STATE OF FLORIDA

ACCURACY AND REPEATABILITY OF GROUND PENETRATING RADAR FOR SURFACE LAYER THICKNESS ESTIMATION OF FLORIDA ROADWAYS

Research Report
FL/DOT/SMO/07-505

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April 2007

STATE MATERIALS OFFICE

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EXECUTIVE SUMMARY

Accurate thickness information of in-service pavements is priceless for estimating their remaining life and establishing rehabilitation strategies. Ground Penetrating Radar (GPR) can be used to estimate pavement thicknesses continuously and nondestructively. The thickness information from the GPR system may provide supplemental information for determining the thickness variability and consequently, the coring frequency. This study aims at assessing the reliability of the GPR system in terms of its accuracy and repeatability for pavement thickness surveys.

A total of 9 in-service pavements have been selected and studied. The results showed that the GPR system is reliable in terms of both accuracy and repeatability. The pavement thicknesses estimated from stationary GPR data resulted in overall average absolute deviations of 0.4 inches for HMA and 0.6 inches for PCC without the aid of calibration cores. These results were further improved to be 0.3 inches and 0.4 inches for HMA and PCC, respectively, when the cores were used to calibrate the velocities.

Keywords: Ground Penetrating Radar, Pavement Coring, Layer Thickness, Nondestructive Testing

INTRODUCTION

BACKGROUND

Accurate pavement thickness is essential for estimation of remaining life and rehabilitation of in-service pavements. Currently, the Florida Department of Transportation's Materials Manual states that a minimum of one core per lane mile should be retrieved for the purpose of layer thickness determination for flexible pavement rehabilitation. The manual also advises that coring frequency may be adjusted depending on thickness variability.

Unlike coring, Ground Penetrating Radar (GPR) can be used to estimate pavement thicknesses continuously and nondestructively. The thickness information obtained from GPR analysis may be used to provide supplemental information for determining the thickness variability and consequently, reduce coring frequency. This study aims at assessing the reliability of the GPR system in terms of its accuracy and repeatability for pavement thickness surveys.

OBJECTIVE

The primary objective of this study is to evaluate the accuracy and repeatability of FDOT's 2.0 GHz air-launched GPR system for measuring the bound surface layer thickness of typical Florida pavements.

SCOPE

Nine test sites around Gainesville, FL were chosen for this study. These sites were chosen to include different pavement types and a wide range of layer thicknesses. To assess the accuracy of the GPR system, pavement thicknesses estimated from GPR surveys were compared to core thicknesses. In addition, to study the repeatability and the effect of survey speed, the data was collected at different operating speeds ranging from 0 to 70 mph and their resulting thickness profiles were evaluated. This report is organized to provide an introductory background on GPR as well as a detailed presentation of the test program and results of this study.

GROUND PENETRATING RADAR

PRINCIPLES OF GROUND PENETRATING RADAR

Ground penetrating radar is a nondestructive tool used to detect and locate subsurface artifacts and features. GPR systems direct short pulses of electromagnetic energy into the ground using an antenna capable of transmitting and receiving signals. When this pulse of energy is transmitted through a layered structure and encounters materials of significantly different electromagnetic properties, a portion of the signal is reflected back to the antenna while the rest continues penetrating into the next layer. The amount of energy that reflects back or continues penetrating is a function of the contrasting electromagnetic properties of the materials. Material interfaces with greater contrasting electromagnetic properties produce reflections of higher amplitude.

Each GPR antenna operates at a range of frequencies and is characterized by its center frequency. The vertical resolution, or ability to resolve a feature such as a pavement layer, is mainly affected by the frequency, or wavelength, of the transmitted signal. The radar pulse has a finite width measured in nanoseconds and the pavement layers must be thick enough for reflections to appear without overlap. In general, higher operating frequencies are needed to resolve thinner layers and hence high frequency antennas with 1.0 GHz or 2.0 GHz center frequency are typically used for pavement thickness surveys.

Horizontal resolution is a function of sampling rate which should be high enough to resolve the horizontal artifact of interest. For instance, in order to detect a subsurface artifact such as a 24 inch pipe, the sampling interval should be less than 24 inches in order to ensure a waveform is collected over the pipe. However, several waveforms are typically required in order to properly characterize an artifact.

The effective depth of penetration of the radar energy is primarily a function of the electrical properties of the material the signal is transmitted through, frequency of transmitted radar signal and overall system characteristics such as power output and receiver sensitivity. Lower frequencies achieve greater penetration depths but decrease vertical resolution.

Electromagnetic wave velocity and strength is determined primarily by a material's dielectric constant (E_r), or its ability to store a charge from an electromagnetic field and then transmit that energy. In general, the greater the dielectric constant of a material, the slower the radar energy will travel through the material.

Attenuation is the measure of energy lost in travel related to the conductivity of the material. Attenuation of radar signals can be significant for conductive materials such as Portland cement concrete, clay and materials with a significant amount of moisture. Table 1 summarizes attenuation, dielectric constant and velocity values for several materials [1].

Sequential waveforms collected over a longitudinal profile can be stacked side by side to create a subsurface map of the pavement system as a function of radar signal travel time through the ground. Amplitudes and arrival times of the reflected signal can be used to estimate pavement thickness. Color coding waveforms to correspond to amplitude intensity is a common technique to aid in visual interpretation of layer properties. Figure 1 shows GPR data collected on a typical flexible pavement. Sequential waveforms positioned vertically make up the first half of the profile while the second half utilizes color coded waveforms.

Table 1. Attenuation, dielectric constant and velocity of various materials.

Material	Attenuation, dB/m	Dielectric Constant	Velocity, m/ns	Velocity, inch/ns
Air	0	1	0.30	11.8
Water	0.1	81	0.03	1.3
Dry Asphalt	2 to 15	2 to 4	0.15 to 0.21	5.9 to 8.4
Wet Asphalt	2 to 20	6 to 12	0.09 to 0.12	3.4 to 4.8
Clay	10 to 100	2 to 20	0.05 to 0.21	1.9 to 8.4
Dry Concrete	2 to 12	4 to 10	.010 to 0.15	3.7 to 5.9
Wet Concrete	10 to 25	10 to 20	0.07 to 0.09	2.6 to 3.7
Dry Granite	0.5 to 3	5	0.13	5.3
Wet Granite	2 to 5	7	0.11	4.5
Dry Limestone	0.5 to 10	4 to 8	0.10 to 0.15	4.2 to 5.9
Wet Limestone	10 to 25	4 to 8	0.10 to 0.15	4.2 to 5.9
Dry Sand	0.01 to 1	4 to 6	0.12 to 0.15	4.8 to 5.9
Saturated Sand	0.03 to 0.3	10 to 30	0.06 to 0.09	2.2 to 3.7
Dry Sandstone	2 to 10	2 to 3	0.17 to 0.21	6.8 to 8.4
Wet Sandstone	10 to 20	5 to 10	0.10 to 0.13	3.7 to 5.3
Saturated Shale	10 to 100	6 to 9	0.10 to 0.12	3.9 to 4.8
Dry Sandy Soil	0. to 2	4 to 6	0.12 to 0.15	4.8 to 5.9
Wet Sandy Soil	1 to 5	15 to 30	0.06 to 0.08	2.2 to 3.0
Dry Loamy Soil	0.5 to 3	4 to 6	0.12 to 0.15	4.8 to 5.9
Wet Loamy Soil	1 to 6	10 to 20	0.07 to 0.09	2.6 to 3.7
Dry Clayey Soil	0.3 to 3	4 to 6	0.12 to 0.15	4.8 to 5.9
Wet Clayey Soil	5 to 30	10 to 15	0.08 to 0.09	3.0 to 3.7

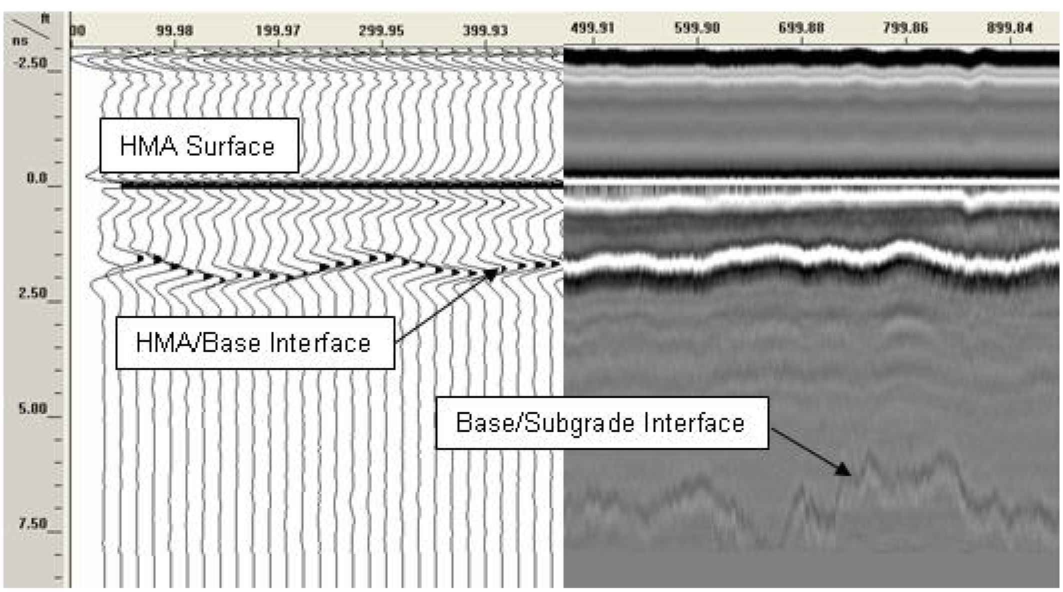

Figure 1. Stacked waveform and color coded GPR display.

