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PAVEMENT OVERLAY THICKNESS EVALUATION USING GROUND PENTRATING RADAR (GPR)

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ABSTRACT

Accurate knowledge of pavement thickness is important information to have both at a network and project level. This information aids in pavement management and design. Much of the time this information is missing, out of date, or unknown for highway sections. Current technologies for determining pavement thickness are core drilling, falling weight deflectometer (FWD), and ground penetrating radar (GPR). Core drilling provides very accurate pin point pavement thickness information; however, core drilling is also time consuming, labor intensive, intrusive to traffic, destructive, and limited in coverage. FWD provides nondestructive estimates of both a surface thickness and total thickness including pavement, base and sub-base. On the other hand, FWD is intrusive to traffic and affected by the limitations and assumptions the method used to estimate thickness. GPR provides pavement overlay thickness estimates with excellent data coverage at highway speed. Yet, the pavement thickness estimation is affected by the assumptions and limitations of the method used for thickness evaluation, and heavy post processing of the data are required to produce thickness estimates. Nevertheless, GPR has been successfully utilized by a number of departments of transportation (DOTs) for pavement thickness evaluation. It is concluded that GPR provided an economic estimate of the pavement overlay thickness by location along highway segments of the Interstate System within INDOT jurisdiction. The accuracy was acceptable for a network level study. This study represents INDOTs' experience utilizing GPR for evaluating pavement overlay thickness by location along segments within the Indiana Department of Transportation (INDOT) jurisdiction.

INTRODUCTION

Pavement thickness is an important property used in pavement rehabilitation design. Underestimating the thickness of the pavement, leads to overestimating the designed pavement rehabilitation thickness. This negatively impacts the economics of the rehabilitation. Overestimating the pavement thickness leads to underestimating the designed pavement rehabilitation thickness. This can decrease the performance, structural stability, and economics of the rehabilitated pavement. The Indiana Department of Transportation (INDOT) manages a highway network system consisting of approximately 11,000 miles of Interstates, US Roads, and State Routes. Information about pavement layer thickness by location along highways within INDOT jurisdiction needs to be collected. Current technologies for determining pavement thickness are core drilling, falling weight deflectometer (FWD), and ground penetrating radar (GPR).

Each of these technologies has distinctions. Core drilling provides an excellent accurate estimate thickness of the pavement at a point. The accuracy of the pavement thickness at a pin point is the main advantage of drilling core method. The disadvantages of core drilling include destruction of the pavement, and one thickness sample is used for characterization of an entire section. Besides, core provides no information about pavement support, and drilling core requires stopping at a location for extended periods of time impeding traffic and exposing the equipment operators.

FWD is the most widely used device for collecting pavement surface deflection data and providing information related to mechanistic pavement design and material properties (Noureldin, 2004). A simplified method for calculating layer thickness directly from FWD deflection testing was developed by (Noureldin, 1993). This method provides an estimate of the total thickness which includes the pavement thickness and support thickness and an estimate of the surface pavement thickness. The advantages of the FWD technology are its capability to measure the total pavement thickness, increase the number of sample sites, and being nondestructive. The disadvantages include the limitations and assumptions of the method used to estimate the thickness, and coverage limitations. Besides, obtaining FWD measurements requires stopping each location for a limited time impeding traffic thus exposing the equipment operators.

GPR, ground penetrating radar, is a high resolution geophysical technique that utilizes electromagnetic radar waves to locate and map subsurface targets including pavement layer contacts. GPR operates by transmitting short pulses of electromagnetic energy into the pavement. These pulses are reflected back to the radar antenna with the amplitude and arrival time that is related to the thickness and material properties of the pavement layers (Wenslick 1999)**.** The advantages of using GPR include excellent data coverage, highway speed data collection, and being nondestructive. The disadvantages include the limitations and assumptions of the method used to estimate the thickness, and heavy post processing of data to estimate the thickness. Nevertheless, GPR has been successfully utilized by a number of departments of transportation (DOTs) for pavement thickness evaluation. The Objective of the study is to utilize GPR to evaluate pavement overlay thickness by location along the highway segments within INDOT jurisdiction.

THICKNESS EVALUATION PRINCIPALS

GPR Thickness Model

The GPR thickness model is a simple mathematical model where the thickness is calculated from estimated radar wave velocity and the two way travel time.

$$Pavement\,Thickness = 0.5 * Radar\ Wave\ velocity * Two\ Way\ Travel\ Time \qquad (1)$$

The travel time is determined by properly identifying the interfaces and their sources in the GPR data. This process is very subjective and at times problematic. Identification of an interface is dependent on the size and shape of the reflected radar wave. The difference between the reflected radar wave and the background noise must be great enough to be detected and tracked. After an interface or anomaly is identified the source must be determined. The source of an interface includes but is not limited to the bottom of a pavement lift, the bottom of the pavement, a rebar layer, bottom of the sub-base, and an artifact of the data collection. In order for the interface to appear in the data, and a thickness value estimated, the following must occur:

1. The radar (EM) wave must propagate, to the targeted interface and return.
2. The radar wave must reflect off the interface target with enough energy to be recorded.
3. The contact must be identified in the GPR record.
4. The radar wave velocity must be estimated for material

The first two items are affected by the physical properties of the pavement layers, and the material underlying the pavement system. In other words, the successful determination of thickness by GPR is strongly dependant on the physical properties of the pavement, the GPR system used, and the data processing interpretation process.

