.3%	-0.04			x	OK
19	7.20	5.12	5.15	0.6%	1930.8	0.7%	-2.08		x		OK
20	2.40	2.74	2.35	16.6%	870.2	1.0%	0.34				OK
21	2.76	5.82	5.45	6.8%	479.4	1.0%	3.06		x		OK
22	3.86	4.10	3.83	7.2%	2072.0	1.2%	0.24				OK
23	8.27	10.24	10.28	0.3%	1251.2	1.7%	1.97		x		OK
24	9.45	9.25	10.20	9.4%	1762.8	1.0%	-0.20				OK
25	4.80	4.92	5.03	2.1%	858.0	1.2%	0.12				OK
26	4.80	5.24	5.23	0.3%	1422.2	1.1%	0.44				OK

gray area = the sites were checked based on Table 13

Use of these alternative asphalt thickness results reduces the overall error in the analysis. For example, through this error checking and alternative interpretation process the average asphalt thickness error of 10.3% for the spring global plate (see Table 7) is reduced to 7.6%, and the base thickness error of 18.7% is reduced to 17.8%

4. SENSITIVITY ANALYSIS

One objective of this study was to determine the sensitivity of the design of reconstructed or rehabilitated pavement to the accuracy of the layer thickness data provided for the design process. In particular, it is of interest to compare the use of as-built and GPR layer thickness to quantify the benefit achieved by using GPR. In order to accomplish this, an overlay design was conducted on each using a fixed traffic loading. Once the overlay thickness has been designed the estimated life of the pavement was calculated using the layer thicknesses from coring (AASHTO, 1993). The overlay thickness and design lives from designs based on as-built and GPR data were compared to the design based on coring data, which is considered “ground truth”. There were three steps to completing this sensitivity analysis:

- Determine the effective structural capacity (number) of the pavement using layer thickness data from as-built plans, GPR, and coring.
- Design an overlay for each site using the effective structural number for each of these 3 cases and a constant traffic loading (design life).
- Compare the design life of the overlayed pavement predicted from the as-built plan and GPR data with the “actual” design life based on the layer thicknesses determined from coring.

The GPR asphalt layer thickness values used in this analysis were those obtained after the error checking procedure described in the last section. It was established earlier in this report that on average as-built layer thicknesses were more accurate than GPR layer thicknesses for unbound layers. When analyzing GPR data in this sensitivity analysis, only the thicknesses for bound layers were determined from GPR while thicknesses of unbound layers were assumed from the as-built plans. For the core thickness data, note that coring was not always able to determine the depth of the base or subbase layers. When calculating the average layer thicknesses at a site from core data, an average is taken based only on the locations where a thickness for a particular layer is available. If only one of the five showed a coring thickness for a particular layer, then that thickness is assumed to be the average for the site. With this method, 11 of the 26 sites have an average layer thickness available for every layer in the pavement. The remaining 15 sites are missing layer thicknesses for at least one layer at all five coring locations.

At sites where base layer data was missing, subgrade modulus used for the ground truth data was assumed to be the modulus calculated using the Boussineq one-layer equation (Equation 2a and 2b). Table 16 compares the backcalculated subgrade modulus of the 11 sites (where coring determined a layer thickness for every layer in the structure) to the estimated modulus from the Boussinesq equation for those. From the table, it can be calculated that the average absolute error of the Boussineq estimated modulus was 11.25%. Coring data in this analysis is considered ground truth. To design an overlay based on the ground truth, the subgrade modulus is divided by two and used along with the structural number from coring in the AASHTO 1993 design equation.

Table 16. Comparison of subgrade modulus backcalculated from coring thicknesses (when possible) to modulus estimated using the Boussinesq one-layer equation.

SITE NO.	BACKCALCULATED	BOUSSINESQ	PERCENT ERROR
03	8230	7000	-15%
06	9700	9000	-7%
07	5880	5000	-15%
10	11770	11000	-7%
12	15430	15000	-3%
13	13400	11000	-18%
16-dry	23700	14000	-41%
16-wet	21900	19500	-11%
18	24250	23500	-3%
19	14760	16000	8%
21	11200	12000	7%
26	8020	8000	0%

