Mississippi Department of Transportation

In Cooperation with the
US Department of Transportation
Federal Highway Administration

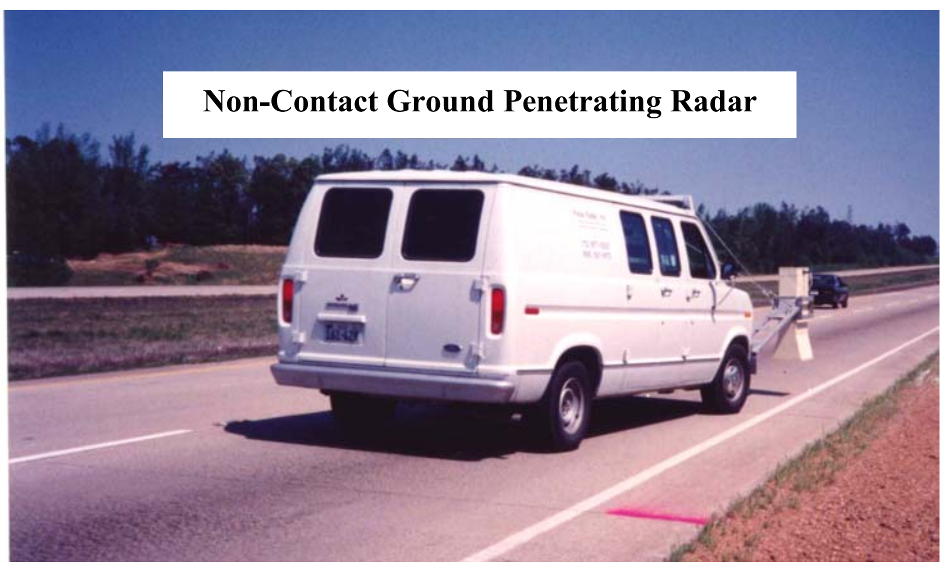
Ground Penetrating Radar Study ─ Phase I

Technology Review and Evaluation

FINAL REPORT

FHWA/MS-DOT-RD-06-182

August 2006



CAIT Report number: UM-CAIT/2006-01

Center for Advanced
Infrastructure Technology
The University of Mississippi
Carrier 203, University, MS 38677 1848, USA
Voice: 662 915 5366 Fax: 662 915 5523
http://www.olemiss.edu/projects/cait/Index.html
cait@olemiss.edu

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
FHWA/MS-DOT-RD-06-182</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Ground Penetrating Radar Study – Phase I
Technology Review and Evaluation</td><td colspan="2">5. Report Date
August 2006</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Waheed Uddin</td><td colspan="2">8. Performing Organization Report No.
MS-DOT-RD-06-182</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
University of Mississippi
Center for Advanced Infrastructure Technology (CAIT)
Department of Civil Engineering, Carrier 203
University, MS 38677-1848</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
SS 182</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Mississippi Department of Transportation
Research Division
P O Box 1850
Jackson MS 39215-1850</td><td colspan="2">13. Type Report and Period Covered
Final Report, 2005-2006</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
University of Mississippi report number UM-CAIT/2006-01</td></tr>
<tr><td colspan="4">16. Abstract
In December 2005 Mississippi Department of Transportation (MDOT) initiated State Study No. 182 on review and evaluation of ground penetrating radar (GPR) technology. This Phase I study has reviewed GPR equipment and data interpretation methodologies used for nondestructive determination of pavement layer thickness values. An extensive literature review was supplemented by review reports from two study consultants, and a comprehensive GPR technology evaluation survey of GPR manufacturer and users in the United States and abroad. There is adequate experience available with data interpretation methodologies and FCC certified or "grandfathered" GPR technologies for reliable and reasonably accurate field assessment of asphalt pavement layer thicknesses. The MDOT is planning to evaluate this technology together with the nondestructive falling weight deflectometer (FWD) tests to enhance the evaluation of asphalt highway pavements and rehabilitation design. A preliminary cost-effectiveness study shows a high benefit/cost ratio of 80-200 based on overlay thickness design of a 10-mile asphalt pavement section. Based on favorable assessment in this study, a follow up larger Phase II study is recommended for field evaluation of the candidate GPR technology with 1- GHz and 2-GHz air-launched horn antennas. A ground-coupled 400/500 MHz antenna is also recommended considering 30-inch or thicker pavements and the lime-treated subgrade layer. A pilot field study in Phase II should be conducted on a test section of a candidate asphalt highway pavement. Upon successful results and validation of improved pavement evaluation and resulting potential cost savings, the MDOT will consider implementing the GPR technology for routine use.</td></tr>
<tr><td colspan="2">17. Key Words
GPR, dielectric constant, asphalt pavement, layer thickness</td><td colspan="2">18. Distribution Statement
Unclassified</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
110</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The support and inputs of Bill Barstis and James Watkins of the Mississippi Department of Transportation is greatly appreciated. Thanks are due to the study consultants, Carl Bertrand of Spectral Measurements LLC and Tom Scullion of Texas Transportation Institute who provided their expert review reports. This report also incorporates the content highlights of their review reports. Thanks are also due to the GPR technology survey responses provided by many consultants-service providers, researchers, equipment manufacturers, and highway agency persons involved in GPR procurement, testing, and implementation. Their names and affiliations are provided in Appendix C.

This report is authored by Waheed Uddin, the Principal Investigator of Sate Study 182, with assistance of CAIT research assistants, doctoral student Bikila Wodajo and undergraduate junior student Drew White.

DISCLAIMER

The University of Mississippi and the Mississippi Department of Transportation do not endorse service providers, products, or manufacturers. Trade names or manufacturers' names appear herein solely because they are considered essential to the purpose of this report.