The radar wave velocity is calculated from the dielectric value of the pavement. The dielectric value is calculated from the ratio of the amplitude of a radar wave reflected off a perfect conductor (metal plate), and the amplitude of the radar reflection off pavement surface or interface (Roddis 1992). The following equation is used to calculate the dielectric:

$$\varepsilon_{r1} = \left[\frac{1 + A_1 / A_p}{1 - A_1 / A_p}\right]^2 \qquad (2)$$

A_p = Amplitude of Return off Metal Plate, A_1 = Amplitude of Surface Return

ε_{r1} = Relative Dielectric Constant Pavement Overlay

The radar wave velocity is calculated using the following formula:

$$V_p = \frac{30.0}{\sqrt{\varepsilon_p}} \text{ (cm/nanosecond)} \tag{3}$$

V_p = Radar Wave Velocity in Pavement; ε_p = Relative Dielectric Constant Pavement

GPR Data Acquisition System

The GPR system consists of a control unit, EM wave transmitting equipment, receiving equipment, and recording equipment. The transmission cycle consists of generating, amplifying, and transmitting a radar wave into the pavement. The receiving cycle consists of receiving and sampling the reflected radar waves. The recording cycle includes converting the received signals from analog to digital data, displaying the data and storing the data.

The transmitting equipment used for the study included the electronics (wave form generators, wave guide, and amplifiers, etc) necessary to produce an ultra wide band radar signal with a central band frequency of 1 GHz, and an air launched antenna for transmission (Danials 1990).

The receiving equipment used for the study included the wave guide, amplifiers, and sampling electronics, and receiving antenna necessary for sampling the reflected waveforms.

The equipment and software purchased from the Pulse Radar was used for the data acquisition. This equipment is a two channel system capable of recording data over both wheel paths simultaneously.

GPR Data Display and Definitions

The GPR equipment records the reflected radar waveform at a given location/time. The reflected waveform is the summation of the recorded reflected radar waves for a given time window, 18 nanoseconds. The reflected radar waveform for a location is digitized and stored by the computer. These digitized values are referred to as samples. A trace is defined as the collection of sequential samples of the digitized waveform, or simply the digitized waveform (see Figure 1).

A GPR record is a group of sequential traces. The X- axis of a GPR record represents time or distance. The Y-axis represents two way travel time, the Z-value is representation of the amplitude of the reflected radar waves (see Figure 2).

THICKNESS EVALUATION METHODOLOGY

The three model parameters necessary to estimate the pavement overlay thickness using GPR are the radar wave travel time to the base of the overlay, the amplitude of the radar wave reflected off a perfect conductor (metal plate), and the amplitude of the reflected return off the pavement surface.

The metal plate amplitude is obtained from the metal plate calibration. The calibration is recorded prior to collecting field data. The average amplitude of the radar waves reflected from the metal plate boundary is used for the metal plate amplitude. The definition of amplitude used for the calculation is the difference between the peak and the trough (see Figure2)

Although the GPR data was collected with a resolution of about 1 trace every 3 feet, it was decided to provide thickness picks at approximately five locations per mile, in order to be consistent with the falling weight deflectometer (FWD) data gathered as part of the network evaluation study (Noureldin 2004). The software provided by the vendor would allow for thickness values to be generated at 5 picks per mile; however, the thickness values were based on an assumed assigned dielectric value. The dielectric values, hence the velocities, were not calculated from the data. This was not acceptable for the study; consequently the following methodology was developed.

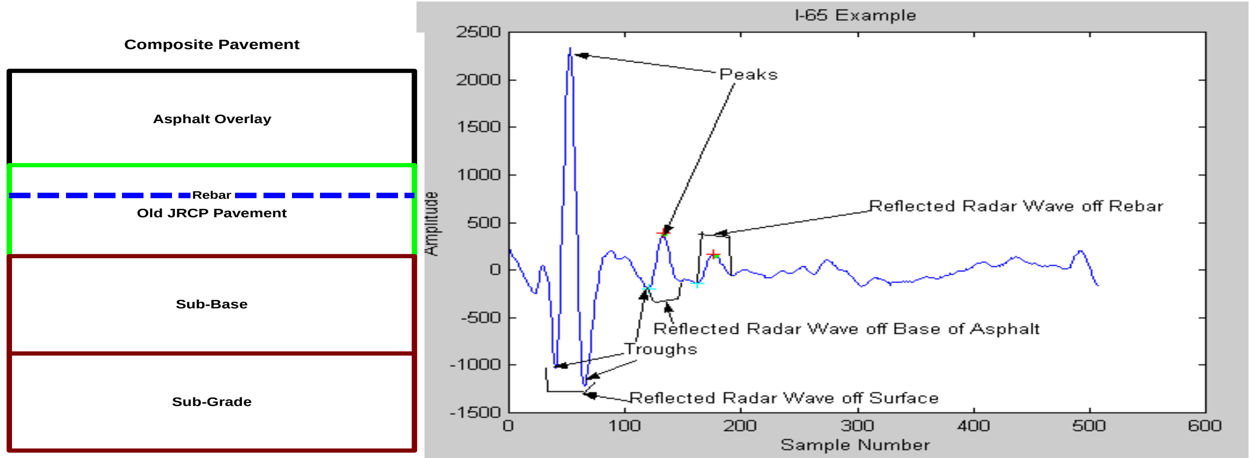


Figure 1: GPR waveform and pavement model; Left, composite pavement model; Right, radar waveform; The X-axis represents the two way travel time of the radar wave, the sample interval is 0.0354 (nanoseconds/sample)