Effective Structural Capacity

The structural number for each site was determined by the sum of the thickness of each layer multiplied by its layer coefficient (Equation 4). Layer coefficients were dependent on the layer's material type and can be found in Table 17. MDT's standard practice is to adjust coefficients of existing layers based on the condition of the materials. The coefficients in Table 17 vary slightly from MDT's coefficients and were not varied based on the condition of the layer because the team did not have the information required to determine the layer condition. However, because the purpose was to compare overlay thicknesses, the findings from this comparison yield applicable results regarding the differences in overlay designs as a result of using GPR, as-builts, or coring data to quantify the existing pavement structure. GPR layer thicknesses for each location were averaged, when available, to represent the entire site. The same was true when calculating the layer thickness for coring data. In order to keep the sensitivity analysis equitable, it was necessary to ignore layers available in as-built plan or GPR data, but unavailable in coring data. For example, at Sites 11 and 14 the auger did not bore through the entire base layer and the thickness of the base could not be established. For this case, the base and subbase layers were ignored when calculating the structural number using as-built or GPR data. The structural numbers of Sites 11 and 14, as an exception, are based solely on the AC layer for all three (GPR, as-built, and coring) designs in order to keep the analysis unbiased and consistent. The purpose of the analysis was to compare results from GPR, as-builts, and coring to determine differences in overlay thickness design. Only using AC layer thicknesses for the two sites where base thicknesses were unavailable for coring would not be adequate for use in an actual overlay design, but for comparison purposes in this analysis, it allowed unbiased evaluation.

$$SN_{eff} = \sum_{i=1}^{n} a_i \times D_i$$

Equation 4

Where,

SN_{eff} = effective structural number pavement structure,
i = layer number,
n = total number of layers excluding the subgrade,
a_i = layer coefficient of layer i, and
D_i = layer thickness of layer i

Table 17. Layer coefficient for different material types.

MATERIAL TYPE	LAYER COEFFICIENT
Plant-mix surfacing	0.33
Recycled surfacing	0.25
Asphalt treated base	0.25
Cement treated base	0.28
Pulverized material	0.12
Unbound base	0.10
Special borrow	0.07
A-1-a base	0.07

Overlay Design

After an effective pavement structural number had been calculated, a future structural number was then calculated using the AASHTO 1993 design equation (Equation 5a) with the desired traffic loading (design life) and the backcalculated (ADAP-based method) modulus of the subgrade divided by two according to MDT's design procedure.

The structural number of the overlay is the difference between the future structural number and the effective structural number (Equation 5b). If the effective structural number was greater than the future structural number, then no overlay was required. The thickness of the overlay was determined by dividing the overlay structural number by the layer coefficient for a new AC layer (0.44). Comparing the overlay thickness of as-built and GPR based designs to the design based on coring determined whether as-built or GPR data caused the pavement to be over or under-designed.

Estimated Pavement Performance

Estimating the true design life of a pavement designed using as-built or GPR data requires assessment of a pavement structure where the designed overlay was placed on top of the existing ground truth structure. The estimated life of the pavement in terms of ESALs was calculated using the AASHTO 1993 design equation (Equation 5a). In the design equation, the true structural number of the pavement is equal to the ground truth structural number of the existing pavement plus the structural number of the designed overlay (Equation 5c). According to MDT standard practice, the subgrade modulus in the design equation was the subgrade modulus calculated from the coring data divided by two. All other inputs in the design equation were kept constant.

$$\log_{10}(W_{18}) = Z_R \times S_o + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07$$

Equation 5a

Where,

W_{18} = predicted number of 18,000 lb ESALs,
Z_R = standard normal deviate (assume -1.645),
S_o = combined standard error of the traffic prediction and performance prediction (assume 0.45),
SN = structural number of pavement structure,
ΔPSI = difference between the initial design serviceability index, p_o, and the terminal serviceability, p_t (assume 2), and
M_R = subgrade resilient modulus (psi)

$$SN_{OL} = SN_{fut} - SN_{eff}$$

Equation 5b

Where,

SN_{OL} = structural number of the overlay,
SN_{fut} = future (design) structural number of the pavement, and
SN_{eff} = effective structural number of the pavement