The contents of this report do not necessarily reflect the views and policies of the sponsor agency.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Overview of GPR for Pavement Evaluation, Pre -1990

Due to pavement aging and high volumes of traffic, the evaluation and maintenance of highway pavements using reliable nondestructive test (NDT) methods at faster speeds have become a necessity for most highway agencies. Several NDT methods have been applied to pavements during the past four decades. These include: deflection testing, thermal infrared imaging, and seismic and geophysical methods. Since the 1960's deflection testing had been a well defined and established method of nondestructive evaluation of pavements for structural assessment. The application of seismic and geophysical methods for pavement evaluation emerged in the 1980's and required specially trained interpretation experts.

Applications of GPR in 1970's and 1980's

Since early 1970's the electromagnetic (EM) wave as a geophysical test method has been used primarily for detection of landmines, evaluation of tunnels and bridge decks, and geological investigations. The pioneering application of high frequency radar at 400 MHz and higher in pavements focused on detection of voids under pavements and underground cavities so that timely repairs can be made. These included were the 1976 study by the Naval Civil Engineering Laboratory in California [1] and 1981 field study by the Cold Regions Research and Engineering Laboratory (CRREL) to detect cavities under concrete pavements [2]. NCHRP Synthesis 237, published in 1981, evaluated the use of pulsed EM waves for detection of voids beneath pavements. The researchers of Synthesis 237 at the Georgia Institute of Technology worked on the feasibility of locating subsurface voids beneath concrete pavements using a pulsed EM wave method. The antenna was a non-contact type. The transmitted pulse was a single sine wave cycle of approximately 1 nanosecond (ns) in time. The microcomputer processed the radar signal returns in an on-line mode and presented the results on a video monitor and on a line printer. Actual signal returns were permanently recorded on magnetic disks. The impulse radar system was mounted on a portable cart. The system is reportedly capable of spatial void location to ±6 in (0.15m) and depth sizing up to 8.5 in (0.2m), with a standard deviation of error of less than 0.5 in (12.7mm). The equipment was tested in the laboratory and used on test lanes constructed with voids. The authors indicated that the speed of highway coverage would remain the same (17.1 mph or 27.5 kmph) maximum) with multiple antennas [3].

Basic Principle of GPR Technology Ground penetrating radar (GPR) is a nondestructive geophysical technique that uses electromagnetic waves to evaluate subsurface information. A GPR unit emits a short pulse of electromagnetic energy and is able to determine the presence or absence of a target by examining the reflected energy from that pulse. An electromagnetic trigger pulse is generated in the control unit and sent to the antenna. In the antenna, each trigger pulse is transformed into a bipolar pulse which has higher amplitude than the trigger pulse. Then the transmitted pulse in the antenna is radiated into the subsurface and reflected at boundaries of materials with different values of the dielectric constant. The reflected portion of the electromagnetic signal travels back to the antenna. The receiver of the antenna detects the returning signal and sends it to the control unit to form a series of pulses, known as a waveform. The part of the signal not reflected continues through the medium until a boundary of different dielectric property is encountered, which causes further reflections. The series of waveforms recorded at the control unit produce an image. The time delay and amplitude of the waves in this image are related to the location and properties of interfaces and buried objects. The presence of disturbances below the pavement, such as voids and debonding of layers, will make the returned GPR signal different from what would normally be expected. Measurement of in situ layer thickness is another advantage of conducting GPR tests at the time of deflection tests. Further discussions on GPR theory, analysis, and applications for asphalt pavements are discussed in Chapter 2.

Evolution of Commercial GPR Technology for Pavement Evaluation In the early 1980's several commercial GPR devices were introduced with claims to detect voids beneath pavements and to measure thickness profiles; these were Penetradar [4], Donohue Remote Sensing van [5], and Gulf Applied Radar GPR van [6]. The 1985 Caltrans study used Penetradar that failed to produce satisfactory results for the purpose of measuring small voids and delaminations. [4]. Several other states including Virginia, Arkansas, Florida, North Carolina, Oklahoma, and Tennessee used Gulf GPR and Donohue GPR vans with non-contact antennas for continuous scanning at driving speeds of 10-20 mph for measuring voids under concrete pavements during the1980's [7, 8]. The antennas were mounted several inches above the pavement surface; they were traditionally called “air-coupled” antennas. For the purpose of this report, the traditional term “air-coupled” is used throughout chapters 1 and 2. (Note: As discussed in chapter 3, the traditional “air-coupled” antennas were re-defined as “air-launched” antennas after the new federal restriction in 2002).

The remote sensing van, developed by Donohue & Associates of Waukesha, Wisconsin, was equipped with both the ground-penetrating radar and the infrared remote-sensing equipment. The major use of infrared thermography was the detection of delaminations. The van also carried a video camera which was used to record surface conditions [5, 8]. The short pulse radar system developed by Gulf Applied Research Corporation of Houston, Texas was called RODAR Pavement Evaluation System. It was a totally self-contained system. It has been used in several States for void detection, pre- and post-grout surveys, and delamination. The radar system carried two antennas behind or in the front of the vehicle, mounted anywhere from 6 to 14 inches off the ground. Because the antennas did not contact the surface, the system can be used at speeds up to 20 mph. The system measured the depth and thickness of layers to approximately 15 inches, depending on the pavement materials. The system was capable of estimating void size from a horizontal standpoint, but the volume can only be roughly approximated. The radar truck was also equipped with (1) a fifth wheel, serving as the basic locating device, and (2) a painting device for painting a reference mark approximately every 1000 feet. The system also included a standard video camera to help interpret the data. A color graphics-based system was developed in the 1990’s to aid in data interpretation. Later, Pulse Radar Inc. marketed a similar GPR van [8].