PAVEMENT THICKNESS ESTIMATION WITH GROUND PENETRATING RADAR

Many techniques to determine pavement layer thickness have been researched and applied to real world applications using combinations of air-launched and ground-coupled antennas. Air-launched antennas are required for highway speed surveys. Most methods deriving thickness from GPR data rely on the following simplified equations [3, 4, 5]:

$$v = \frac{c}{\sqrt{E_r}} \quad \text{where} \tag{1}$$

v is the velocity of the radar through a material,
c is the speed of light in free space (11.8 in/ns), and
E_r is the dielectric constant of the layer.

Then the thickness can be calculated as:

$$h = v \cdot \frac{t}{2} = \frac{ct}{2\sqrt{E_r}} \quad \text{where} \tag{2}$$

h is the layer thickness and
t is the two-way travel time of the radar energy.

A common method of deriving thickness (or velocity) information from radar waveforms generated by an air-launched antenna is by comparing the reflection amplitudes associated with layer interfaces with amplitudes generated from a perfect reflector. Since the radar signal cannot penetrate metal, a metal plate placed below the antenna will produce a perfect reflection. Reflection amplitudes received from pavement layer interfaces will be less than those received from the metal plate. The ratio between the layer interface reflection amplitude and the perfect reflection amplitude is used to estimate the dielectric constant of the layer from the following equation:

$$E_r = \left(\frac{1 + \frac{A_o}{A_p}}{1 - \frac{A_o}{A_p}} \right)^2 \quad \text{where} \tag{3}$$

A_o is the reflection amplitude from the layer, and
A_p is the reflection amplitude from a perfect reflector

REPORTED GROUND PENETRATING RADAR ACCURACY

Many state agencies, academic institutions and service providers have reported on the accuracy of GPR to estimate the thickness of pavement layers. Some of these studies were initiated almost 20 years ago. Following are excerpts from some studies conducted within the last five years.

Illinois Center for Transportation [3]: A report published in 2006 described an evaluation of nine flexible pavements in Virginia using a 1 GHz air launched GPR system. This system was able to estimate the asphalt layer with an average absolute error of 5.6 percent. This error was reduced to less than 4 percent when using a correction factor based on core data. A comparison of data collected while stationary and at highway speeds indicated no significant differences. Also, an algorithm based on the common midpoint method, a geophysical technique employing two antennas and their operation geometry, was developed to eliminate the need for core data to produce more accurate thickness estimations.

Virginia Tech Transportation Institute [4]: A 2003 report detailed the use of a 1 GHz air launched GPR system to measure layer thickness of a new flexible pavement as part of a Quality Control/Quality Assurance tool. This system was able to identify three HMA layers consisting of an asphalt treated base and two intermediate layers. Thickness errors for these three layers were reported to be:

- 0 to 12.9 percent with a mean of 3.7 percent for the HMA base layer (4 inch plan thickness)
- 0.7 to 5 percent with a mean of 2.9 percent for the HMA layer above the base (3 inch plan thickness)
- 0 to 7.7 percent with a mean of 2.2 percent for the HMA layer below the wearing surface (2 inch plan thickness)
- An average error of 2.2 percent was determined for all layers

Kentucky Transportation Center [5]: In 2002, the Kentucky Transportation Center published a report documenting an accuracy study of a GPR system employing a 1 GHz air launched antenna to measure the surface thickness of four flexible pavements less than 2 inches, one 8 to 9 inch flexible pavement and a concrete pavement 9 to 12 inches thick. A comparison of thickness estimated by GPR and core measurements found that ground truth data greatly increased accuracy. Using multiple ground truth cores to assist in thickness interpretation, the study reported accuracy of:

- 0.4 to 10.3 percent for flexible pavements less than 2 inches
- 1.3 to 2.7 percent for flexible pavements between 8 and 9 inches
- 0.1 to 14.2 percent for concrete pavements between 9 and 12 inches

The study also reported that while further testing is required, data suggested that a wet surface does not influence surface thickness estimation and GPR surveys were repeatable.

Infrasense, Inc. [6]: A 2001 study showed GPR was used to estimate the HMA thickness of four asphalt overlaid concrete pavements near New York City, New Haven and Chicago. Thickness comparisons of 89 cores and GPR estimations resulted in an average difference of -0.1 inches and an average absolute error of 0.4 inches. Correction factors from core data were not used to obtain this accuracy. Concrete thickness was not reported but condition assessments were made based on dielectric contrasts of the concrete and asphalt interface.

Most thickness accuracy studies have focused on asphalt surface layers with little regard to base and subgrade layers. This is likely due to difficulties in retrieving ground truth data for these layers and evidence shows that variations in upper layer thickness measurements have the most impact on surface layer stiffness estimates from backcalculation using falling weight deflectometer data [6, 7, 8, 9].

FLORIDA DOT GROUND PENETRATING RADAR SYSTEM

Florida DOT's GPR system consists of a Geophysical Survey Systems, Incorporated (GSSI) SIR 20 and two 2.0 GHz air-launched antennas. The antennas can be mounted from the front or rear of a customized van, as shown in Figure 2. The mounting system allows the antennas to slide and lock in place so that they can be positioned at any lateral location along the roadway. The antennas are normally positioned along the inside and outside wheel paths in the front of the van.

Figure 2. Front and rear mounted antennas.

For most roadway operations, a 12 ns time window is used and each scan is comprised of 512 samples per antenna. Using these settings, one scan per foot can be achieved at highway speeds and 3 scans per foot at approximately 15 mph. A Nitestar distance measuring instrument or a distance encoder provided by GSSI is used to trigger data collection. A Trimble Global Positioning System may also be used to provide location information.

Operation of the system can be controlled via a laptop computer accessible from the front seats or a workstation in the rear of the van. Typically, GPR surveys require a two man operation so that the passenger can note pertinent information and assist with set up and break down of the system.

TEST PROGRAM

SELECTED SITES

Eleven sites located near Gainesville, FL were selected for accuracy and repeatability studies. Table 2 summarizes each of the selected test sites. The test sections were categorized into four different pavement types: Flexible, rigid, HMA overlaid PCC and PCC overlaid HMA. Flexible pavements were further subdivided into three thickness ranges. Thin (≤ 4 inch), medium (> 4 and ≤ 10 inch) and thick (> 10 inch) sections. All sections are 1 mile long except for SR 16 which is 0.5 mile long.

Table 2. Inventory of selected test sites

Pavement Type	Thickness Range (in.)	County	Roadway ID	Begin MP	End MP	Average Core Thickness (in.)
Flexible	Thin (≤ 4)	Bradford	SR 16	8.757	8.257	2.8
		Alachua	SR 24	15.600	14.600	4.1
	Medium (4 to 10)	Alachua	SR 24	14.400	13.400	7.4
		Alachua	SR 329	9.222	8.222	5.4
		Bradford	SR 100	18.360	19.360	5.1
	Thick (> 10)	Alachua	SR 20	7.440	8.440	10.4
		Bradford	SR 200	0.160	1.160	12.0
		Alachua	SR 26	4.172	3.172	12.9
Rigid	---	Duval	SR 228	4.090	5.090	6.7
HMA/PCC	---	Volusia	SR 5	9.955	8.955	3.1 / 7.3
PCC/HMA	---	Volusia	SR 5	11.462	10.462	7.8 / 2.9

ACCURACY STUDY

To assess the accuracy of the pavement thicknesses estimated using FDOT's 2.0 GHz GPR antennas, the estimated thicknesses were compared to core thicknesses. During data collection, the GPR van traveled no faster than 15 mph and made complete stops at the coring locations to collect stationary GPR data. When the van came to a stop, the pavement surface directly below the antennas were marked for coring and a marker was also inserted in the GPR data to indicate these locations. Figure 3 shows both the marked locations on the pavement and the marker in the GPR data.

At each site, a total of ten cores were retrieved, five from the inside and outside wheel paths each. After the cores were taken, the thicknesses were measured and recorded. For each core, three thickness readings approximately 120˚ apart along the circumference were taken and averaged.

It was found that the GPR data collected on SR 329 and SR 200 were extremely noisy throughout the entire length of the sections. An example of noisy and clean GPR scans is shown in Figure 4. Possible causes of the noise include presence of cellular telephone towers, commercial radio or television stations, weather and airport search radars that generate electromagnetic radiation.