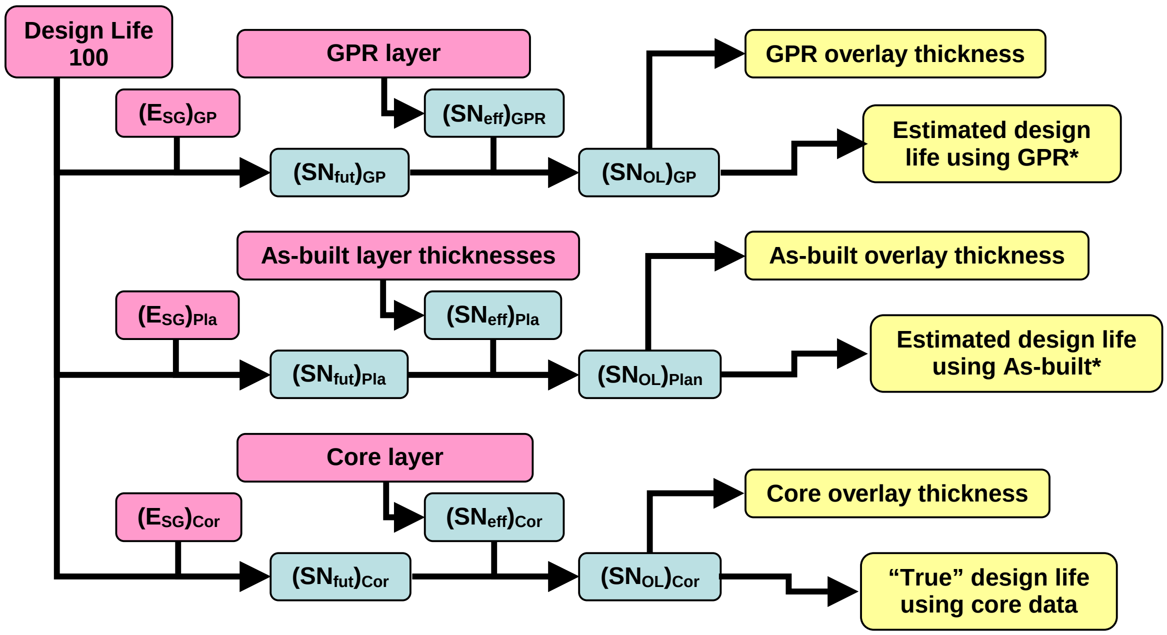
$$(SN_{act})_X = (SN_{OL})_X + (SN_{eff})_{Core}$$

Equation 5c

Where,

X = dataset used in design (i.e., as-built or GPR),
SN_{act} = the actual structural number of the pavement with the designed overlay,
SN_{OL} = structural number of the overlay, and
SN_{eff} = effective structural number of the pavement

Essentially, the sensitivity analysis had seven inputs (as-built layer thicknesses and subgrade modulus, GPR layer thickness and subgrade modulus, coring layer thickness and subgrade modulus, and design life in terms of traffic) and five outputs (as-built plan overlay thickness, GPR overlay thickness, coring overlay thickness, estimated as-built plan design life, and estimated GPR design life) as shown in Figure 21.



*Estimated design life is based on GPR (or as-built) overlay thickness placed on existing pavement structure obtained from core results

Figure 21. Sensitivity analysis inputs and outputs.

4.1. Sensitivity Analysis Results

Table 18 provides results of the overlay design for all sites in the analysis. The future structural number, SN_{fut}, was iteratively calculated based the subgrade resilient modulus, E_{SG}, and a design life of 100 million ESALs, W_{18}. The overlay structural number is the difference between the future structural number and the effective structural number. The overlay thickness (inches) is shown for as-built plan, GPR, and coring designs. If the required future structural number was greater than the effective structural number of the existing pavement, no overlay was required (i.e., $SN_{OL} = 0$). Figure 22 is graph of the overlay thickness at each site. The graph shows that typically overlay thickness were relatively close in comparison of as-built, GPR, and coring designs.

Table 18. Design of overlay thickness.