Detection of Voids under Pavements and Subsurface Cavities

Voids under concrete pavements lead to partial loss of subgrade support, increased deflections, and increased load stresses. This can result in a significantly reduced fatigue life. Void detection is important as a part of pavement condition evaluation, yet it remains one of the most uncertain aspects of field testing and evaluation. If the situation is not assessed in advance, slabs break due to excessive tensile stresses that may result in expensive undersealing maintenance or slab replacement. Voids beneath the pavement can vary in depth from as small as one thousandth of an inch, causing partial loss of support, to a much larger depth of several inches. The effect of any depth of void is detrimental on the performance of the concrete pavement. Generally, the idea of measuring voids under pavement leads one to the assumption that large cavities will be measured. However, void size (depth) may vary from the delamination state adjacent to joints to a considerably larger dimension. Estimation of the dimension of a void area beneath concrete pavements is important to calculate quantity for undersealing work. Traditional manual methods for detecting voids involve subjective judgment, such as visual inspection, manual sounding, proof rolling, and deflection testing.

Unlike deflection testing for structural evaluation, which is a well defined area of pavement measurement, voids beneath Portland cement concrete pavements are poorly defined and measurement results are difficult to evaluate properly. During the 1980's void detection was in its technical infancy as was x-ray evaluation of the human body some 30 years ago. Nevertheless, the detection of voids beneath concrete pavements is an important consideration in planning maintenance treatments to restore support to the slab and extend the life of a pavement. Therefore, the emergence of nondestructive impulse radar techniques has been welcome by highway agencies.

FHWA Pavement Equipment Study (1985-87)

Most available NDT equipment and methods for pavement condition assessment were evaluated in a pre-SHRP (Strategic Highway Research Program) study sponsored by the Federal Highway Administration (FHWA) during 1985-87 [8, 9, 10]. That study evaluated three technology categories which were distress survey equipment and methods, deflection measuring devices, and equipment for measuring voids under pavements. In the last category of void detection under pavements the following methods were considered: Proof Roller method, Deflection method, falling weight deflectometer (FWD), Impulse Response method, Transient Dynamic Response method, and GPR equipment [8, 9]. Two specific GPR devices (Gulf and Donohue) were studied using the test data collected by the state highway agencies of Arkansas, Florida, North Carolina, Oklahoma, and Tennessee. All these results showed and proved that GPR was more reliable in detecting the voids below the pavements than other methods. However, the existing equipment was unable to estimate the thickness of a void area beneath concrete pavements. At the time of that study, the grey image output of a radar unit required the interpretation of a trained specialist. The FHWA report further concludes [8]:

- Ground penetrating radar holds good promise for reliable and cost-effective measurements of voids beneath concrete pavements. It is a rapid test method that does not require extensive traffic control and lane closures. Preliminary data interpretation can be made in the field. The data interpretation is complex, requiring specially trained technicians.
- GPR is perhaps the most promising new technique, but it has a very complex grey image output that is difficult to interpret. Improvements are needed for data interpretation techniques in the field and in the office. The use of a color video monitor by Gulf Applied Radar has enhanced the data analysis procedure.
- "Honeycombing" in the concrete can influence the results. Void thickness cannot be determined by radar. Problems in the interpretation of outputs have been reported when voids are full of water.

NCHRP Synthesis 255 (1998) and NCHRP Synthesis 357 (2006)

NCHRP Synthesis 255, published in 1998, evaluated the use of GPR for assessing subsurface conditions through a survey of highway agencies in the US and Canada [11]. About 60 % of those with GPR experience used consultants/service providers for GPR investigation of their pavements and only 11 agencies owned GPR equipment. Most common GPR applications were reported as pavement layer thickness, void detection under pavements, bridge deck delamination, layer delamination and depth to steel dowels, buried objects, depth to bedrock, asphalt stripping, and scouring around bridge piers[11, 12]. The synthesis report also recommended improving GPR equipment to produce more reliable and consistent results, developing better software for interpreting and displaying results, and establishing performance based specifications and measurement standard for GPR [11].

A recent report on NCHRP Synthesis 357, published in 2006, evaluated the use of geophysical methods for transportation projects through a survey of highway agencies and other selected entities in the US and Canada [13]. About 75 % DOTs use geophysical methods, and greater than 50 % use seismic and GPR methods. Most agencies reported success in their GPR testing results. The case studies were supplied by several agencies (Federal Lands Highway Division, Colorado DOT, New Hampshire DOT, Wisconsin DOT). The synthesis clearly indicates that GPR methods are useful tools. As discussed in Chapter 3, the federal restriction on the use of radio frequencies in the ultrawide band that interfere with cell phones took effect in July 2002. Since that time this federal regulation has made a significant impact on the routine use of GPR for pavement evaluation.

1.2 GPR Application in Mississippi and Other States

GPR for Nondestructive Evaluation of Concrete Highways in Mississippi

In the MDOT state study 110, the jointed concrete pavement of US Highway 78 in Marshall County was evaluated in 1994, as described by Uddin [14]. The side-by-side field testing program involved the use of the MDOT falling weight deflectometer (FWD), van mounted Pulse Radar GPR equipment, van mounted EnTech thermal infrared imaging system, and manual distress survey and mapping of selected slabs. The 1-GHz air-coupled antennas were mounted in front of the van about 18 inches above the pavement surface at outside and inside wheelpaths for this study. The continuous radar data was collected covering approximate 12-inch wide paths along the inside and outside wheelpaths for the entire length of the pavement. The data was collected at crawl speed of about 2 mile (3 km) per hour due to short length of the test sections and for safety of the equipment and project staff. The GPR van was followed by the thermographic imaging van with an arrow board truck traveling at the back of all test vehicles. Figure 1 (a) shows the GPR vehicle and thermal infrared imaging van. The GPR data was collected at a rate of 50 data points per second. The GPR scanning methodology used in this study was consistent with ASTM D4748-87, Standard Test Method for Determining the Thickness of Bound Layers Using Short Pulse Radar [15].