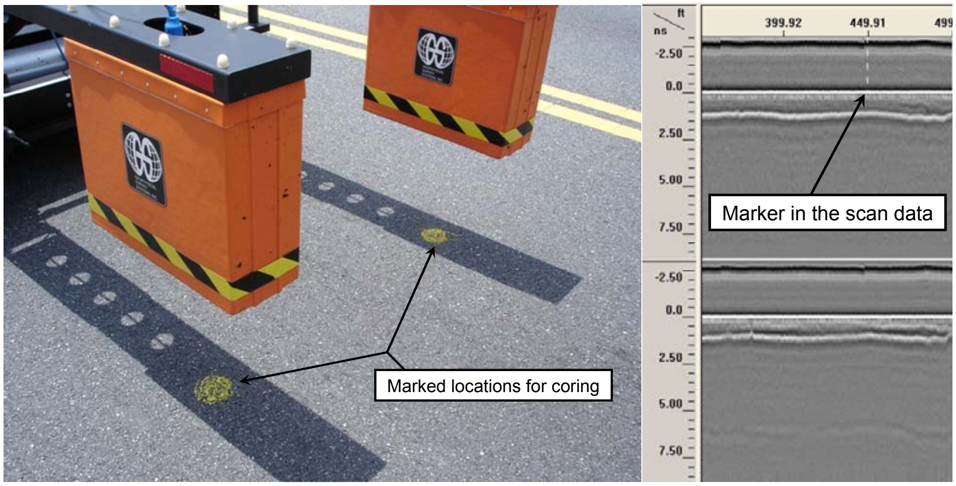

Figure 3. Marked locations for coring on the pavement and in the GPR data

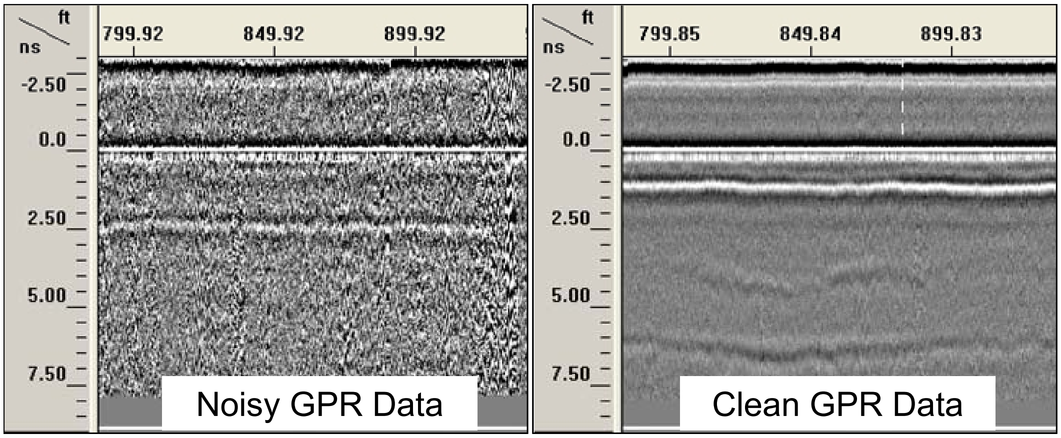

Figure 4. Noisy and clean GPR data

The sites with noisy GPR data were revisited to see if any structures or towers could be identified as causes of noise. In fact, a tower located on SR 329 near the test section was identified to be interfering with the 2.0 GHz antennas. As the GPR van traveled closer to that particular tower, the GPR signal became noisier. A picture of the GPR van and the tower is shown in Figure 5. The use of this tower and its operating frequency range is not known at this point and is under investigation. Further study is needed to understand, characterize and if possible, eliminate the noise.

Since the objective of this study is to assess the accuracy of the GPR system at its natural condition, that is, not subjected to noise, SR 329 and SR 200 were excluded from the analysis and will not be considered in this report.

Figure 5. A tower that interfered with GPR data on SR 329.

HMA Accuracy Data Analysis

The collected GPR data was processed using GSSI's RADAN 6.5 software. The software allows the user to view the reflected waves in color coded setting prior to picking the interface reflections. If the bound surface layer is composed of multiple sublayers with dissimilar dielectric properties, the GPR data will show the reflections from the interface between the sublayers in addition to the HMA/base interface reflection. The user can either pick all the identifiable interface reflections (multiple interface picking) to distinguish between the different sublayers or pick only the reflections from the HMA/base interface (single interface picking). Both picking options were considered for the accuracy study. Figure 6 shows a picture of a typical core, the raw and the processed data as an example.

After the interface reflection has been picked, the depth to the corresponding interface can be estimated using the method based on equations (1) through (3) presented earlier. The propagation velocity of the radar wave through the pavement layer can be estimated from the reflection amplitudes. A more accurate propagation velocity can be obtained by calibrating it through the ground truth value from a core. For this study, the layer interface depths were estimated both with and without the use of ground truth data.

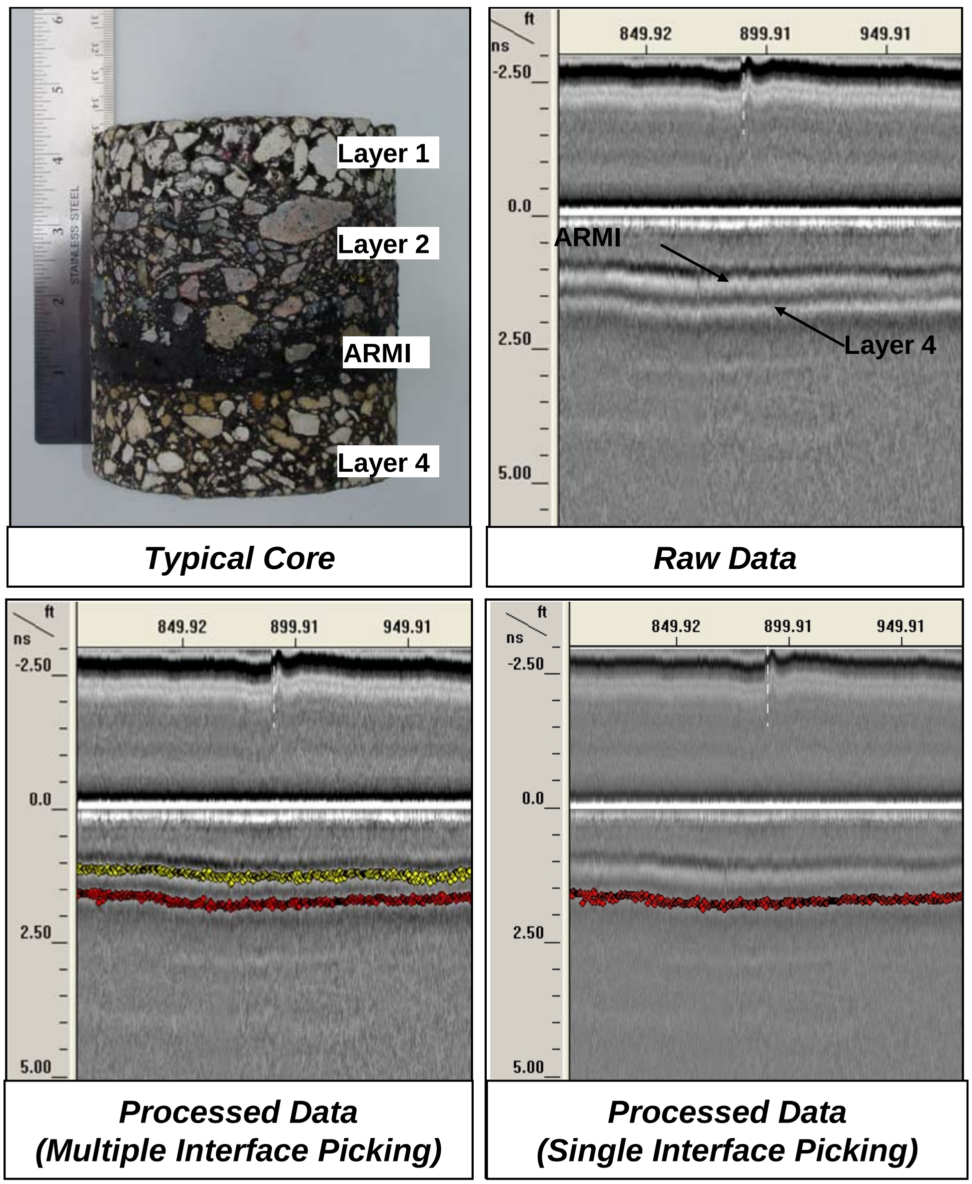

Figure 6. Typical core and GPR profiles

Analysis Results – Asphalt Thickness Accuracy
Pavement thicknesses determined from the GPR analysis were compared to those from the cores. All flexible pavements and composite pavements with HMA surface have been considered.

Thickness Estimation without Ground Truth Data: Surface layer thicknesses were estimated from the GPR data without the use of ground truth data. Figure 7 shows a plot between core thicknesses and thicknesses estimated from multiple interface picking method. As can be seen from the figure, most of the thickness predictions were within ± 1.0 inch away from the core thicknesses. Only two outliers were present outside the ± 1.0 inch deviation range with the largest deviation being 1.6 inch (16.5 percent error) above the line of equality.