Site No.	As-Built						GPR						Coring					
	E_{SG}	W_{18}	SN_{fut}	SN_{eff}	SN_{OL}	Thk	E_{SG}	W_{18}	SN_{fut}	SN_{eff}	SN_{OL}	Thk	E_{SG}	W_{18}	SN_{fut}	SN_{eff}	SN_{OL}	Thk
01	13,040	1.00E+08	5.42	1.17	4.25	9.7	22,250	1.00E+08	4.57	2.42	2.15	4.9	14,500	1.00E+08	5.25	2.16	3.09	7.0
02	13,510	1.00E+08	5.36	1.17	4.19	9.5	21,600	1.00E+08	4.62	2.29	2.32	5.3	14,500	1.00E+08	5.25	2.60	2.65	6.0
03	7,960	1.00E+08	6.30	2.79	3.51	8.0	7,870	1.00E+08	6.32	3.09	3.23	7.3	8,230	1.00E+08	6.23	3.24	3.00	6.8
04	17,950	1.00E+08	4.90	1.17	3.73	8.5	16,130	1.00E+08	5.07	1.86	3.21	7.3	12,500	1.00E+08	5.49	1.38	4.11	9.4
05	16,830	1.00E+08	5.00	3.55	1.46	3.3	16,730	1.00E+08	5.01	3.58	1.43	3.3	14,500	1.00E+08	5.25	3.61	1.64	3.7
06	9,510	1.00E+08	5.97	2.39	3.58	8.1	9,730	1.00E+08	5.93	2.55	3.38	7.7	9,700	1.00E+08	5.94	2.42	3.52	8.0
07	6,060	1.00E+08	6.82	2.39	4.43	10.1	6,130	1.00E+08	6.80	2.51	4.29	9.7	5,880	1.00E+08	6.88	1.78	5.10	11.6
08	21,680	1.00E+08	4.61	2.39	2.22	5.0	20,750	1.00E+08	4.68	2.61	2.07	4.7	17,000	1.00E+08	4.99	2.57	2.42	5.5
09	24,150	1.00E+08	4.45	2.40	2.05	4.6	39,600	1.00E+08	3.76	2.58	1.18	2.7	25,000	1.00E+08	4.40	2.58	1.82	4.1
10	11,200	1.00E+08	5.68	2.32	3.36	7.6	11,240	1.00E+08	5.68	2.32	3.36	7.6	11,770	1.00E+08	5.60	2.65	2.94	6.7
11	24,760	1.00E+08	4.41	2.97	1.44	3.3	30,420	1.00E+08	4.12	4.10	0.02	0.0	18,500	1.00E+08	4.86	3.61	1.24	2.8
12	15,840	1.00E+08	5.10	3.60	1.51	3.4	16,500	1.00E+08	5.04	3.95	1.09	2.5	15,430	1.00E+08	5.14	3.93	1.21	2.8
13	12,070	1.00E+08	5.55	2.57	2.99	6.8	12,720	1.00E+08	5.46	2.73	2.74	6.2	13,400	1.00E+08	5.38	3.27	2.10	4.8
14	7,190	1.00E+08	6.49	1.19	5.30	12.0	7,490	1.00E+08	6.41	1.33	5.08	11.5	8,000	1.00E+08	6.29	1.17	5.12	11.6
15	8,890	1.00E+08	6.09	1.96	4.13	9.4	9,020	1.00E+08	6.07	2.04	4.03	9.2	9,000	1.00E+08	6.07	2.02	4.05	9.2
16-dry	22,710	1.00E+08	4.54	6.20	0.00	0.0	24,650	1.00E+08	4.42	6.27	0.00	0.0	23,700	1.00E+08	4.48	6.85	0.00	0.0
16-wet	20,300	1.00E+08	4.71	6.20	0.00	0.0	21,200	1.00E+08	4.65	6.05	0.00	0.0	21,900	1.00E+08	4.60	6.85	0.00	0.0
17	12,530	1.00E+08	5.49	2.40	3.09	7.0	14,800	1.00E+08	5.21	3.11	2.11	4.8	14,000	1.00E+08	5.30	3.48	1.83	4.2
18	23,850	1.00E+08	4.47	5.14	0.00	0.0	23,900	1.00E+08	4.47	4.73	0.00	0.0	24,250	1.00E+08	4.44	5.13	0.00	0.0
19	16,380	1.00E+08	5.05	4.48	0.57	1.3	13,660	1.00E+08	5.34	3.79	1.55	3.5	14,760	1.00E+08	5.22	3.21	2.01	4.6
20	13,060	1.00E+08	5.42	3.79	1.63	3.7	12,950	1.00E+08	5.43	3.75	1.68	3.8	12,500	1.00E+08	5.49	3.78	1.71	3.9
21	10,660	1.00E+08	5.77	5.18	0.59	1.3	11,480	1.00E+08	5.64	5.85	0.00	0.0	11,200	1.00E+08	5.68	6.00	0.00	0.0
22	5,650	1.00E+08	6.96	1.46	5.51	12.5	5,640	1.00E+08	6.97	1.53	5.43	12.3	6,500	1.00E+08	6.68	1.46	5.22	11.9
23	18,890	1.00E+08	4.82	5.41	0.00	0.0	21,320	1.00E+08	4.64	5.87	0.00	0.0	15,000	1.00E+08	5.19	6.04	0.00	0.0
24	16,880	1.00E+08	5.00	2.60	2.40	5.5	18,560	1.00E+08	4.85	2.55	2.30	5.2	12,500	1.00E+08	5.49	2.69	2.81	6.4
25	7,410	1.00E+08	6.43	1.76	4.67	10.6	7,470	1.00E+08	6.42	1.80	4.61	10.5	7,500	1.00E+08	6.41	1.84	4.57	10.4
26	8,170	1.00E+08	6.25	2.90	3.34	7.6	8,350	1.00E+08	6.21	3.05	3.16	7.2	8,020	1.00E+08	6.28	3.04	3.24	7.4