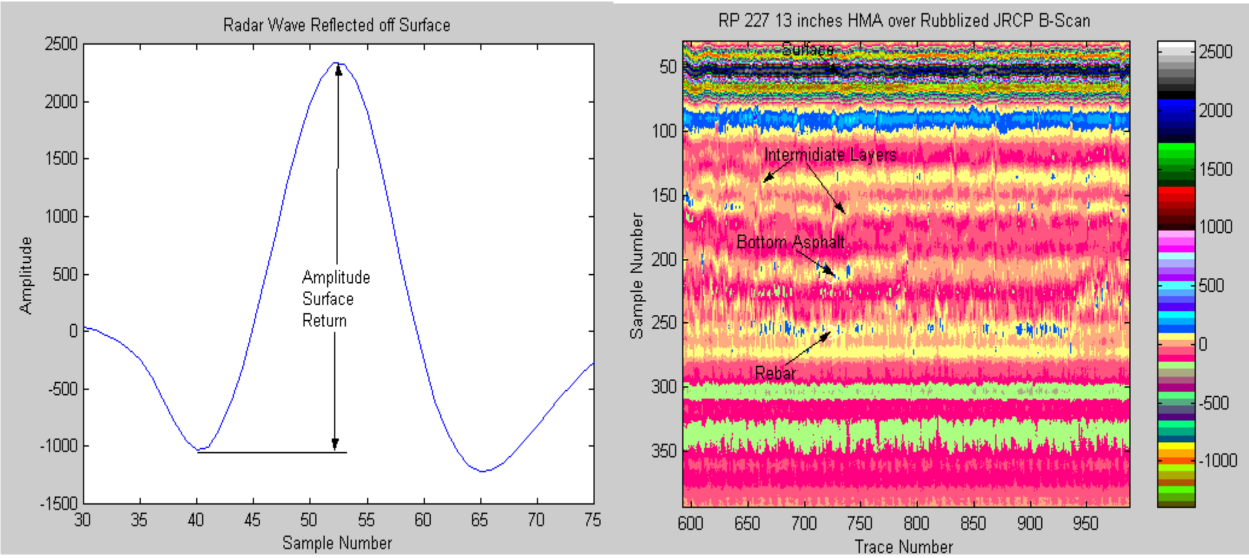


Figure 2: Left; explanation of amplitude X-axis represents travel time Y-axis amplitude Right; GPR record, X-axis represents distance increasing to the right. The Y-Axis represents 2-way travel time, and the Z-axis is color coded amplitude

Data Interpretation Process

The data analysis process was carried out in the following steps.

1. Interfaces were identified one pick per 500 feet.
2. Discontinuities in the data were located, such as bridges etc.
3. Dielectric analysis was conducted
4. Thickness values were calculated for each mile

The interfaces were identified using the vender software package. The only pavement stratigraphy information utilized was a basic intuitive best guess of the overlay thickness provided by the INDOT engineers. Initially the clearest identifiable interface closest to the intuitive thickness was selected as the bottom of the pavement. Interfaces were selected every 500 feet except in breaks in the pavement (see Figure 3). A text output file is generated containing the thickness values, assumed dielectric constant, and the distance. The GPR record was scanned again for the start and end of breaks in the pavement. This information was output in a text file. A binary file containing the amplitude of the surface return, and a binary file containing the distance values were extracted from the data file.

The overlay dielectric values were calculated for all of the traces in the GPR record using the amplitude file and the average metal plate amplitude. Equation 2 was used for the calculation. All of the dielectric values contained in pavement breaks were eliminated.

The GPR record was split up into regions. An average dielectric value was calculated for each region. This dielectric value was then assigned to every pick in the region. An example of a regional dielectric plot is included as Figure 4 (see Figure 4). New thickness values were then calculated for each pick using the new dielectric values and the thickness from the software calculated using an assigned dielectric value using the following equation. The following equation transforms the pick thickness into a travel time, and then back to a thickness using the calculated dielectric.

$$tk_n = tk_p \left(\sqrt{\frac{\varepsilon_p}{\varepsilon_r}} \right) \tag{4}$$

tk_n = Calculated Thickness , tk_p = Pick Thickness, ε_p = Pick Dielectric, ε_r = Regional Dielectric

ERROR ANALYSIS

There is ample opportunity for errors to creep into GPR pavement thickness evaluation. Blunders, systematic errors, and random errors are all present. Therefore, a thorough analysis based on rigorous mathematics and realistic data is necessary.

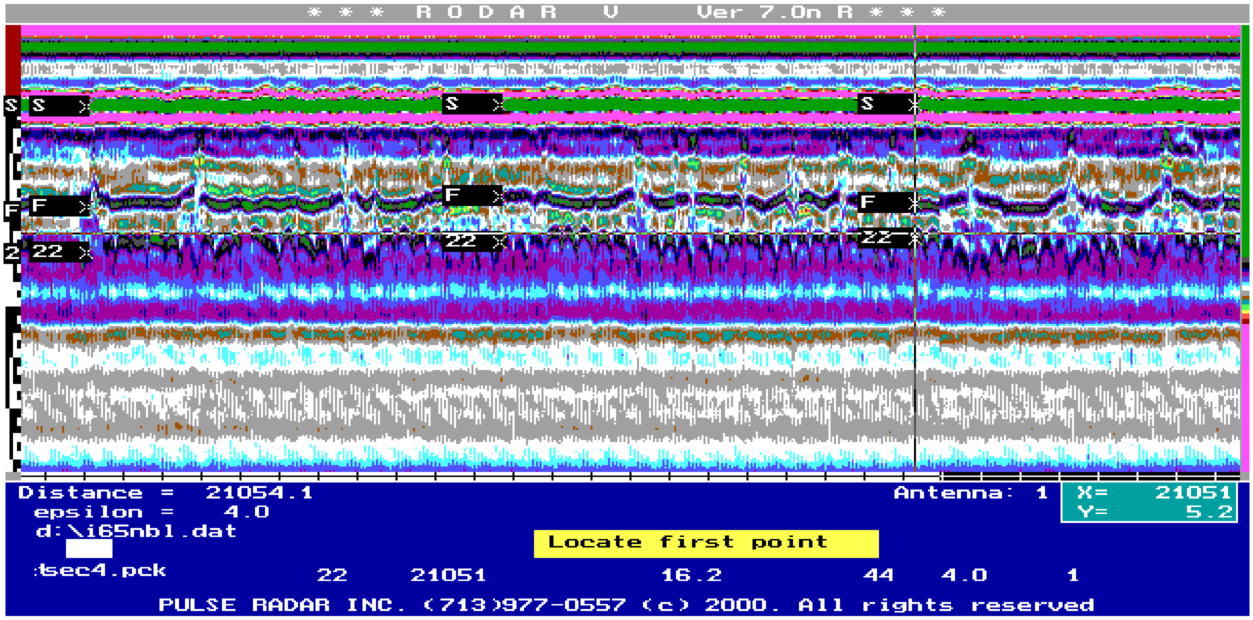
Blunders

One of the most common sources of blunders is misidentification of the base of the pavement. This can lead to gross errors in pavement thickness. Often the source of the interface may be misidentified. For example, the application of an emulsifying agent to the top of the base support, during construction, can cause the top part of the base, impregnated by the agent, to have dielectric values very similar to that of the asphalt overlay. Consequently, the source of the interface identified as the base of the asphalt in the data in reality is the bottom of the impregnated base.