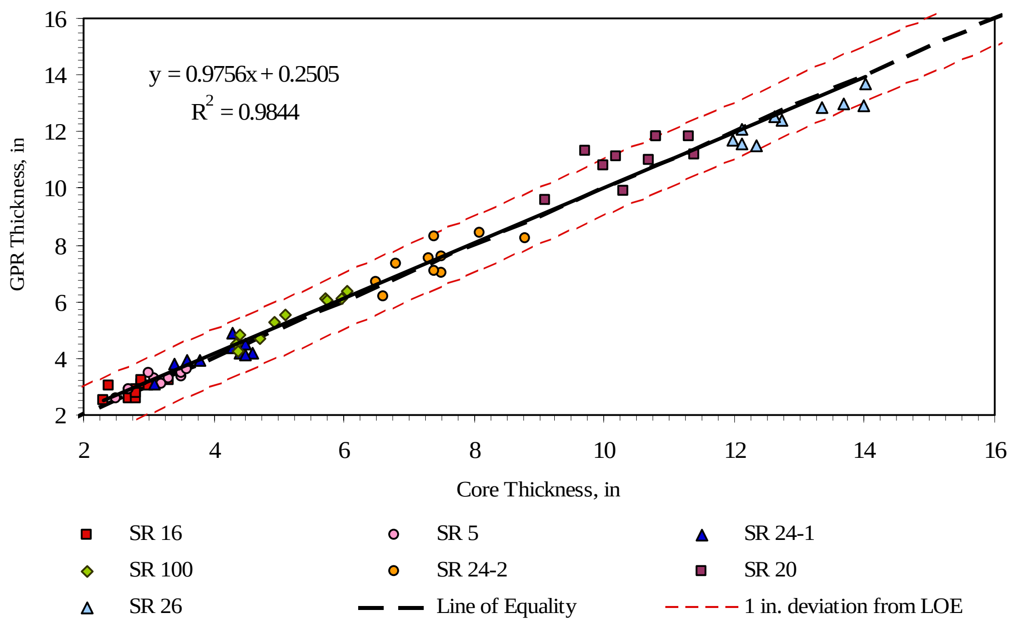

Figure 7. HMA thickness plot, multiple interface picking without velocity calibration

Figure 8 shows the estimated thicknesses using single interface picking. A total of eleven data points showed deviations greater than ± 1.0 inch with the largest being 2.0 inch (20.6 percent error). Clearly, the multiple interface picking results in more accurate thickness estimation and should be preferred when ground truth values are not available.

Both figures show that the GPR analyses resulted in over-prediction of most core thicknesses from SR 20 and under-predictions of those from SR 26. Despite these over- and under-predictions, the overall trend of the thickness estimation seems to be parallel to the line of equality. The equations of the trend lines shown in the figures also support this since their slope values are very close to 1.0. The y-intercepts of the regression equations were 0.25 inch and 0.37 inch for multiple and single interface picking methods, respectively. These values suggest that, on average, the thickness values from the GPR analysis are slightly greater than the actual thicknesses.

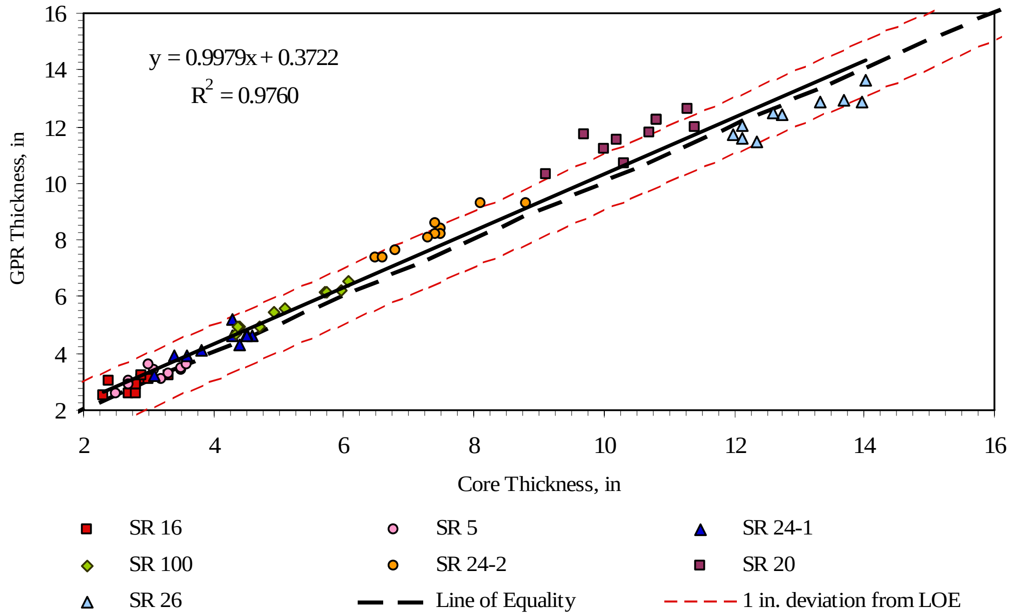

Figure 8. HMA thickness plot, single interface picking without velocity calibration

In order to assess the accuracy of the GPR, averages of absolute deviations and percentage errors were calculated as:

$$Avg.\,Abs.\,Dev. = \frac{\sum_{i=1}^{n} \left| h_{GPR,i} - h_{Core,i} \right|}{n} \tag{4}$$

and

$$Avg.\,Abs.\,\%\,Error. = \frac{\sum_{i=1}^{n} \left\{ \frac{\left| h_{GPR,i} - h_{Core,i} \right|}{h_{Core,i}} \right\}}{n} (\times 100\%) \quad \text{where} \tag{5}$$

$h_{GPR,\,i}$ is the thickness of the i th core estimated from the GPR analysis,
$h_{Core,\,i}$ is the measured thickness of the i th core, and
n is the number of cores.

Table 3 summarizes these averages. The overall average absolute deviation and percent error for multiple interface picking were 0.4 inch and 5.6 percent. These values were increased to 0.5 inch and 8.0 percent for single interface picking.

Table 3. Deviation and Error of HMA thickness prediction without velocity calibration

State Road	Avg. Core Thickness (in)	Multiple Interface Picking		Single Interface Picking	
		Avg. Abs. Deviation (in)	Avg. Abs. % Error	Avg. Abs. Deviation (in)	Avg. Abs. % Error
16	2.8	0.2	6.8	0.2	7.5
5	3.1*	0.1	4.9	0.2	5.8
24	4.1	0.3	6.1	0.3	7.1
100	5.1	0.3	4.7	0.4	8.6
24	7.4	0.4	5.4	0.9	11.8
20	10.4	0.7	7.0	1.2	11.5
26	12.9	0.5	3.7	0.5	3.7
Overall	**6.5**	**0.4**	**5.6**	**0.5**	**8.0**

* HMA overlaid PCC. The thickness shown is for the HMA layer.

Thickness Estimation with Ground Truth Data: More accurate thickness values can be obtained when the radar wave velocity is calibrated using ground truth information. For each section, two cores (one core per antenna) were randomly selected and used for velocity calibration. Using the calibrated velocities, the thicknesses of the remaining core locations were estimated. The results are shown in Figures 9 and 10 for multiple and single interface picking, respectively. All predicted thicknesses lie within ±1.0 inch deviation from the line of equality with the maximum absolute deviation being 0.9 inch for both picking methods. The advantage of the velocity calibration can be clearly seen.

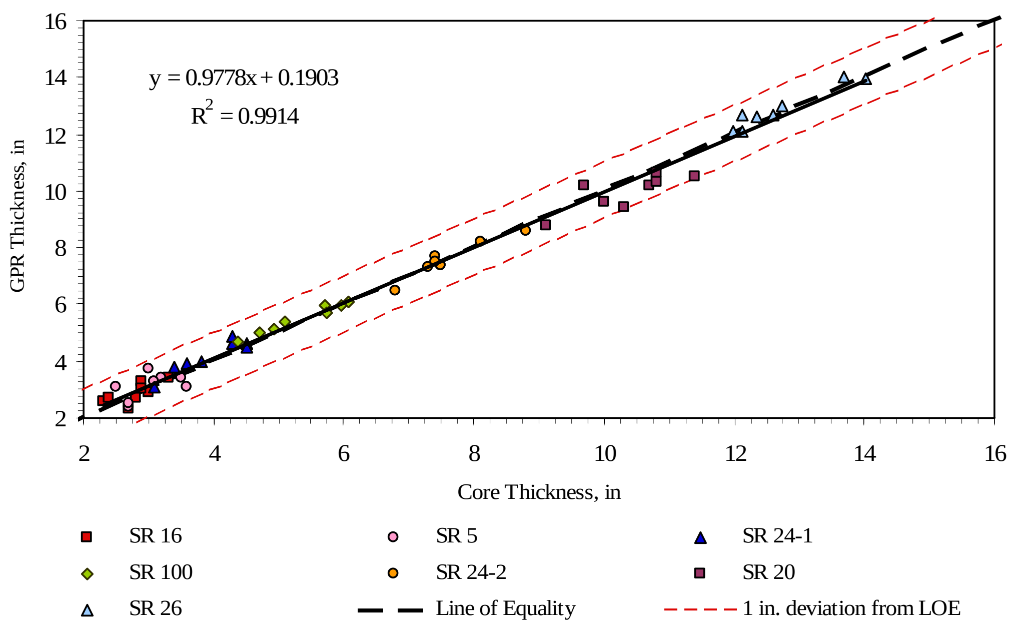

Figure 9. HMA thickness plot, multiple interface picking with velocity calibration