The GPR pulse travels in air at the speed of light and at slower speed through the pavement. The firing of the pulse to its return to the antenna is very accurately timed. This travel time is a function of the thickness of each layer and a material electrical property known as "dielectric constant". The amount of energy reflected at the discontinuity is a function of the wave impedance of the two materials. At the interface between materials with similar dielectric properties, such as two lifts of an asphalt concrete pavement, most of the energy passes through the interface and very little is reflected back. Conversely, where the difference in dielectrics is significant, such as an asphalt layer over concrete or a structural layer over base course, much of the energy is reflected back and very little is passed to the next medium. This analysis provides a very useful technique in determining concrete or asphalt pavement layer thickness. The Pulse Radar van also used a color video monitor display, which presented the information contained in the return signal in an appropriate format for interpretation by the operator. This display was a two-dimensional screen image. Since the data to be displayed was three-dimensional (two spatial dimensions and signal amplitude), color enhancement was used to provide added dimension. The continuous radar data images were later interpreted and tables of concrete layer thickness and observations on possible voids or moisture damage under the concrete surface layer were provided by the GPR service provider. Figure 1 (b) shows a sample of the thermal infrared image.

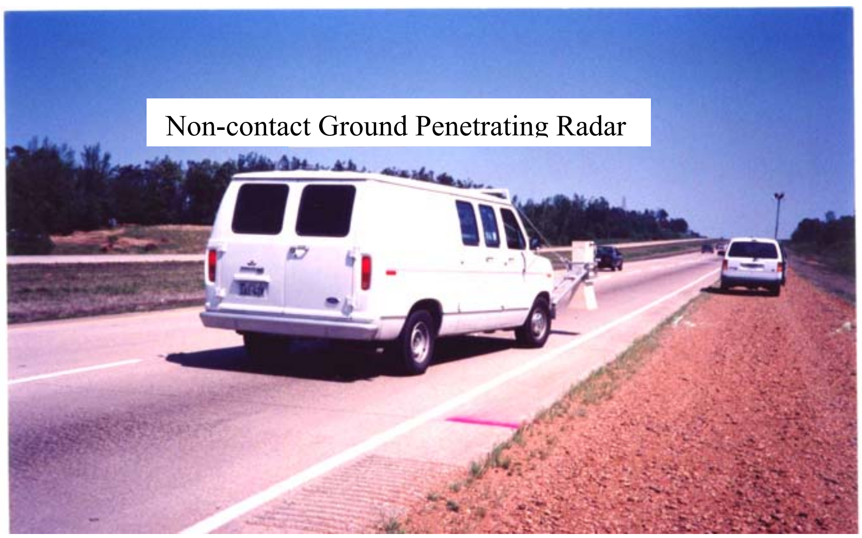


Figure 1(a). The GPR vehicle and thermal infrared imaging van on US Highway Test site in Marshall County, Mississippi [14]

The goals of the destructive evaluation were to identify slabs having voids, map these void areas, and measure concrete slab thickness in selected slabs. The related key findings were [14]:

1) The void area beneath the concrete layer in one section, identified by the infrared thermographic image and GPR, was later verified by the presence of grout layer between the concrete and cement treated base (CTB) layers of the core extracted from the slab. The GPR scan could not map the void areas that well because it sampled only 12-inch wide scan under each air-couple antenna travel path.
2) Cores were extracted after a review of GPR and thermographic imagery outputs to measure and verify concrete slab thickness and cement treated base layer thickness. The GPR was most successful to provide concrete pavement thickness along this 11-mile section in each direction, as verified by the independent coring at 12 test slab locations.

The average value of GPR derived concrete thickness for these 12 slabs was 10 inches that agreed with the average concrete core thickness of 10 inches.

3) The GPR output was unable to provide reliable interpretation of the underlying CTB layer thickness. Cores were used to measure the CTB layer thickness.

4) The detailed layer thickness data improved the modulus values backcalculated from the FWD deflection data.

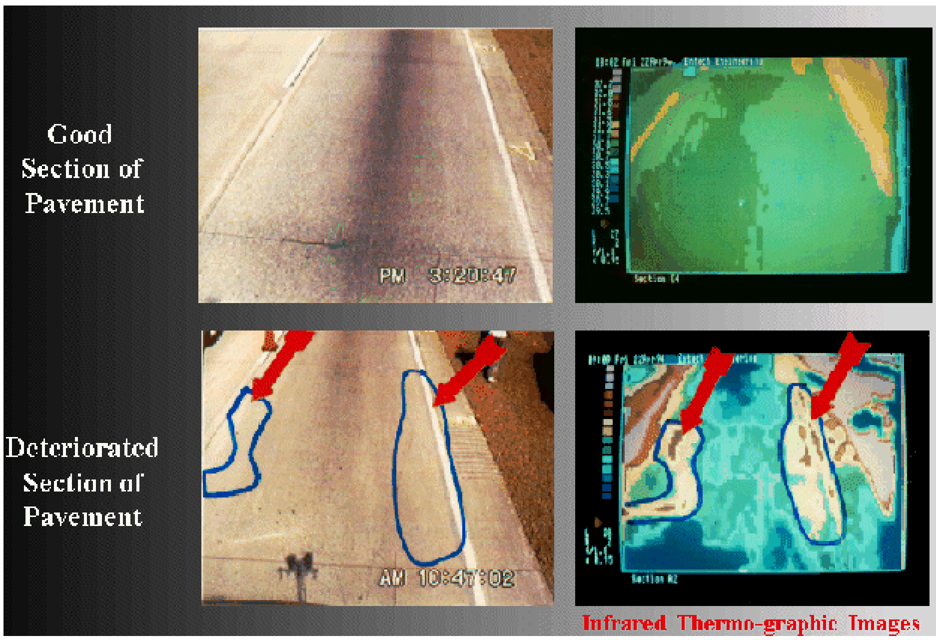
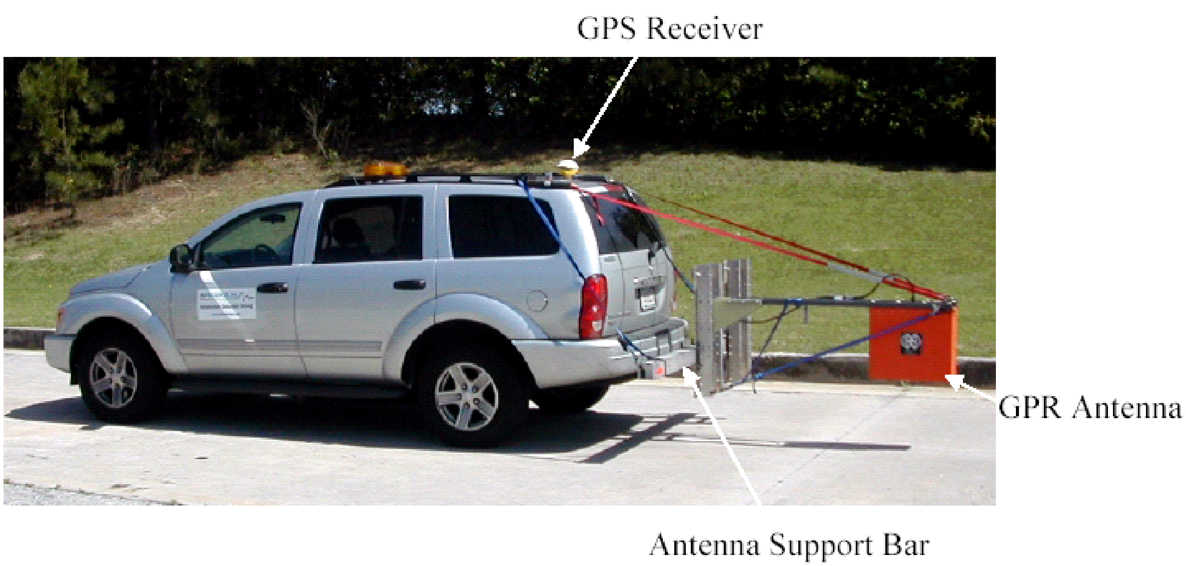