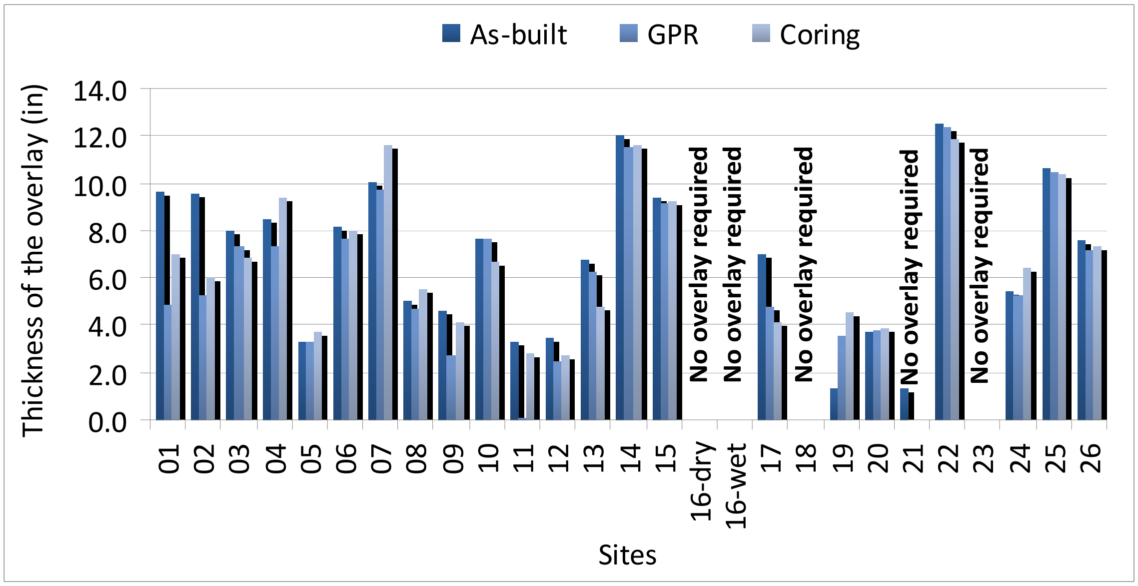


Figure 22. Site overlay thicknesses.

Table 19 shows the error in overlay thickness using as-built and GPR layer thicknesses. Positive error indicates that as-built or GPR over-designed and negative error indicates an under-design. Overlay error and surface layer thickness error will only correlate if all other factors used in the design procedure were kept constant. The design based on coring used a different subgrade modulus and subsurface layer thicknesses than the design using as-built or GPR data. For example, Site 11 had an average surface layer thickness error of 13.4% an overlay thickness error of -2.8 inches, while Site 20 hand an average surface layer thickness error of 16.6% and an overlay thickness error of -0.1 inches. This is because the base thickness at Site 20 compensated for the lack of surface layer thickness to produce a subgrade modulus and effective structural number that was very close to the ground truth.

Table 19. Error in overlay thickness (inches).