Systematic Errors

Equipment instabilities are a source of systematic error in pavement thickness evaluation. Equipment instabilities are very evident in the following calibration file example.

Each point in the Figure 5 represents the amplitude value of surface return off a metal plate for one trace (see Figure 5). One calibration file was collected in the morning after the equipment was warmed up for about 45 minutes, but before the thickness data was collected. The second calibration file was collected after the thickness data was collected. The morning calibration file is very unstable the values ramp up and down with vertical discontinues (see Figure 5). There is a major difference in the calibration file collected before verses after. The after calibration file is more stable, and was used for the thickness calculations. However, this does not mean the calibration file is more accurate, the file is just more precise and consistent. These results would suggest one short calibration file is not sufficient for thickness studies.



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 :tsec4.pck          22    21051            16.2          44    4.0      1
          PULSE RADAR INC. (713)977-0557 (c) 2000. All rights reserved
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Figure 3 Example of Interface Selection; F is the base of the asphalt and 22 is the reflection off the rebar

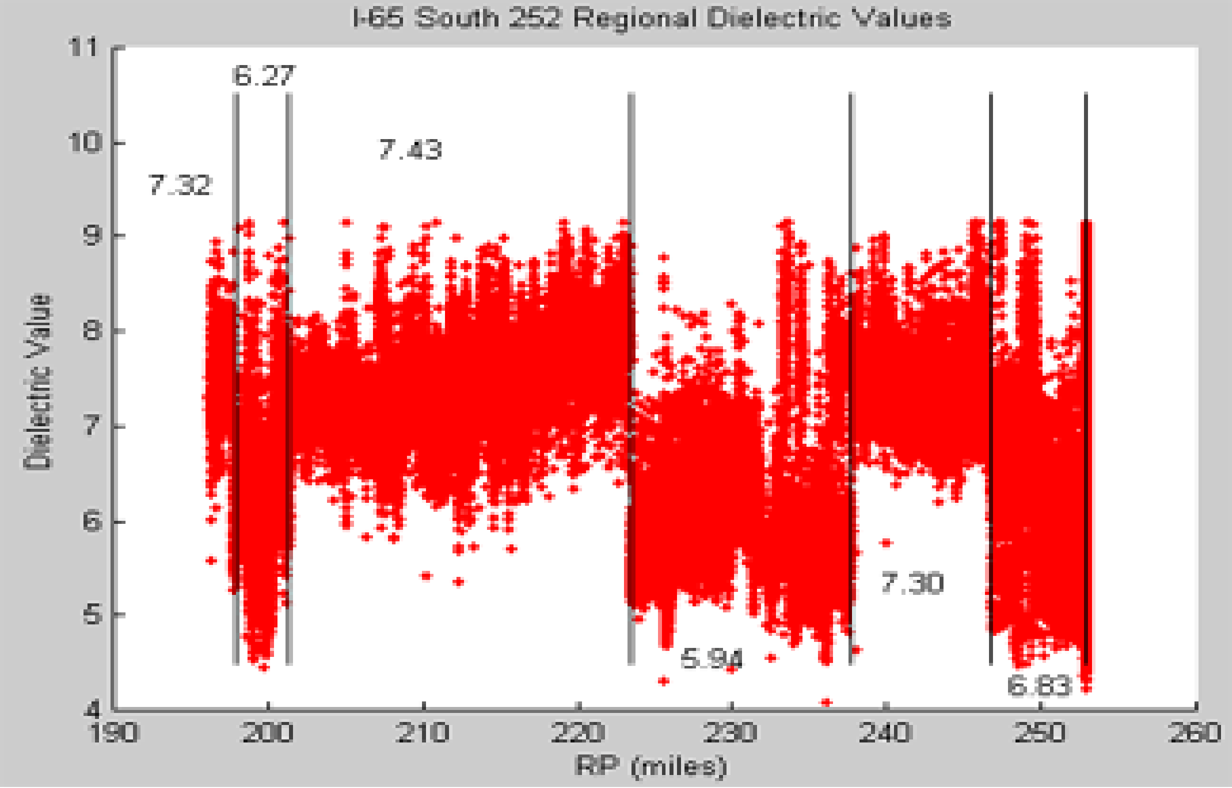

Figure 4 Regional Dielectric Example; each trace between the vertical black lines is assigned the noted dielectric value.

Random Errors

There are random errors associated with each of the three parameters, metal plate amplitude, surface return amplitude, and travel time used to calculate the thickness. These errors were propagated into the errors in thickness using the variances of the model parameters. The following equations describe the standard deviation of the thickness assuming no correlation between parameters. Equation 5 describes the standard deviation of the thickness due to variance in amplitudes assuming no variance in the travel time. Equation 7 details the standard deviation of the thickness due to the variance of all model parameters.

$$\sigma_D(v) = \frac{2D}{A_p^2 - A_s^2}\sqrt{A_s^2\sigma_{A_p}^2 + A_p\sigma_{A_s}^2} \Rightarrow \tag{5}$$

$$\frac{\sigma_D(v)}{D} = \text{relative error} = \frac{2}{A_p^2 - A_s^2}\sqrt{A_s^2\sigma_{A_p}^2 + A_p\sigma_{A_s}^2} \tag{6}$$

$$\sigma_D = c\left(\sqrt{\left(\frac{2tA_s}{\left(A_p + A_s\right)^2}\right)^2\sigma_{A_p}^2 + \left(\frac{-2tA_p}{\left(A_p + A_s\right)^2}\right)^2\sigma_{A_s}^2 + \left(\frac{\left(A_p - A_s\right)^2}{\left(A_p + A_s\right)^2}\right)\sigma_t^2}\right) \tag{7}$$