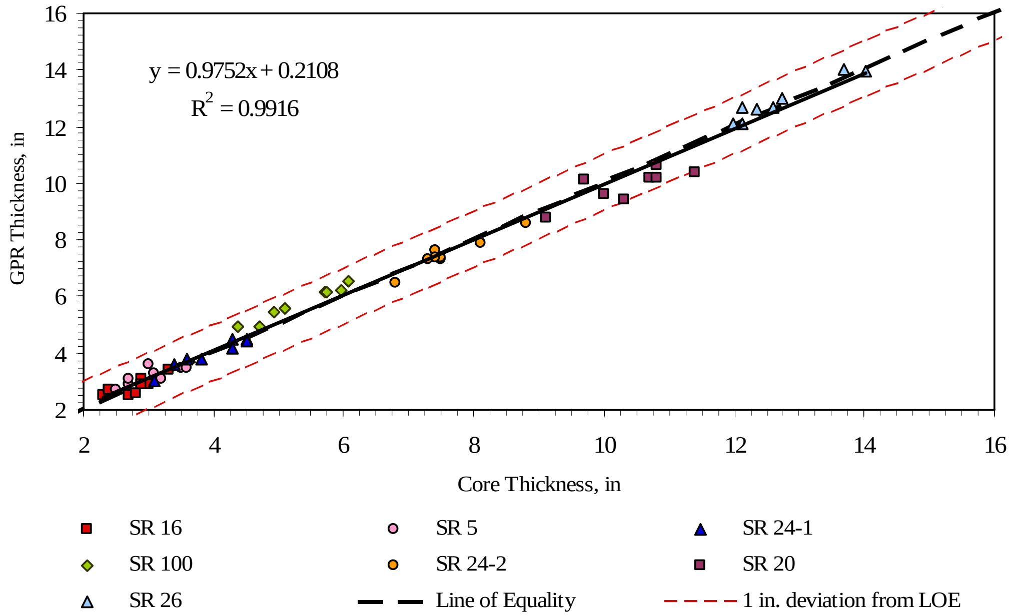

Figure 10. HMA thickness plot, single interface picking with velocity calibration

Again, the averages of absolute deviations and percent errors were calculated using equations (4) and (5) and are summarized in Table 4. The averaged deviations for all sites are within 0.5 inch and the percent errors are less than 10 percent except for SR 5 which is a composite pavement.

Table 4. Deviation and Error of HMA thickness prediction with velocity calibration

State Road	Avg. Core Thickness (in)	Multiple Interface Picking		Single Interface Picking	
		Avg. Abs. Deviation (in)	Avg. Abs. % Error	Avg. Abs. Deviation (in)	Avg. Abs. % Error
16	2.8	0.2	8.4	0.2	6.1
5	3.1*	0.4	11.9	0.2	7.8
24	4.1	0.2	6.1	0.1	3.0
100	5.1	0.1	2.0	0.2	4.1
24	7.4	0.2	2.0	0.2	2.0
20	10.4	0.5	5.0	0.5	5.1
26	12.9	0.2	1.7	0.2	1.7
Overall	**6.5**	**0.3**	**5.5**	**0.3**	**4.9**

* HMA overlaid PCC. The thickness shown is for the HMA layer.

The relatively higher error on the composite pavement may be due to the PCC layer attenuating a significant amount of the radar energy. Also, notice that the single interface picking shows better results in terms of the absolute deviation and percent error for pavements with thin HMA layer, i.e., SR 16 and SR 5. The average absolute percent error of the multiple interface picking showed a slightly higher value than single interface picking. Again, this may be attributed to the errors from the thin HMA layers. Nonetheless, the difference in the overall average absolute deviations of the two picking methods is negligible.

PCC ACCURACY DATA ANALYSIS

The above analysis was repeated for PCC thicknesses. A total of three pavement sections were considered: One rigid pavement in SR 228 and two composite pavements (HMA overlaid PCC and PCC overlaid HMA) in SR 5. Note that the GPR showed sublayers only in the HMA layer of the blacktopped pavement which was analyzed by picking multiple interfaces. However, the other two sites did not show any sublayer interfaces, and hence multiple and single interface picking could not be distinguished.

Figure 11 shows a portion of the GPR data collected over SR 228. Joints can be seen in the PCC/base interface as spikes at a constant interval of 20 ft. They appear as spikes in the GPR data because the joints are filled with materials that are different from concrete such as sealants, moisture, soil, air, dust, etc. Due to these joints, the PCC pavement is non-homogeneous in the direction of travel and the PCC/base interface appears as hyperbolas. In addition, potential voids or moisture could be identified at the interface which made identification of the interface more difficult.

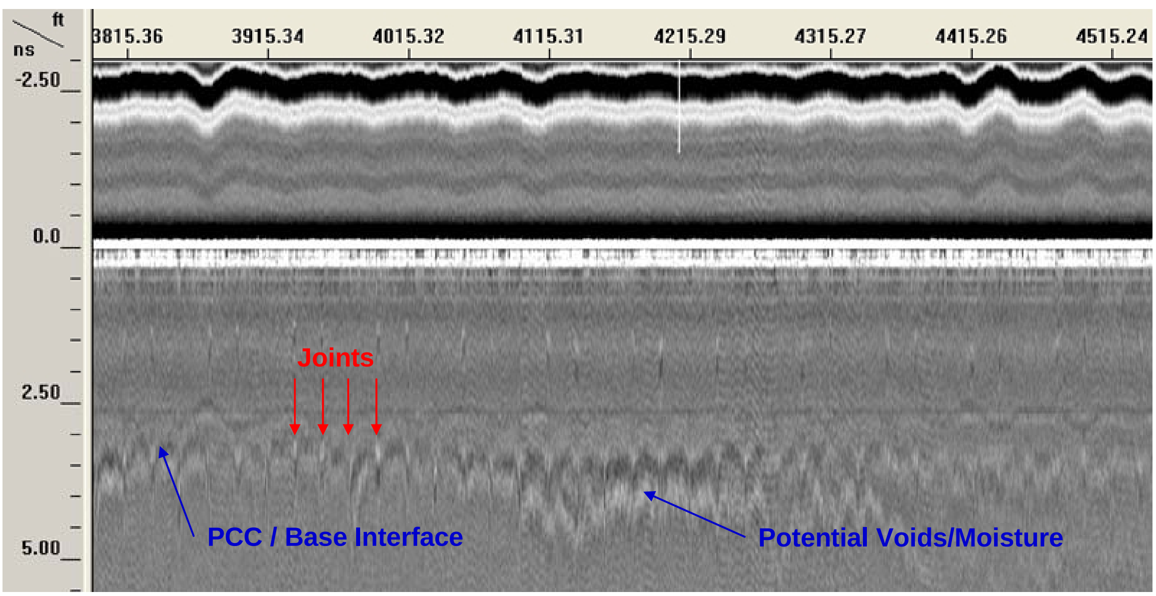

Figure 11. Typical GPR data from SR 228 showing dowel bars and interface fluctuation

Analysis Results – PCC Thickness Accuracy

Figure 12 shows the plot between the measured and predicted PCC thicknesses without velocity calibration. The figure clearly shows that the GPR over-estimates the PCC thicknesses and the prediction is especially poor for the blacktopped pavement. In addition to the fact that PCC attenuates much of the radar energy, this PCC layer was overlaid below a 3 inch HMA layer. Combination of these facts may have made the thickness prediction difficult due to attenuation of radar energy, reduction in depth of penetration and weakening of reflection amplitudes. Note that, errors are also compounded with multiple layers. Errors made in predicting HMA thickness will be carried over to PCC thickness prediction.

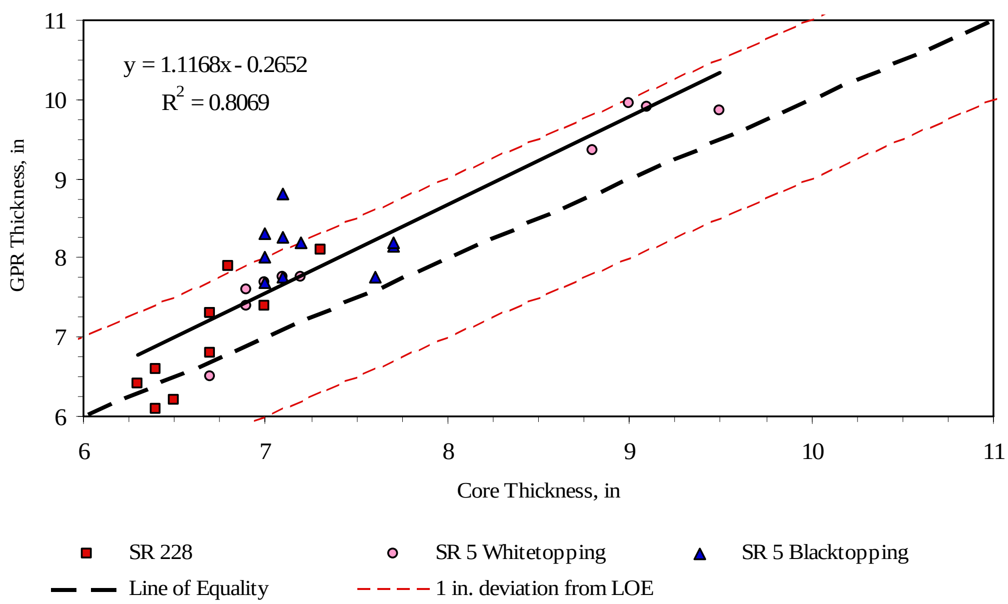

Figure 12. PCC thickness plot, without velocity calibration

Figure 13 shows the result after the radar velocity has been calibrated with ground truth data. The predictions are slightly improved with fewer data points outside the ±1 inch deviation from the cores. More data that covers a wide range of PCC thicknesses is needed to better understand the reliability of the GPR system in PCC thickness estimation.