SITE	AS-BUILT	GPR
01	+2.7	-2.1
02	+3.5	-0.7
03	+1.2	+0.5
04	-0.9	-2.0
05	-0.4	-0.5
06	+0.2	-0.3
07	-1.5	-1.8
08	-0.5	-0.8
09	+0.5	-1.4
10	+1.0	+0.9
11	+0.5	-2.8
12	+0.7	-0.3
13	+2.0	+1.4
14	+0.4	-0.1

SITE	AS-BUILT	GPR
15	+0.2	-0.0
16-dry	+0.0	+0.0
16-wet	+0.0	+0.0
17	+2.9	+0.6
18	+0.0	+0.0
19	-3.3	-1.0
20	-0.2	-0.1
21	+1.3	+0.0
22	+0.6	+0.5
23	+0.0	+0.0
24	-0.9	-1.1
25	+0.2	+0.1
26	+0.2	-0.2

There are advantages and disadvantages to under or over-designing an overlay. The tradeoff is initial construction cost versus the resulting service life. When a pavement overlay is over-designed, the initial construction cost of the overlay is greater than necessary, but the pavement is expected to last longer than the design life. Conversely, when a pavement overlay is under-designed, the overlaid pavement does not last as long expected, but initial construction costs are less. Table 20 shows the true life (in terms of ESALs) of the overlaid pavement. Sites 16-dry, 16-wet, 18, 21, and 23 were excluded from the analysis, since the design from coring data indicated that no overlay was required. Figure 23 graphs the service life of each pavement design (As-Built and GPR) with ground truth (coring) design set at 100 million ESALs.

Table 20. Estimated true pavement service life.

SITE NO.	AS-BUILT		GPR		CORING		DESIGN LIFE ERROR	
	SN_{act}	W_{18} (M)	SN_{act}	W_{18} (M)	SN_{act}	W_{18} (M)	AB*	GPR
01	6.41	463.57	4.31	24.71	5.25	100.00	364%	-75%
02	6.79	731.67	4.92	62.85	5.25	100.00	632%	-37%
03	6.74	185.16	6.46	132.86	6.23	100.00	85%	33%
04	5.11	58.52	4.59	27.07	5.49	100.00	-41%	-73%
05	5.06	77.18	5.04	74.60	5.25	100.00	-23%	-25%
06	6.00	109.14	5.80	84.19	5.94	100.00	9%	-16%
07	6.22	44.88	6.07	37.21	6.88	100.00	-55%	-63%
08	4.79	74.38	4.64	59.78	4.99	100.00	-26%	-40%
09	4.63	142.50	3.76	34.71	4.40	100.00	42%	-65%
10	6.01	173.45	6.01	172.08	5.60	100.00	73%	72%
11	5.06	134.33	3.63	13.65	4.86	100.00	34%	-86%
12	5.44	150.89	5.02	83.85	5.14	100.00	51%	-16%
13	6.26	318.69	6.01	232.94	5.38	100.00	219%	133%
14	6.47	125.56	6.25	95.39	6.29	100.00	26%	-5%
15	6.16	111.41	6.05	97.41	6.07	100.00	11%	-3%
17	6.57	515.42	5.58	146.90	5.30	100.00	415%	47%
19	3.78	10.54	4.76	51.71	5.22	100.00	-89%	-48%
20	5.41	89.06	5.47	96.34	5.49	100.00	-11%	-4%
22	6.97	139.56	6.89	128.09	6.68	100.00	40%	28%
24	5.09	56.46	4.99	48.94	5.49	100.00	-44%	-51%
25	6.51	112.57	6.45	105.30	6.41	100.00	13%	5%
26	6.39	113.97	6.20	90.51	6.28	100.00	14%	-9%