σ_{D} = Standard deviation Thickness, $\frac{\sigma_D}{D}$ = Relative Error

A_p = Metal plate Amplitude, A_s = Surface Return Amplitude, D = Thickness

$\sigma_{A_s}^2$ = Variance Surface Return Amplitude, $\sigma_{A_p}^2$ = Variance Metal Plate Amplitude,

σ_t^2 = Variance Trave Time, t = Travel Time of Radar Wave, c = Speed of Light in Vacum

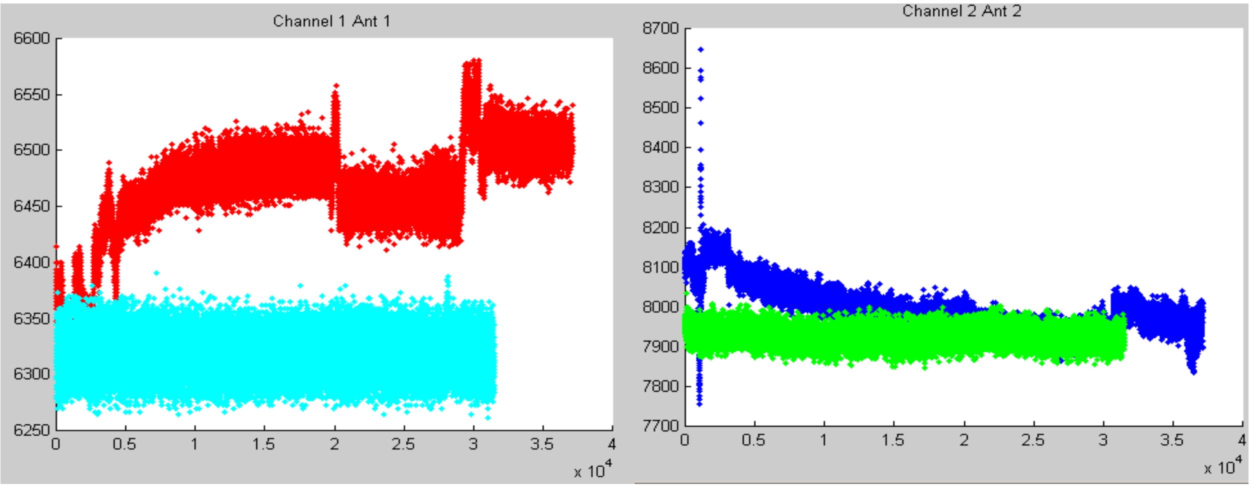

Figure 5 Systematic/Random error example: each point is an amplitude value; Left, Channel 1 Red is the morning file, Cyan afternoon File; Right, Blue is for morning file. Green is for afternoon file. Note the spread of points for each file is correlated to the standard deviation or random error. The difference between files on a given day represents systematic error.

An analysis of random error was done for the I-65 case study. The results are included in Table 1. The standard deviation of the metal plate amplitude was calculated from the metal plate calibration file. Standard deviations of the surface return amplitudes were calculated for each dielectric region in the case study. The travel time standard deviation was estimated using the standard deviation of a group of traces located within the pavement region. The standard deviation of thickness using Equation 7 is an estimate of the expected best precision of the pavement thickness estimates.

Table 1 Random Error I-65 Case Study

Pavement Overlay	19.0 cm Asphalt	33.0 cm Asphalt	30.5 cm Concrete
Metal Plate Amplitude	8,139.9	8,139.9	8,139.9
Standard Deviation Metal plate Amplitude	28.9	28.9	28.9
Surface Return Amplitude	3,739.5	3,311.5	3,437.7
Standard Deviation Surface Return Amplitude	90.2	126.1	149.7
Travel Time (nano-seconds)	2.69	5.6	6.1
Standard Deviation Travel Time	0.22	0.22	0.07
Standard Deviation Thickness			
Standard Deviation Amplitude only (mm)	5.4	12.3	13.7
Standard Deviation Relative Amp only (%)	2.8	3.7	4.5
Standard Deviation All Parameters (mm)	12.7	19.0	17.4
Standard Deviation Relative All (%)	6.7	5.8	5.7

CASE STUDIES

Interstate Network Study

GPR was used to test the truck lane for both directions of traffic (east – west or north – south) of the INDOT Interstate system at highway speed. The methodology described above was used to evaluate the thickness. The results were then compared with FWD thickness values. These FWD thickness values were generated using a simplified method for backcalculating thickness directly from FWD deflection basin data developed by Noureldin (Noureldin 1993).

A majority of the Indiana interstate system is consists of a composite pavement with an asphalt overlay over concrete pavement. The rebar present in the concrete pavement reflected the radar waves causing an interface in the data. This was one of the interfaces selected and interpreted for much of the data. Changes in the stiffness of the concrete around the rebar lead to calculating the thickness down to the rebar as the FWD surface thickness (see Figure 6).

The GPR thickness to the rebar compared favorably with the FWD surface thickness values in some instances the thickness was slightly lower. An example from I-69 is included (see Figure 7). Both the GPR and the FWD results compare well with the model. The average GPR overlay thickness of 17 cm compares well with the model value of 18 cm. The average GPR thickness to rebar 29 cm and the FWD surface thickness of 27 cm compare well to the model thickness of approximately 31 cm. The average FWD total thickness 62 cm compares well with the model thickness of 64 cm.

Validation Studies

Three studies were examined to validate GPR thickness results based on ground truth. Three sections of two state roads were selected to be drilled for ground truth. Core holes were drilled at the RP every mile of the sections. The section includes a 20 mile section of US 41 northbound between RP 28 and 47, an 11 mile section of SR32 eastbound between RP 62 and RP 72, and a 12 mile section of SR 32 eastbound between RP 87 and RP 98. The last study used historical thickness estimates for a concrete rehabilitation study site on I-65 between RP 217 and 239. The GPR data presented is from the southbound driving lane. GPR thickness values were evaluated with two methodologies. The methodology described above was used to calculate the thickness for each mile, and this thickness was compared with the ground truth for each mile. For the second methodology, a small group of traces located around the hole/RP location was extracted. The dielectric values, travel time values, and thickness values were calculated for each trace. The thickness average thickness was then calculated for the location. This average value was then compared with ground truth.