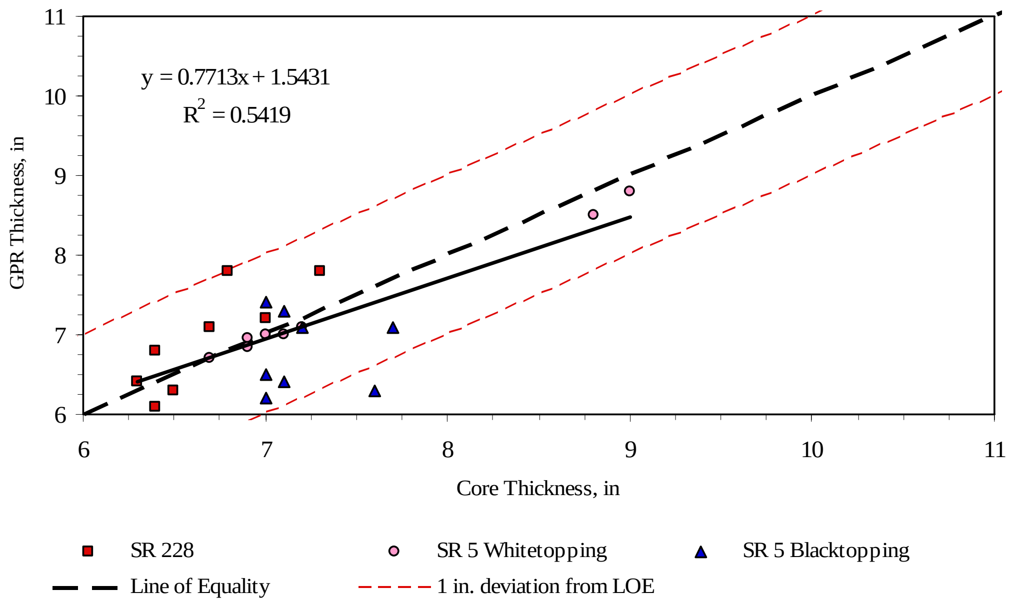

Figure 13. PCC thickness plot, with velocity calibration

Table 5 summarizes the results in terms of the deviation and percent errors, calculated from equations (4) and (5). Again, note that the multiple and single interface picking were not distinguished since there were no sublayers found in the homogenous concrete material. Without velocity calibration, the absolute deviations ranged between 0.1 in. and 1.7 inch with an average of 0.6 inch while the absolute percent error ranged between 1.5 and 23.1 percent with an average of 8.8 percent. With velocity calibration, the absolute deviations were reduced to range between 0.0 inch and 1.3 inch, with an average of 0.4 inch. The minimum, maximum and the average absolute percent errors were 0.0 , 17.1 and 5.0 percent, respectively.

Table 5. Deviation and Error of PCC thickness prediction with and without velocity calibration

State Road	Avg. Core Thickness (in)	Without Velocity Calibration		With Velocity Calibration	
		Avg. Abs. Deviation (in)	Avg. Abs. % Error	Avg. Abs. Deviation (in)	Avg. Abs. % Error
228	6.7	0.5	6.6	0.4	5.7
5 (PCC/HMA)	7.8*	0.6	7.6	0.1	1.2
5 (HMA/PCC)	7.3*	0.9	12.0	0.6	7.9
Overall	**7.3**	**0.6**	**8.8**	**0.4**	**5.0**

* Does not include HMA thickness

Summary of Accuracy Study Results

The results of accuracy study in terms of the absolute deviations and percent errors of the GPR derived thicknesses are summarized in Table 6.

Table 6. Summary of accuracy results

Layer Type	Velocity Calibration	Interface Picking	Abs. Deviation (in.)			Abs. % Error		
			Avg.	Min.	Max.	Avg.	Min.	Max.
HMA	No	Multiple	0.4	0.0	1.6	5.6	0.0	16.5
		Single	0.5	0.0	2.0	8.0	0.0	20.6
	Yes	Multiple	0.3	0.0	0.9	5.5	0.0	24.0
		Single	0.3	0.0	0.9	4.9	0.0	20.0
PCC	No	Multiple	0.6	0.1	1.7	8.8	1.5	23.1
	Yes	Multiple	0.4	0.0	1.3	5.0	0.0	17.1

REPEATABILITY STUDY

The advantage of the air-launched GPR system is that it is capable of collecting the data at highway speeds without the need of traffic closure. In order to assess the reliability of the GPR data collected at different speeds, the GPR repeatability has been studied. The same test sites that were investigated for the accuracy study have also been used for the repeatability study. At each site, the GPR data was collected at two different speeds ranging from 20 mph to 70 mph depending on the speed limit of the sites. The frequency of the data collection was kept at 1 scan/ft. regardless of the speed. Table 7 shows the low and high speeds at which the GPR data was collected for all the sections, along with the supplemental information for convenience.

Table 7. Operated survey speeds of repeatability study

Pavement Type	State Road	BMP	EMP	Low Speed (mph)	High Speed (mph)
Flexible	16	8.757	8.257	20	40
	24	15.600	14.600	50	70
	100	18.360	19.360	40	60
	24	14.400	13.400	50	70
	20	7.440	8.440	50	70
	26	4.172	3.172	30	50
Rigid	228	4.090	5.090	50	70
Composite (HMA/PCC)	5	9.955	8.955	45	65
Composite (PCC/HMA)	5	11.462	10.462	45	65

Repeatability Data Analysis

At each site and for each wheel path, a total of six runs were made for the repeatability study, three at each speed. The three data sets at each speed have been processed and the thickness information was extracted without velocity calibration to produce three thickness profiles over the entire length of the section. The resulting thickness profiles were averaged and compared for different speeds. Also included in this comparison is the GPR data that was collected during the accuracy study. This accuracy data was collected at a speed of less than 15 mph between coring locations and was collected while the van came to a complete stop on the coring locations.

In addition, to evaluate the reliability of the thicknesses predicted from the GPR data collected at highway speeds, the locations for coring were identified in the thickness profiles and the predicted thicknesses were compared to the measured thicknesses.

Analysis Results

For simplicity, the results will be shown only for SR 16, SR 20 and SR 228 that are representative sections for thin HMA, thick HMA and PCC sections.

Figures 14 and 15 show the repeatability plots for the inner and outer wheel paths of SR 16, respectively. SR 16 is a pavement with a thin HMA layer and the repeatability data was collected at the lowest speeds (20 and 40 mph). Both figures show excellent agreement throughout the length of the section between the data collected at speeds 20 and 40 mph. However, a horizontal shift can be seen between the data collected at less than 15 mph and those collected at 20 and 40 mph. This could be due to the difficulty of capturing the exact beginning location when the data is collected at highway speed. It should be noted that for the accuracy data collected at less than 15 mph the van had stopped at the beginning of the section to insure an accurate assessment of that location in the GPR data. On the other hand, for the repeatability data a marker was inserted in the GPR data as the van was traveling over the beginning of the section at highway speed which may create a starting offset in the GPR data. Nonetheless, the thickness profiles show a very consistent overall trend which implies that the GPR data is not significantly influenced by the speed. Also shown in the figures are the core thicknesses at their corresponding locations. The core thicknesses are in excellent agreement with the accuracy data. Again, the horizontal offset that is present in the repeatability data makes the detection of the exact core location difficult when the data is collected at highway speeds. In order to minimize this offset, it is recommended that more markers be inserted while the GPR data is being collected. These markers should be linked to physical objects with known mileposts [9].