* AB = as-built

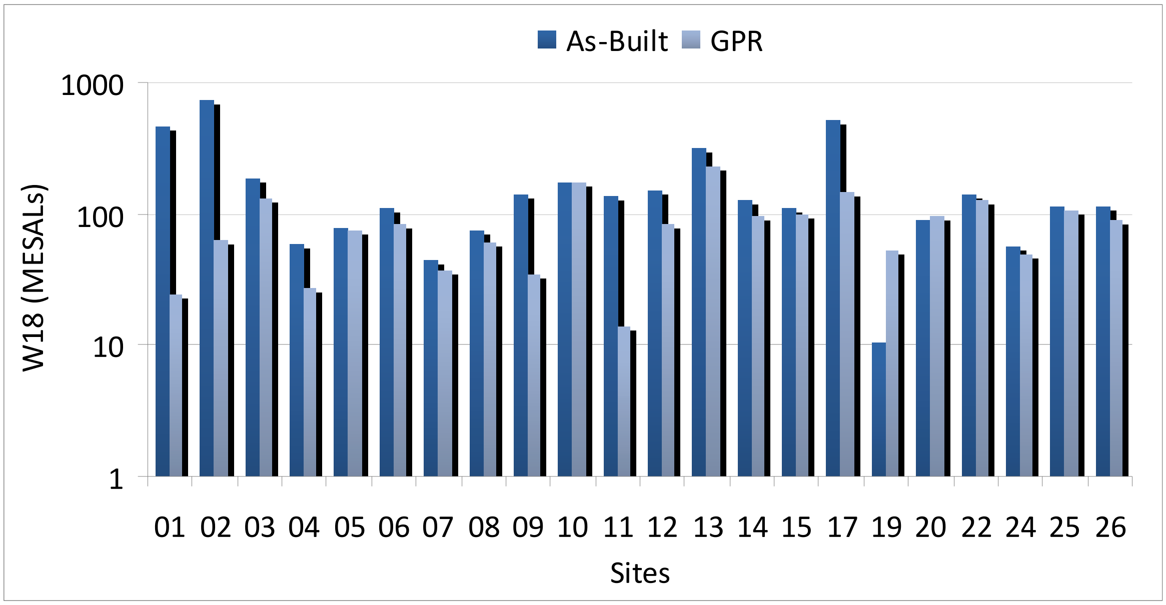


Figure 23. Estimated service life of overlayed pavement.

Table 21 summarizes the error between overlay thicknesses and service life of pavements designed using as-built and GPR data. Designs using as-built plan and GPR data had close to the same average overlay thickness error at under-designed sites. This suggests that as-built plan and GPR data would typically under-design a pavement by the same extent. However, at over-designed sites, as-built plan had a greater overlay thickness error than GPR data. Meaning, the as-built was more likely to over-design a pavement by a greater extent than GPR data would.

Table 21. Average thickness and service life errors for under/over-designed sites.

Overlay	Error	Average of Under-Designed Sites	Average of Over-Designed Sites
As-built overlay relative to ground truth (coring) overlay	Error in thickness (in.)	1.1	1.1
	Error in service life	41%	135%
GPR overlay relative to ground truth (coring) overlay	Error in thickness (in.)	1.0	0.7
	Error in service life	39%	53%

Table 22 describes the number of under and over-designed sites in this analysis, as well as the total average absolute thickness and service life errors. The table indicates that using as-built plan data is more likely to over-design a pavement and using GPR data is more likely to under-design a pavement. Based on the total absolute error, as-built overlay designs have a greater absolute error than GPR overlay designs.

Table 22. Total average absolute thickness and service life errors.

Overlay	Number of Sites Under-Designed by 1 Inch or More	Number of Sites Over-Designed by 1 Inch or More	Total Absolute Overlay Thickness Error (in)	Total Absolute Service Life Error (%)
As-built overlay relative to ground truth (coring) overlay	2	6	0.9	105%
GPR overlay relative to ground truth (coring) overlay	7	1	0.7	43%

Summary

The results for the sensitivity analysis indicate that designs from as-built thickness are more likely to over-design a pavement and designs from GPR thickness are more likely to under-design a pavement. On average, sites are under-designed to the same extent using either as-built or GPR data, but as-built data will over-design pavements to a greater extent than GPR data. Over-designing a pavement will cost more, but the pavement will last longer. Under-designing a will cost less, but the pavement will not last as long.

5. CONCLUSIONS

A test program has been carried out at 26, 500-foot long sites representing all climactic regions of Montana. The testing included GPR measurements of pavement layer thickness, FWD measurements at 5 locations within each site, and core and auger measurements to directly determine layer thickness and base moisture at the FWD locations. The testing was carried out in the spring of 2010 and repeated in the fall of 2010 to investigate seasonal effects.

The GPR data was analyzed and correlated with the core layer thickness data to assess the accuracy of GPR. The results of analyzing the data collected in the spring and fall were compared. An error checking procedure was developed using the FWD data to identify potentially erroneous GPR interpretations and to suggest more appropriate alternatives. The GPR data, core data, and data from as-built plans were used to carry out overlay designs and predict the remaining life of the overlaid pavement. The overlay designs from the as-built and GPR data were compared to those from the core data to assess the overlay thickness error and design life error associated with these two approaches.

The following summarizes the conclusions of this study.