Figure 1 (b). Thermal infrared imageries for a good slab and a poor test slab [14]



(GSSI 1-GHz antenna Model 4108; SIR-20 GPR data acquisition was also used to collect Trimble Ag114 GPS station data.)

Figure 2. GPR survey van used by Infrasense, Inc. at the Georgia GOT study [24]

Other Examples of GPR Applications for Pavement Evaluation

The use of GPR evolved from detection of voids and anomalies under pavements to delamination in bridge decks and estimation of pavement layer thickness in the late 1980's through the 1990's [16-20]. Significant enhancements in GPR scan data interpretation have been achieved since then for asphalt mix density evaluation, moisture damage detection in asphalt and base layers, identification of voids and utilities under pavements, and determination of more accurate thicknesses of surface asphalt and underlying base and subbase layers [21-23]. Generally, a high frequency (1 GHz or more) antenna is used for non-contact GPR surveys at highway speeds. The Mississippi study [8] and most of the published papers on the application of GPR to evaluate subsurface voids were based on utilizing high frequency (1 GHz) air-coupled antenna that were operated at highway speeds. Due to the limitation of penetration depth of high frequency antennae, voids could only be detected when they were close to the pavement surface, such as beneath the concrete layer. In a recent study, a low frequency (400 MHz) ground-coupled antenna was utilized to locate the location and size of the subsurface voids below the pavements in downtown Louisville, Kentucky [23]. The 2002 federal restrictions on GPR equipment using radio frequencies in the range of 0.9- 3 GHz that interfere with cell phones and global positioning satellite (GPS) receivers made a significant impact on the routine use of 1-GHz antennas developed for GPR pavement evaluation. The significance of this law and its consequences on the effectiveness of GPR technology for pavement evaluation are discussed in detail in Chapter 3.

The results of the Georgia DOT pavement evaluation study, conducted on several miles of I-20 and I-75 interstate highways, have been published in 2005 by Hammons et al. [24]. The study involved applications of GPR, FWD, infrared thermography, and a seismic method for detecting and mapping asphalt stripping. An independent evaluation was done by coring. The GSSI model SIR-20 system with the "grandfathered" 1-GHz horn antenna model 4108 was used for the GPR survey at a rate of 2 scans per foot. The GPR data acquisition system recorded distance measuring instrument (DMI) output and differential GPS stationing for location referencing data. Figure 2 shows the GPR van used on the project. The GPR data was found effective to measure layer thickness and the areas of moisture damage [24].

In most routine applications the estimation of layer thicknesses from non-contact GPR surveys has been particularly useful in conjunction with FWD surveys. More reliable layer thickness data improve FWD data analysis to backcalculate accurate in situ modulus values of pavement layers.

1.3 Study Objectives

The primary objectives of this research are:

(1) Conduct an extensive literature review and interviews with manufacturers and users on the use of GPR and its limitations for asphalt pavement layer thickness evaluation.

(2) Establish candidate GPR testing and interpretation methods that can provide reliable layer thickness data at highway speeds for use with the FWD deflection data and the ELMOD version 5 backcalculation program.

(3) Plan a Phase II field study based on favorable results of Phase I.

1.4 Research Significance

If a side-by-side GPR survey can improve the reliability of pavement layer thickness and subsequently the analysis of FWD deflection data, improved overlay design and rehabilitation strategies can be produced that will result in substantial cost savings. The MDOT specifically requires many asphalt highway projects to be evaluated annually for structural integrity and rehabilitation. The effective use of GPR with FWD data analysis can assist in achieving the objective of enhanced pavement assessment. More accurate in situ layer thicknesses from GPR data may decrease the asphalt overlay thickness or extend the pavement life. This will lower the life-cycle cost of rehabilitation and result in substantial savings every year.

2. GPR TECHNOLOGY FOR ASPHALT PAVEMENT EVALUATION

2.1 GPR Principle, Data Analysis, and Operation

It is useful and important to understand the basic theory involved in GPR data collection and analysis to enhance the decision-making process for acquiring GPR services or procuring and implementing a dedicated GPR system. Therefore, a synthesis of reviewed literature and related on-line information is presented in this chapter. The following sections on GPR theory, data interpretation, and equipment components are based on the synthesis of published papers and reports [25-35].