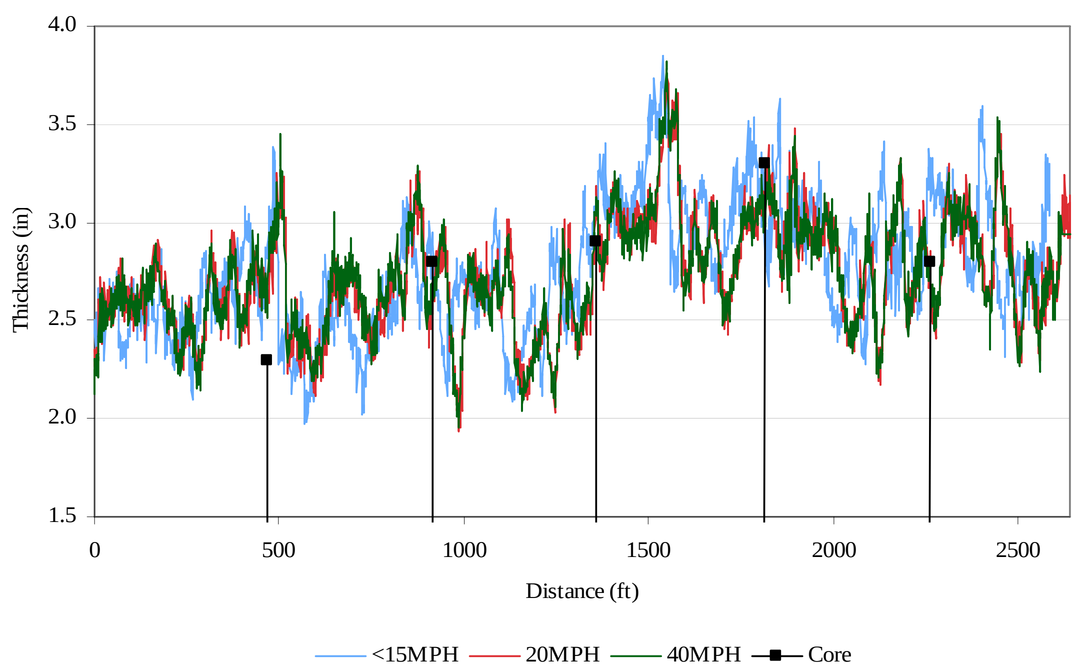

Figure 14. Thickness profiles of SR16 IWP collected at 20 and 40 mph

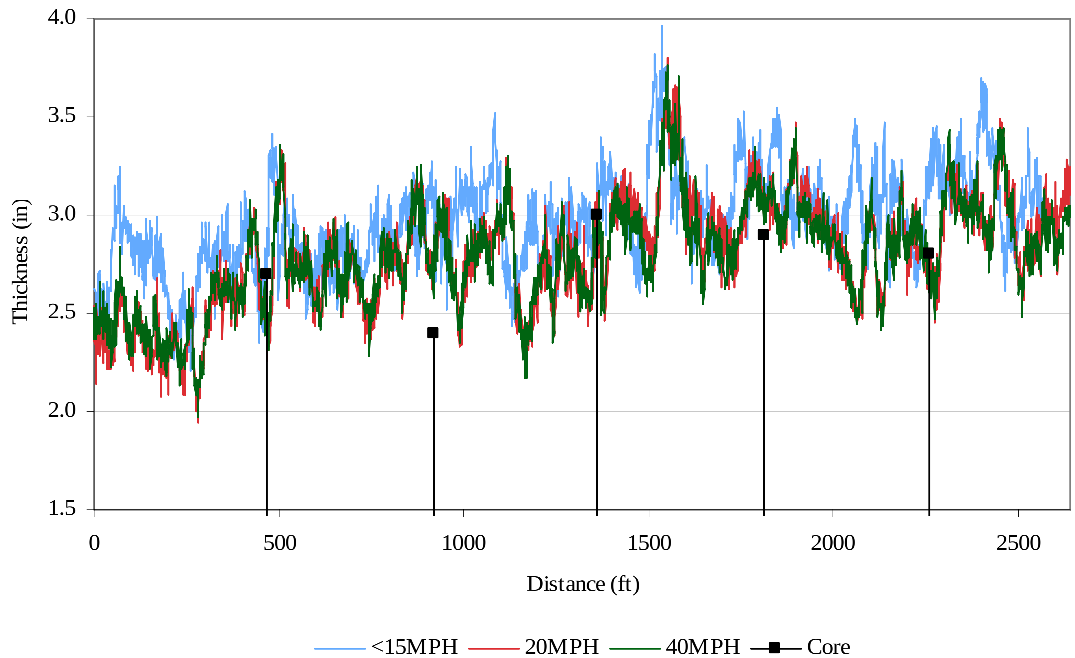

Figure 15. Thickness profiles of SR16 OWP collected at 20 and 40 mph

Figures 16 and 17 show the repeatability results for SR 20 which is composed of a thick HMA layer. The GPR data was collected at the highest speeds of 50 and 70 mph. The thickness profiles show excellent repeatability and accuracy.

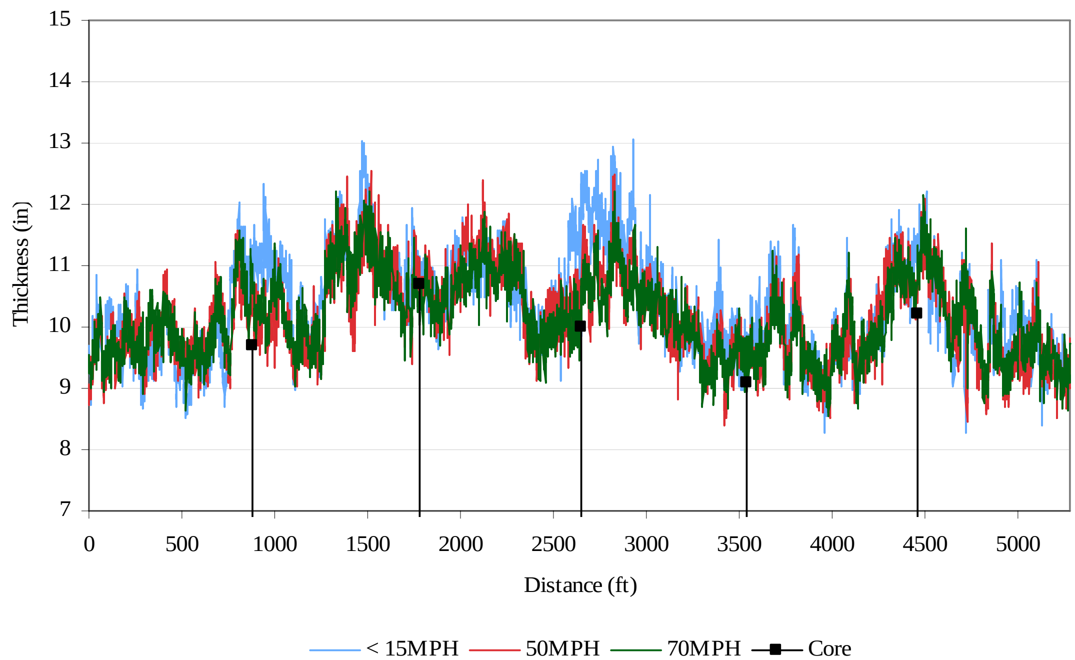

Figure 16. Thickness profiles of SR20 IWP collected at 50 and 70 mph

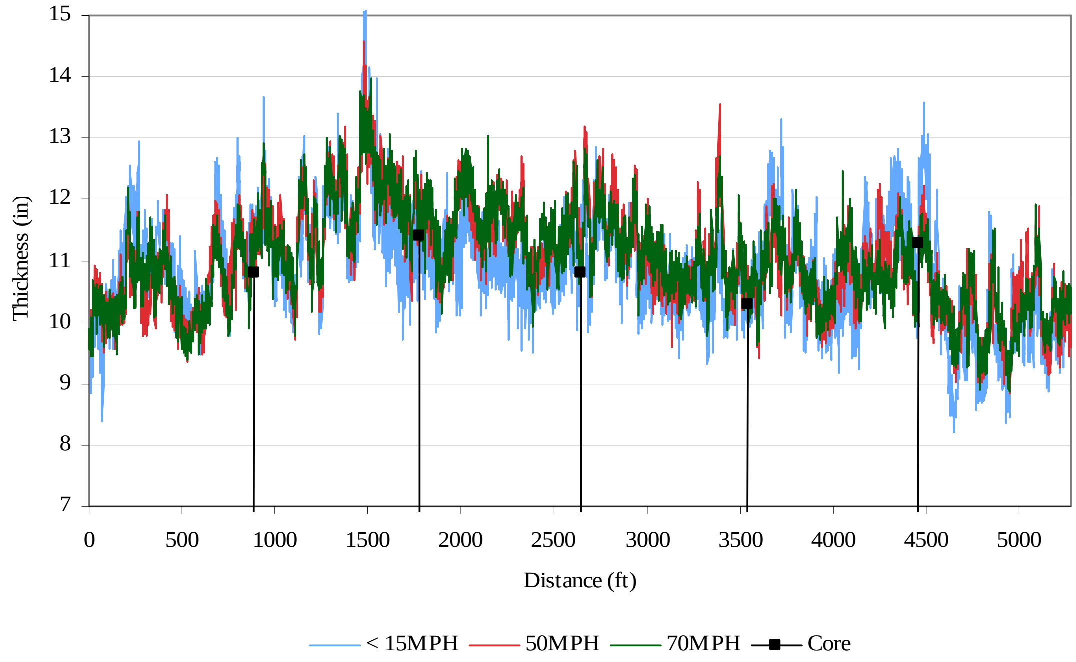

Figure 17. Thickness profiles of SR20 OWP collected at 50 and 70 mph

The repeatability plots for SR 228 are shown in Figures 18 and 19. Recall that SR 228 is a rigid pavement and the repeatability data was collected on 50 and 70 mph. They are in excellent agreement with the data collected at creep speed.