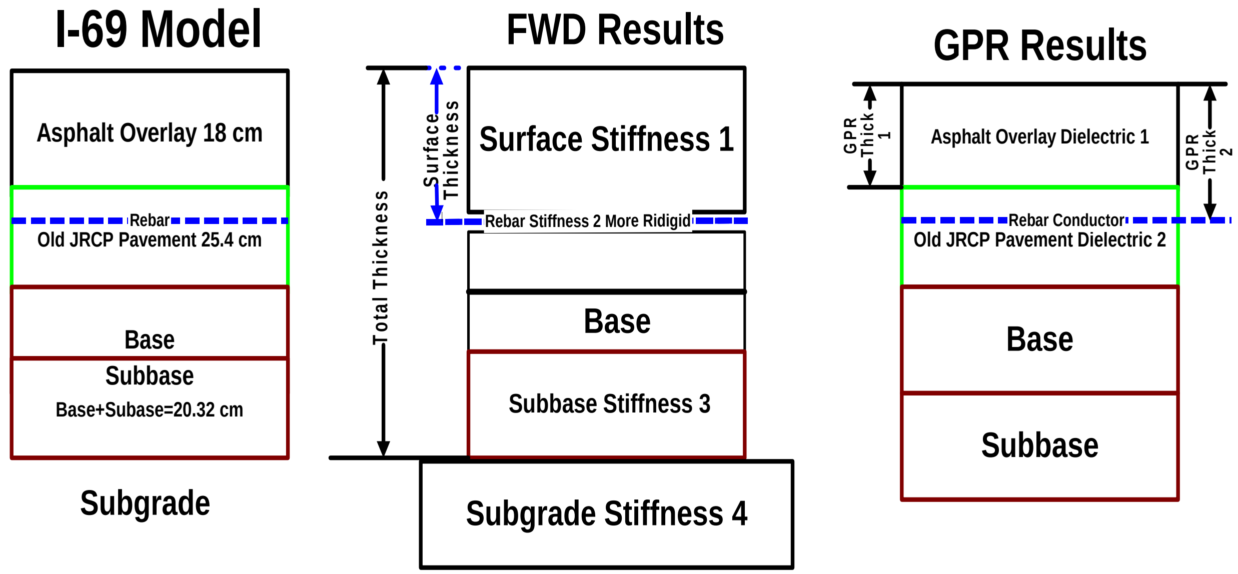

Figure 6 Models, Left Pavement, Center FWD, Right GPR

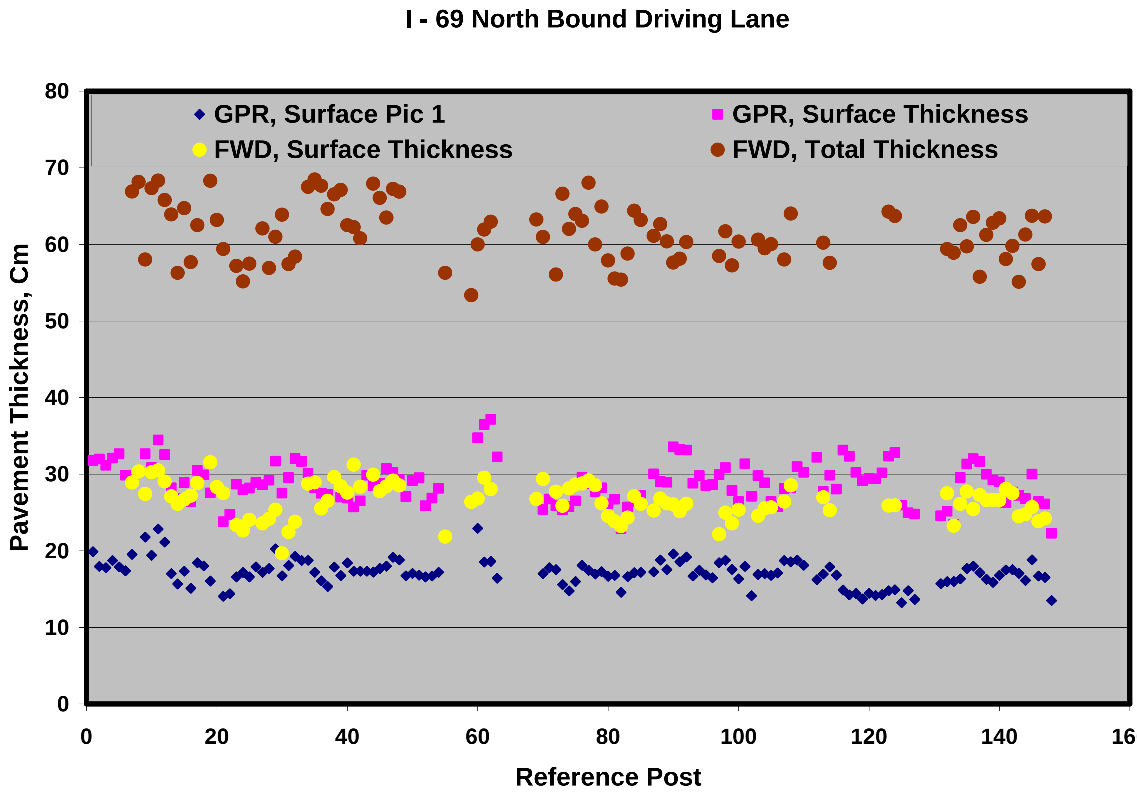

Figure 7 Results of Initial Thickness Study Interstate I-69.

The accuracies listed in the table below are calculated by dividing the absolute value of the difference between the ground truth and the GPR calculated by the ground truth.