GPR Theory and Issues in Data Interpretation

The success of GPR is based on EM waves operating in the frequency range where displacement currents dominate and losses associated with conduction currents are minimal [27]. Short EM impulses from GPR propagate in the medium having pulse duration of ≤1 ns (1 x 10^9 sec). The GPR technology is based on Maxwell’s equations, which describe the propagation of EM waves with a medium. For this report detailed mathematical derivation of the EM wave equation from Maxwell’s equations is not necessary. However, for nonmagnetic medium only one parameter, dielectric permittivity defines this interaction. All pavement materials (asphalt, non-reinforced concrete, base, subbase) and subgrade soils and rocks are essentially nonmagnetic mediums.

Both the propagation velocity of the pulses and the intensity of the reflections are a function of the dielectric properties of the materials, which are defined by the complex permittivity ε^* of the material;

$$\varepsilon^* = \varepsilon' - i\,\varepsilon'' \qquad\qquad i = \sqrt{-1}$$

where ε' is the real part of complex permittivity (also called the dielectric constant); ε'' is the imaginary part of complex permittivity. For virtually lossless materials, such as materials with very low electric conductivity, which mostly applies to concrete/masonry and asphalt materials in a dry condition, the imaginary part ε'' can be neglected.

In a vacuum or in air, EM waves travel at the velocity of light, c, at 3 x 10^8 m/sec [35] or 11.8 inch/ ns. The wave velocity is reduced when traveling in any other medium.

EM wave frequency (f) and the angular frequency (ω) are related by: $\omega = 2\,\Pi\,f$.
The wavelength, λ, inside a medium is related to f and EM wave velocity, v, by:

$\lambda = v/f = c/[f\,(\varepsilon_r)^{0.5}]$, where ε_r is the relative dielectric constant.

For example, in free space a 1-Ghz frequency wave has a wavelength of 0.3 m. Its wavelength is reduced to 0.1 m in concrete if the concrete has a dielectric constant of 9. However, as the dielectric constant increases, loss factor of the material also increases (the imaginary part of the complex permittivity), limiting the penetration depth of the wave into concrete. The tradeoff between the ability to detect and the penetration depth must be considered on the basis of EM properties [35]. Decreasing the frequency will increase the wavelength and penetration depth.

Assuming that we are dealing only with displacement currents and that the medium is lossless, the following data analysis simplifies, as explained by Reppert et al. [27]. The wave equation, in the propagation regime for electric displacement currents, is given in Eq. (1):

$$\nabla^2 E = \mu\varepsilon \frac{\partial^2 E}{\partial t^2}, \qquad (1)$$

where E is the electric field, μ is the magnetic permeability and ε is the permittivity. In general, μ and ε can be function of several parameters. If any of these two properties is a function of the EM wave frequency (f), the medium is known to be dispersive.

The permittivity can be defined as $\varepsilon = \varepsilon_0\,\varepsilon_r$, where ε_0 is the permittivity of free space (a lossless medium) and ε_r is the relative dielectric constant. Using phasor notation, Eq. (1) can be represented as shown in Eq. (2), where ω is the angular frequency ($\omega = 2\,\Pi\,f$):

$$\nabla^2 E = -\omega^2 \mu\varepsilon E \qquad (2)$$

The velocity for an EM wave in a dielectric is given by:

$$\upsilon = \frac{1}{\sqrt{\frac{\mu\varepsilon}{2}}\left(\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}}+1\right)^{\frac{1}{2}}}, \qquad (3)$$

where σ represents electrical conductivity. At high frequencies and/or very low conductivity, Eq. (3) reduces to:

$$\upsilon = \frac{1}{\sqrt{\mu\varepsilon}}. \tag{4}$$

The following findings of Reppert et al. [27] are important for pavement applications:

- For lower radar frequencies the dielectric properties and electrical conductivity play a dominant role in determining the velocity of a medium.
- For insulating materials such as dry rocks or concrete or asphalt layer, dielectric properties alone determine the velocity of the EM wave.
- For frequencies greater than 100MHz, Eq. (4) is a good approximation of the wave velocity.
- For frequencies below 100 MHz, the use of Eq. (4) will depend on the conductivity of the medium.
- For frequencies above 100 MHz, velocity is essentially independent of frequency and dependent only on the dielectric constant and the magnetic permeability.

Most pavement construction materials in dry condition (rock, aggregate, concrete, asphalt) are electrical insulators with zero or very low electrical conductivity [20, 27]. Therefore, Eq. (4) applies and dielectric constant alone determines the velocity of the EM wave in each of these materials. Pavement and earth materials rarely have a magnetic permeability appreciably different from unity. Therefore, changes in velocity must be due to changes in dielectric constant or changes in resistivity of the medium. Therefore, for these materials, at high frequencies or high resistivity, the velocity of an EM wave is determined only by the relative dielectric constant of the medium [27]. If the dielectric constant of a material under study is known, the depth of the reflectors and their positions can be determined from the propagation time, as shown in Figure 3. The reflection at material with higher dielectric constant results in phase shift of reflected signal of 180^o [28]. Table 1 shows typical values of relative dielectric constants for a variety of pavement and earth materials, which can be used for interpretation of GPR data.