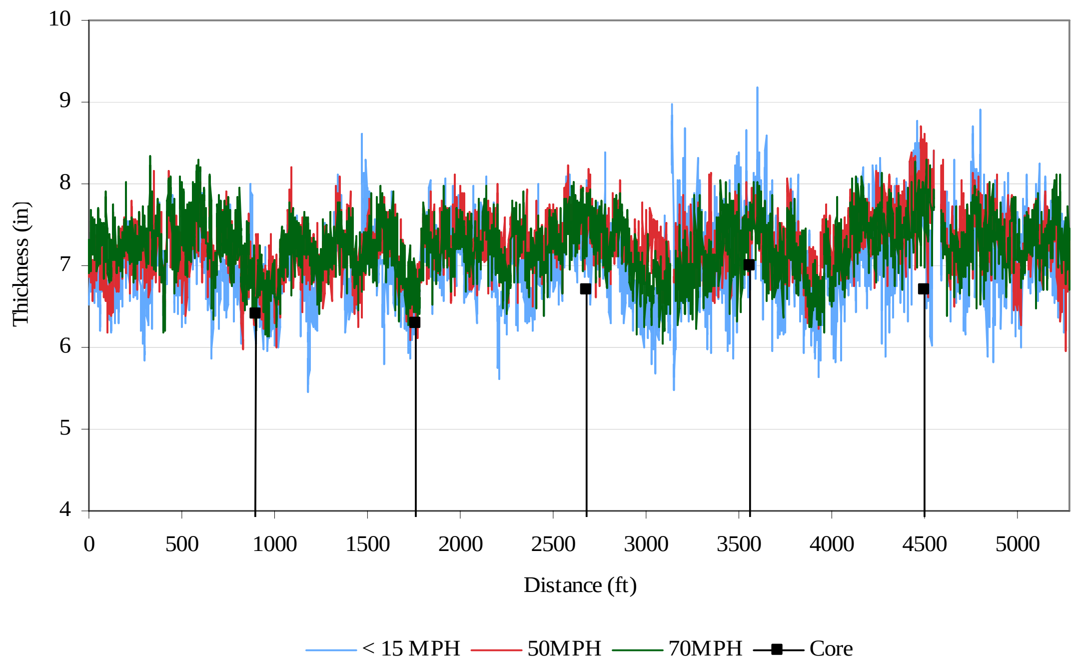

Figure 18. Thickness profile of SR228 IWP collected at 50 and 70 mph

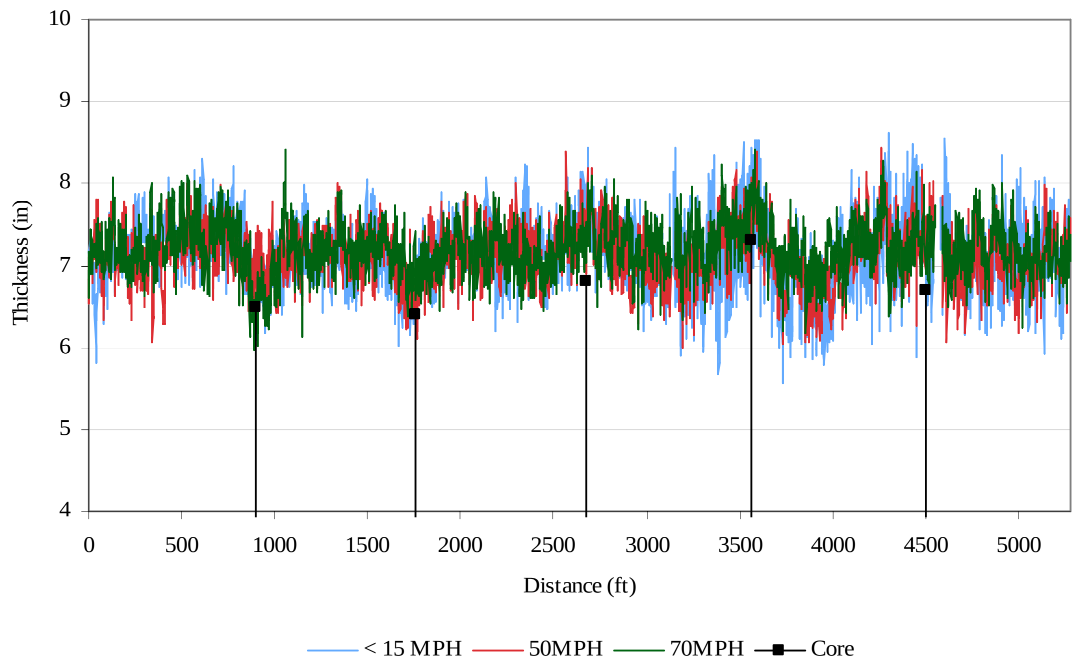

Figure 19. Thickness profile of SR228 OWP collected at 50 and 70 mph

Pavement thicknesses at the coring locations were also extracted from the repeatability data and were compared to core thicknesses. Similar to the accuracy study, the average absolute deviations of the extracted thicknesses were calculated for the low and high speeds from equation (4). These values are summarized in Table 8. The average absolute deviation from the accuracy study (stationary GPR data) is also shown in the table.

Table 8. Average absolute deviation of the repeatability data

State Road	Avg. Core Thickness (in)	Pavement Type	Average Absolute Deviation (in)		
			Stationary	Low Speed	High Speed
16	2.8	HMA	0.2	0.2	0.2
24-1	4.1	HMA	0.3	0.3	0.3
100	5.1	HMA	0.3	0.4	0.4
24-2	7.4	HMA	0.4	0.4	0.4
20	10.4	HMA	0.7	0.5	0.6
26	12.9	HMA	0.5	0.5	0.5
228	6.7	PCC	0.5	0.6	0.5
5	3.1	**HMA**/PCC*	0.1	0.3	0.2
5	7.3	HMA/**PCC***	0.9	1.3	1.2
5	7.8	**PCC**/HMA*	0.6	0.7	0.8
5	2.9	PCC/**HMA***	0.2	0.4	0.4

* The row corresponds to the layer with bold text.

One can immediately observe that, the data collected at highway speeds is compatible with the stationary data. The table also shows that for all sites, the average absolute deviations of the top surface layer were less than 1 inch regardless of the pavement type, thickness of the top surface layer or speed of the GPR vehicle during data collection.

CONCLUSIONS

A total of 11 in service pavements were selected to evaluate the accuracy and repeatability of the Ground Penetrating Radar (GPR) system. Two sections were dropped from the study due to interferences in radar signals and the remaining 9 sections were surveyed and cored for the study. HMA thicknesses ranged as low as 2.5 inches and as high as 14.0 inches. For the accuracy study, pavement thicknesses were estimated from stationary GPR data and were compared to the actual core thicknesses. Different layer picking options and the use of calibration cores were also addressed.

The results of the accuracy study showed that the GPR system is capable of estimating the layer thicknesses accurately, especially for HMA layers. The overall average absolute deviations of the GPR thicknesses obtained from the data were 0.4 inch for HMA and 0.6 inch for PCC without the aid of calibration cores. These results were further improved when the cores were used to calibrate the velocities. The average absolute deviations after velocity calibration were determined to be 0.3 inch and 0.4 inch for HMA and PCC, respectively. Further study is recommended as to cover a larger number of rigid and composite pavements with a wide range of PCC thicknesses.

Nonetheless, it should be emphasized that the accuracy of the GPR system may be significantly affected when noise is present in the data due to external interferences. Further study is necessary to better understand the noise in terms of its source, frequency, amount and possible solutions.

The repeatability of the GPR system was studied using the data collected at variable speeds. The system showed excellent repeatability for speeds ranging from less than 15 mph up to 70 mph. The thickness predictions from the data collected at highway speeds were very reliable. However, it is strongly recommended that when the data is collected at highway speeds, more markers be inserted in the GPR data in order to minimize the offset errors. These markers should be linked to physical objects with known mileposts.

This study has shown that the GPR system is reliable for surveying pavement thicknesses. It is strongly recommended that the GPR system be used as a tool for assisting in pavement thickness determination. The thickness information provided by the GPR may be valuable for pavement management since it can be used to help determine the coring locations and reduce frequency instead of randomly selecting them. More accurate thickness information can be obtained when the core thicknesses are used as feedback into the GPR analysis for calibration of radar velocities.

REFERENCES

1. Daniels, D.J, *Surface-Penetrating Radar,* The Institution of Electrical Engineers, London, 1996.
2. Conyers, L. B. and Goodman, D., *Ground-Penetrating Radar An Introduction for Archaeologists*, Altamira Press, 1997.
3. Al-Qadi, I.L., K. Jiang, and S. Lahouar, *Analysis Tool for Determining Flexible Pavement Layer Thickness at Highway Speeds,* Transportation Research Record No. 06-1923, Washington D.C., 2006.
4. Al-Qadi, S. Lahouar, and A. Loulizi, *Successful Application of GPR for Quality Assurance/Quality Control of New Pavements*, Transportation Research Record No. 03-3512, Washington D.C., 2003.
5. Willett, D.A., and B. Rister, *Ground Penetrating Radar "Pavement Layer Thickness Evaluation."* Research Report KTC-02-29/FR101-00-1F, Kentucky Transportation Center, Lexington KY, December 2002.
6. Irwin, H.L., W. Yang, and R. Stubstad, *Deflection Reading Accuracy and Layer Thickness Accuracy of Pavement Layer Moduli.* Nondestructive Testing of Pavements and Backcalculation of Pavement Layer Moduli, ASTM STP 1026, American Society for Testing and Materials, Philadelphia PA, pp. 229-244, 1989.
7. Rwebangira, T., R. Hicks, and M. Truebe, *Sensitivity Analysis of Selected Backcalculation Procedures*, Transportation Research Record No. 1117, Washington D.C., 1987.
8. Briggs, R.C., T. Scullion, and K. Maser, *Asphalt Thickness Variation on Texas Strategic Highway Research Program Sections and Effect on Backcalculated Moduli*, Transportation Research Record 1377, Washington D.C., 1992.
9. Zaniewski, J.P., and M. Hossain, Effect of Thickness and Temperature Corrections on Prediction of Pavement Structural Capacity Using Falling Weight Deflectometer Data, Transportation Research Record No. 1377, Washington D.C., 1992.
10. Choubane, B., S. C. Ross, J. G. Moxley, and B. Dietrich, Application of Ground Penetrating Radar to Pavement Evaluation, Geophysics, 1st International Conference on the Application of Geophysical Methodologies and NDT to Transportation Facilities and Infrastructure, Missouri Department of Transportation and Federal Highway Administration, St. Louis Missouri, Dec. 11-15, 2000.