Table 2 Validation Study Accuracy Results

Study	Pavement Type	Overlay Material	Method 2 Relative Accuracy (%)	Method 1 Relative Accuracy (%)
I-65	Composite	31 cm Concrete	4.5	8
I-65	Composite	33 cm Asphalt	2	1.9
I-65	Composite	19 cm Asphalt	13.2	11
US-41	Composite	17 cm Asphalt	16.4	
US-41	Composite	11 cm Asphalt	9.6	
US-41	Concrete	25 cm Concrete	3.7	
US-41	Composite	Combination of Both 17 and 11 cm		15
SR-32	Composite/Asp	Asphalt Variable Thickness	16.6	11.4

A number of studies have been conducted by other departments of transportation. These GPR studies were evaluated using the second method. An overview of the accuracies of some of these studies is included in the following table (see Table 3). The relative accuracy sections of road within the validation studies fell within the range of accuracies published in other reports ((Attoh-Okine, 1993), (Maser, 1994a), (Maser, 1994b), (Wenzlick, 1999), (Willet, 2002)).

Table 3 Published Accuracies

Funding Agency	Same Vendor as NDOT Study	Relative Accuracy Results
Kansas DOT	YES	7.5% - 10%
Strategic Highway Research Program (SHRP)	YES	8%
Minnesota DOT	YES	3% - 6.5%
Missouri DOT	YES	4% - 11.3%
Kentucky DOT	NO	5.82% - 165.02%

I65 Case Study. All pavements in this study were composite. The first six mile section between RP 217 and 222 consists of 30.5 centimeters concrete overlay over joint reinforced concrete pavement (JRCP). The second six mile stretch between 223 and 228 consists of 33 centimeters of HMA overlay over rubblized JRCP. The remaining 9 miles between RP 229 and RP 238 consists of 19 centimeters of fiber modified HMA over JRCP.

The data for this study was collected using 508 samples per trace at vehicle speed of approximately 55 MPH. Consequently, the traces were about 1 meter apart. The thickness values agree well with the historical data for the first two sections. However, the thickness values do not agree well with historical data for the last section. There was much more variability in the constructed thickness for the last area.

US41N Case Study. The first fifteen miles of this study between RP 28 and 42 was composite pavement consisting of an asphalt overlay between 10 and 15 centimeters over 21.5 to 24 centimeters concrete. The remaining five miles, between RP 43 and RP 47, was a concrete pavement between 25.5 and 26 centimeters.

The data for this study was collected using 508 samples per trace at a vehicle speed of approximately 55 MPH, which yields traces were about 1 meter apart. For this study pavement thickness values were calculated using metal plate amplitudes from a number of different calibration files. All of the calibration files were recorded using the same equipment settings. There was a noticeable difference in the thickness values calculated using the different calibration files (see Figure 8). The series labeled Orig are the thickness values evaluated using the original metal plate calibration file. The variability of the thickness values is partially due to the instability of the GPR system discussed earlier.

SR32E Case Study. The first eleven miles of this study between RP 62 and 72 was asphalt pavement between 18 and 37 centimeters. The second section of this study between RP 87 and 98 was a composite pavement consisting of an asphalt overlay between 15 and 20.5 centimeters over 18 to 21.5 centimeters concrete.

The data for this study was collected using 254 samples per trace at a vehicle speed of approximately 55 MPH. The traces were therefore about 0.52 meters apart. The results of this case study were not favorable. The First section was not composite; consequently, the variability of the pavement thickness contributed to the error. The interfaces were much harder to locate in the data. This also led to increased error (see Figure 9)

CONCLUSIONS

The Interstate network study was a blind study without ground truth; consequently, the validation studies were conducted to study the accuracy of the GPR thickness values. The base of the asphalt overlay and the reflection off the rebar of the underlying concrete were readily identifiable in the data. The base of concrete pavements was much harder to identify due to small changes in the dielectrics at the pavement support boundary. The random error analysis for a section of I-65 demonstrated that the best expectable relative thickness estimate at one standard deviation would be within a range of 5.7% to 6.7% of the pavement thickness.

The validation studies based on ground truth showed the relative accuracy varies in different studies within a range of 2%-16.6%. These results are consistent with most of the published studies. Variability in thickness decreased the accuracy of some composite pavement and all the asphalt pavements. Also, the asphalt pavement base in some case study might be hard to identify, which will possibly cause blunders in interface identification.

GPR provided an economic estimate of the pavement overlay thickness by location along highway segments of the Interstate System within INDOT jurisdiction. The accuracy was acceptable for a network level study. The accuracy of the GPR thickness values are dependant on the pavement stratigraphy.

REFERENCES

Attoh-Okine, B. (1993). Engineering-Economic Assessment of Paved Road Thickness Using Ground Penetrating Radar (GPR), Doctoral Dissertation University of Kansas.

Daniels, J. (1990). Fundamentals of Ground Penetrating Radar. Soft Earth Associates Inc., Westerville, Ohio

Maser, K (1994a). Ground Penetrating Radar Surveys to Characterize Pavement Layer Thickness Variations at GPS Sites, Strategic Highway Research Program Report SHRP-P-397

Maser, K. (1994b). Ground Penetrating Radar Survey of Pavement Thickness on MN/Road Sections. Minnesota Department of Transportation Office of Minnesota Road Research Report # MN/RC-95/06

Noureldin, A. (1993). New Scenario for Backcalculation of Layer Moduli of Flexible Pavements, TRR 1448, Washington D.C.

Noureldin, A., Zhu, K., Li, S., Harris, D. (2004), Network Pavement Evaluation Using Falling Weight Deflectometer and Ground penetrating Radar, TRR 1860 Washington D.C.

Roddis, W.,Maser, K., Gisi, J. (1992). Radar Pavement Thickness Evaluations for Varying base conditions. TRR 1355 Washington D.C.