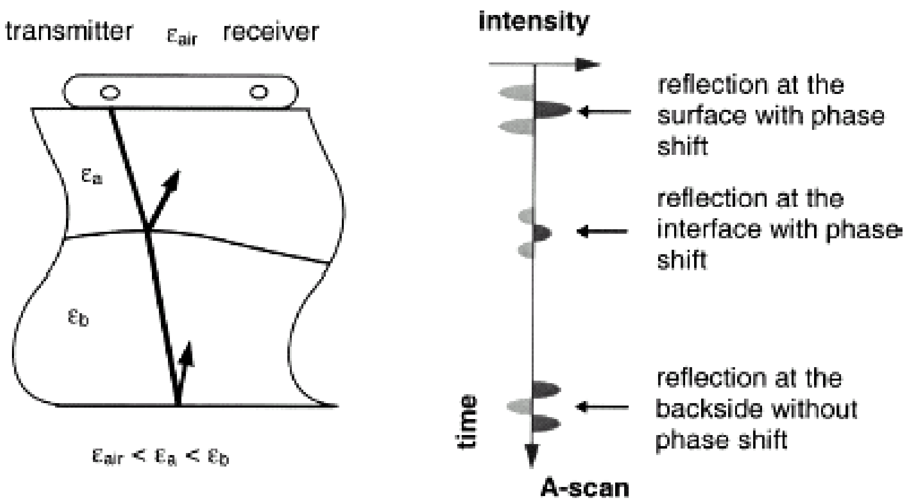


Figure 3. Principle of GPR reflection at surface, interface and backside of test structure [28]

Table 1. EM Properties of typical mediums encountered during GPR testing of pavement and earth materials [12, 25, 28, 32]

Medium/Material	Dielectric constant	Medium/Material	Dielectric constant
Asphalt, Wet	6 – 12	Dry and non-frost susceptible soils	4 – 9
Asphalt	3 – 5	Moist and slightly frost susceptible soil	9 – 16
Dry concrete	5 – 8	Highly frost susceptible and water susceptible soil	16 – 18
Moist concrete	8 – 16	Plastic and unstable soil	28 –
Dry masonry	3 – 5	Dry sand	3 – 5
Moist masonry	5 – 26	Saturated sand	20 – 30
Granite	5 – 7	Silts	5 – 30
Basalt	8	Shale	5 – 15
PVC	3	Clays	5 – 40
Ice	4 – 8	Rocky soil	7
Water	81	Limestone (dry)	7
Air	1	Limestone (saturated)	4 – 8

The velocity of the EM wave decreases with an increase in the dielectric constant. Eq. (5) can be used to calculate a layer thickness, d, if the velocity through the medium, v, and t, time between reflections are known.

$$d = v\,(t/2) \tag{5}$$

GPR is primarily used for anomaly detection and electromagnetic velocity determination of the shallow subsurface. Velocity analysis for common midpoint (CMP) surveys, using ground-coupled antennas, gives the velocity structure above a reflector at a single location [27]. Knowing the electromagnetic velocity structure of the shallow subsurface is important in identifying electrical properties of different reflectors. The electrical properties are related to the material composition of the reflectors.

Considerations for Good GPR Antenna Design and Performance

A GPR survey is most frequently conducted by recording EM wave reflection profiles. Therefore the antenna design and performance is the most critical part of all GPR systems. The antenna must have broad bandwidth for short pulse radiations and low clutter. For deeper applications a GPR is operated in KHz and MHz range. The antenna is placed on the ground surface to achieve greater penetration, better energy coupling, and less surface scattering. For example 200 to 500 MHz antennas are used for voids, cavities and buried utilities under pavements. Several GSSI models [34] are being used by the pavement community; for example the 400 MHz ground-coupled model antenna used in the Kentucky study [23]. These low frequency systems offer good penetration and in favorable soil conditions they can identify objects such as culverts or voids to a depth of 15 to 20 ft. However, with all GPR systems there is always a trade-off between depth of penetration and near surface resolution. These systems are not useful for finding key items for highway engineers such as the thickness of the upper layer.

For shallow applications, such as pavement evaluation and detection of buried landmines, 1-2 GHz frequency range provides reasonable results considering resolution and penetration depth. Lower operating frequency of 1 GHz will penetrate deeper than a higher frequency of 2 GHz. For production use in pavement applications it is desirable to have air-coupled antennas mounted on a holding bracket attached with the front or rear bumper of the survey vehicle so that data can be collected at highway speeds. The elevated antenna off the ground also reduces antenna-ground and antenna-target interactions, which result in lesser antenna clutter. However, this also creates the following two concerns regarding to scan resolution and depth of penetration; (1) reduction in radar efficiency as a large percentage of the incident energy will be reflected at the surface and not penetrate the pavement and (2) undesirable antenna movement caused by the surface roughness. Such problems get worse as the antenna height increases. A solution to this problem is to keep minimum height above the surface and develop software analysis tools which monitor and account for the height of the antenna above the pavement.

Other considerations in antenna design and operations are; the use of radiation on an oblique angle or as a focused beam on a normal incident angle, signal processing routines, selection of appropriate low-pass and high-pass frequency filters, samples per scan rate, and scan rate per second and per foot of target surface. Further examination of these issues is beyond the scope of this study. Furthermore, all commercial GPR antennas and data acquisition systems are proprietary and patented where these detailed system specifications may not be available to the user or purchaser. Therefore, it is vital that comprehensive performance-based specifications be developed considering most of the issues and past experiences with the grandfathered GPR systems and newer federally certified systems, as discussed in Chapter 3.

Limitations in Traditional GPR Data Interpretation and Constraints

Due to the non-uniqueness of radar image analysis, errors may occur in interpreting the layer material composition or anomalies. Examples of multiple interpretations are: Is the hyperbola in the image caused by a buried pipe or by a boulder; and does the anomaly indicate the boundary of a saturated sand layer, water-table or clay layer? A situation may occur when a low-velocity layer is located above a high-velocity layer, where no reflections can be obtained below the high velocity layer. This is one of the issues in GPR data interpretation [27].

The traditional GPR data interpretation method for determining the composition of a reflector is based on:

- radar wave velocity analysis using travel times for the reflected waves
- time delay between reflections and intensity or amplitude of each reflected wave

However, there are some limitations associated with GPR data interpretation, such as the velocity of the medium or its dielectric property below the lowest reflector cannot be determined. Other difficulties and constraints in GPR data interpretation are due to signal dispersion, attenuation, scattering and clutter due to antenna-radiation surface patterns.