1. Seasonal Variations in GPR Results

The GPR results, averaged over each site, changed very little with the change in season. On average, the difference between the bound layer thickness between spring and fall data sets was 0.20 inches, and the difference between base layer depths between spring and fall data sets was 0.39 inches

2. Effect of Data Collection Rate (GPR scans/foot)

Tests carried out at 5 and 2 scans per foot showed very little difference in the result. The average difference is 0.07 inches for the thickness of the asphalt layer and -0.02 inches for the depth to the bottom of the first base layer.

3. Comparison of GPR and Plan Data to Core Data

<u>Asphalt Thickness</u>

The initial analysis of the GPR data showed the average absolute asphalt thickness error when compared to cores to be within 9.7% when using a separate calibration plate at each site, and 10.3% when using a single calibration plate for the entire survey. For the data collected in the fall, the average absolute error was 11.0% using the on-site calibration. By comparison, the average absolute asphalt thickness error in the as-built plan data when compared to cores was 15.2% in the spring and 16.9% in the fall.

Base Thickness

The accuracy of the GPR data for the depth of the base layers differed with layer depth. The average absolute base depth error was approximately 18.5% for the depth to the bottom of the first base layer, and 8.5% - 10.5% to the depth of the bottom of the second layer. The corresponding figures for the accuracy of the as-built plan data are 12.7% and 11.6% respectively. This result shows that for the measurement of the depth of base layers, GPR does not offer a significant advantage in accuracy when accurate plan data are available.

4. Data Checking and Quality Control of the GPR Data Analysis

The analysis presented in Section 3.4 concluded that unreasonable backcalculated AC layer modulus and high backcalculation error can indicate inaccurate surface layer thicknesses. Backcalculated layer modulus and backcalculation error were used to specify criteria that can identify layer thicknesses which require further investigation. Using these criteria, four sites were identified and alternative GPR thickness interpretations were made for three of the sites. Use of the alternative thickness data reduced the asphalt error from 10.3% to 7.6%.

5. Analysis of Sensitivity to GPR and As-Built Plan Errors

Results from the sensitivity analysis determined that overlay designs using as-built layer thicknesses yielded overlay design error which averaged 0.9 inches vs. 0.7 inches for GPR. Service life error based on these overlay designs averaged 105% using the as-built data vs. 43% for the GPR data. This result shows that, although the GPR data can have errors, the use of GPR considerably reduces the design error that would occur using as-built plan data alone.

6. RECOMMENDATIONS AND IMPLEMENTATION

The work presented in this report has documented the accuracy potential for using GPR for pavement thickness evaluation. The work has also provided a checking and quality control procedure for improving the accuracy, and has shown the impact of improved accuracy on pavement rehabilitation design. MDT currently uses its GPR system as part of a statewide FWD data collection process, and has expressed an interest in expanded applications of its GPR technology. Considering the findings of this report and the MDT interests, the following, the following recommendations are proposed.

1. Implement the data checking/quality control procedure described in Section 3.4.

The goal of the proposed procedure is to reduce the number of situations where identification of incorrect layer boundaries yields large thickness errors. Implementing this procedure will require additional analysis time, but will ultimately yield better quality data

2. Periodically check thickness calculations at calibration sites.

As part of this project, layer thickness conditions at 26 sites have been carefully documented. It is recommended that two or more of these sites be designated as "calibration sites", and that twice each testing season, these sites be re-surveyed to compare layer thickness calculations to the previously documented values. The calibration sites should be chosen to represent a range of thicknesses and environments, and should be ones where the GPR was most accurate according to the results presented in Table 6. The layer thickness checks should be based on the average thickness determined for the full length of the site.

3. Conduct plate calibration testing once a month during the testing season.

The results presented in this report show that the small accuracy improvement gained by conducting a plate calibration at each site did not merit the extra effort and field exposure involved. However, since antenna characteristics can change over time, we recommend that plate calibrations be conducted at approximately one month intervals during the testing season, and that the data from the most recent plate calibration test be used for data analysis.

4. Utilize GPR Data for Overlay Design

The existing structural capacity of pavements receiving mill and fill or overlay rehabilitation is characterized by a structural number, which is calculated by multiplying each layer thickness by an appropriate structural coefficient. The sensitivity analysis described in Section 4 shows that using GPR layer information as an input into the calculation for structural number produces more accurate overlay designs and predictions of remaining life, when compared to using as-built plan data.

7. REFERENCES

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