Wenzlick, J., Scullion, T., Maser, K. (1999). High Accuracy Pavement Thickness Measurement Using Ground Penetrating Radar, Report for Missouri Department of Transportation Research Development and Technology Division, Report RDT 99-003

Willet, D., Rister, B. (2002). Ground Penetrating Radar Pavement Layer Thickness Evaluation, Kentucky Transportation Center Research Report # KTC-02-29/FR101-00-1F

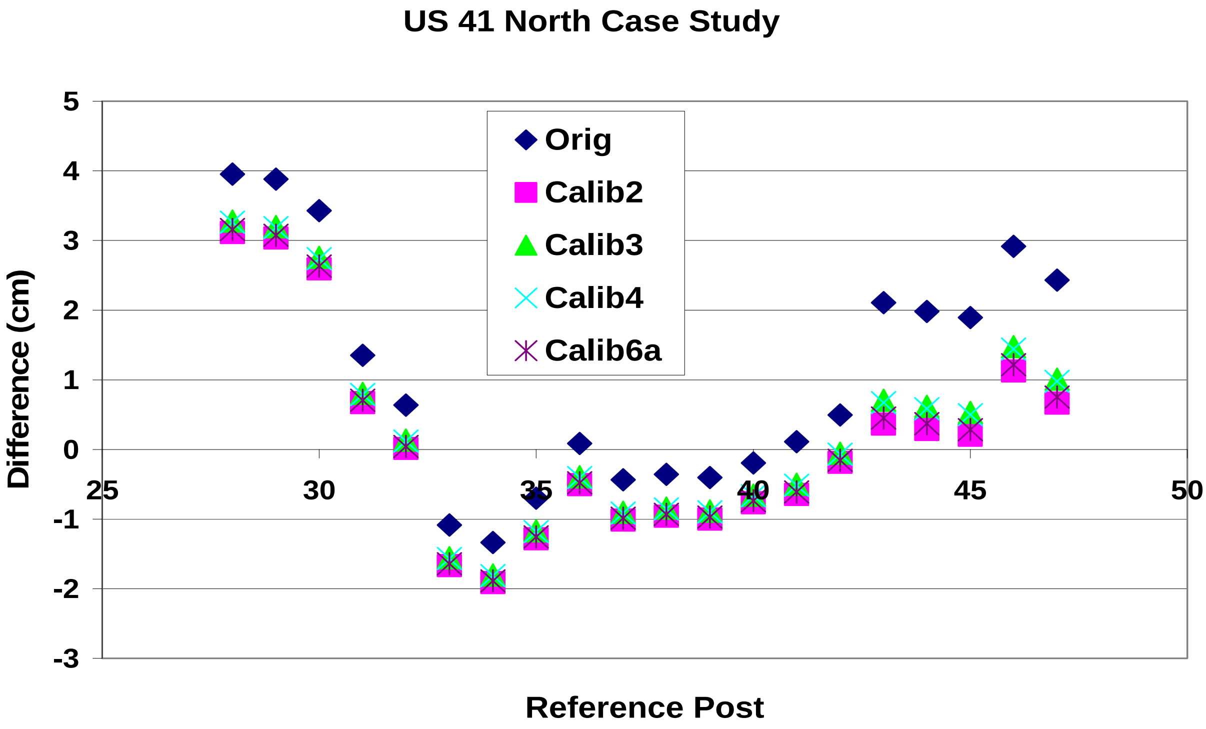

Figure 8 Results, US-41 Case Study, difference between GPR thickness and core thickness using different calibration files. All GPR results obtained using method 2.

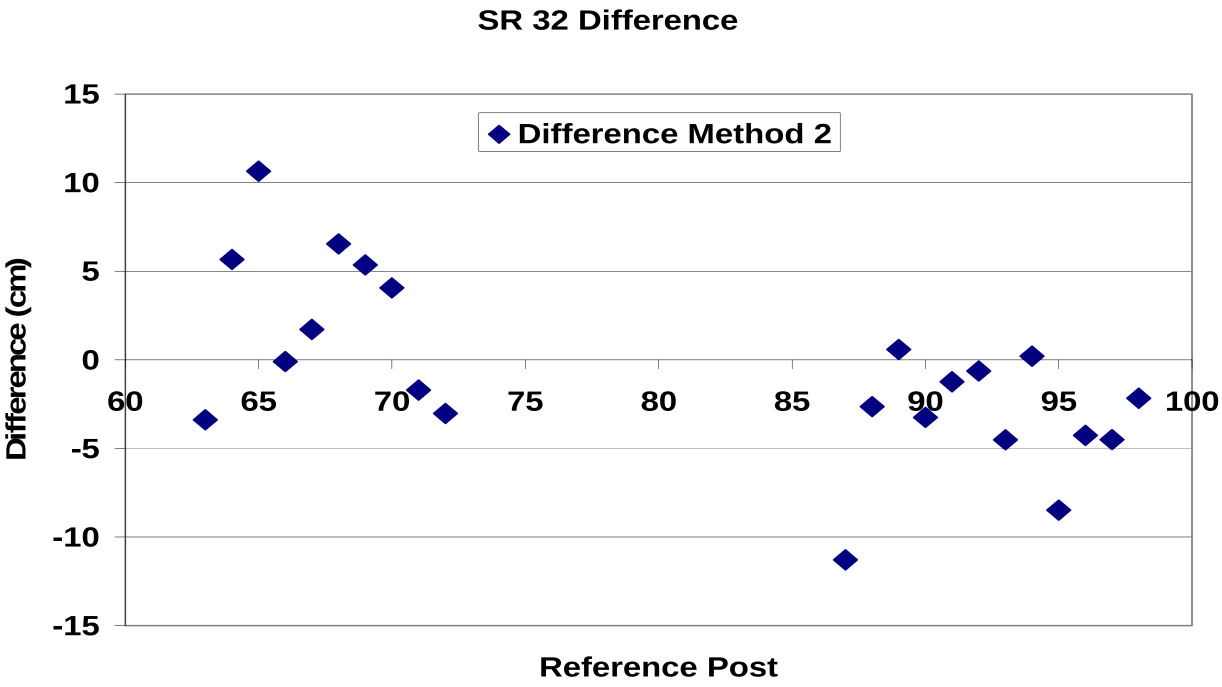

Figure 9 Results, SR-32E case study, difference between GPR thickness and core thickness