The resolution and penetration depth of radar signals are influenced by many other factors, such as signal frequency and material properties (including electrical conductivity, dielectric constant, and moisture). In general, the electrical conductivity determines how far the signal penetrates through a medium. The higher the electrical conductivity, the greater the attenuation of signal, and the less the penetrated depth is. The contrast of dielectric constants controls the proportion of energy transmitted and reflected at material interfaces.

Under favorable conditions the radar signal travel time is primarily affected by changes in the dielectric properties of the material which may be caused by variations in saturation, material constituency and texture, temperature and pore fluid composition (such as saline water) [25]. In general GPR performs best in unsaturated coarse- or moderately coarse-textured sediments and in some rocks such as granite. GPR performance is often poor in electrically conductive environments such as systems saturated with saline water or dominated by clays [25]. As the dielectric constant of water is 80 and air is 1, a material saturated with water has a higher dielectric constant compared to the same material in an unsaturated state [25, 31].

Environmental conditions, such as moisture content and temperature, can cause difficulties in locating subsurface voids. The moisture content includes both soil moisture content and moisture in the voids. The higher the moisture content, the more the result of GPR is influenced. When the voids are dry, partially-dry or filled with water, the GPR patterns show up differently. Ambient temperature is another factor to consider in the application of GPR to pavements. Jaselskis et al. [31] have demonstrated in their NCHRP IDEA study for asphalt materials that in the EM frequency range of 100 Hz to 12 GHz that (1) permittivity slightly increases with temperature, the higher the asphalt pavement density, the higher the permittivity, (3) moisture strongly increases permittivity, (4) the attenuation of the signal and penetration depth in the medium is affected by these changes in the asphalt dielectric properties.

Discussions on some critical issues related to GPR operations and data interpretations follow:

- Due to non-uniqueness of radar image interpretation and mostly manual analysis, errors may occur in interpreting the layer material composition or anomaly.

- A situation may occur when a low-velocity layer is located above a high-velocity layer, where no reflections can be obtained below the high velocity layer, for example the subgrade soil properties.
- Subjective judgment is often used which may need corroboration from physical evidence, such as (a) the hyperbola in the image is caused by a buried pipe or by a boulder and (b) the anomaly indicates the boundary of a saturated sand layer, water-table or clay layer?
- Presence of water in the medium can also decrease the wave velocity making it more difficult to get reasonable interpretation for pavement layers. Freezing and spring thaw conditions add to more complications in data interpretations.
- Needs for laboratory evaluation of dielectric properties of location-specific construction materials in relation to moisture effects and treated materials for use in GPR calibrations to enhance results. Examples are: the asphalt treated drainage layer, cement treated base, and lime treated subgrade used for highway construction in Mississippi.
- GPR performance is often poor in electrically conductive environments such as systems saturated with saline water or dominated by clays.
- Guidelines are needed on optimum height of air-coupled antennas and for survey speed on a pavement in good condition to very rough pavement. This is important for scan resolution and depth of penetration considering a reduction in radar sensitivity and undesirable clutter created by the surface roughness.

GPR Equipment Components and Operation

A typical GPR system consists of the following components.

- Antenna (Transmitter/Isolator/Receiver)
- Data acquisition /Signal processor computer and software
- Scanned image display
- Data interpretation software
- Data processing software integration with DMI, GPS, and video or digital image (typically required with air-coupled antenna/GPR systems for pavement applications)

The following discussion of the various components of a radar system is based on the past studies by Uddin [8, 14] and reviewed literature and equipment brochures.

The function of the transmitter is to generate a known waveform. The name “short pulse radar” is derived from the fact that the transmitted waveform of such a system is actually a very narrow pulse, which typically might last on the order of one-billionth of a second. Such a short pulse is necessary to improve the ability of the radar to distinguish smaller objects and features under the ground. During the transmit cycle, the isolator provides a direct path from the transmitter to the antenna. The antenna serves two functions. First, it provides a smooth electromagnetic transition from the transmitter to the ground. The second function of the antenna is to direct the radiated electromagnetic energy into the ground in a desirable pattern. The antenna is designed so that the great majority of the radiated energy is directed into the ground and very little is radiated in other directions.

The electromagnetic wave transmitted by the antenna travels in the radiated direction until it strikes a discontinuity in the electromagnetic properties of the media. A portion of the wave passes through the discontinuity and a portion is scattered or reflected in other directions away from the discontinuity. Such a discontinuity is almost always associated with a material change in the media. The first such discontinuity is associated with the air-ground interface. At this interface, a portion of the incident wave is scattered back away from the ground and a portion propagates into the ground. Next, the wave traveling within the ground strikes the next discontinuity (pavement-base interface or pavement void area). Again, a portion of the incident energy is reflected away from the discontinuity, with the remainder continuing in the downward direction. The portion of the wave reflected by the discontinuity (void under pavement) forms the basis for target detection and assessment.

The GPR antenna can be mono-static (the same antenna transmits and receives) or bi-static that contains two antennas, one transmitting and one receiving antenna. Most commercial antennas used for non-invasive GPR applications on highway pavement are bi-static. The receiving antenna collects the electromagnetic energy in the return reflection, or echo, and delivers it to system receiver and sampler. The receiver captures weak target signals and amplifies them for subsequent processing. The receiver typically gates, filters, mixes, and samples the incoming signals to shift the incoming waveform to a desired frequency band and to reduce the signal contamination produced by electrical noise and reflections (called “clutter”) from objects that are not of interest to the radar operator. Of the two primary signal contaminants, noise and clutter,

clutter is the more severe in typical ground-penetration applications and is the principal limitation of the radar system's ability to detect faint target echoes caused by moisture or temperature effects.

Following signal reception, the output of the receiver is then passed to the signal processor which extracts the desired information from the received signal. The final radar system component in the field is the display, which presents the information contained in the radar return signal in an appropriate format for interpretation by the operator. Detailed radar scanned data interpretation is performed in the office using a stand-alone data interpretation software for structural assessment of pavements and to determine layer thickness and other desired properties.

In the 1980's and early 1990's the Donohue & Associates, Inc., Gulf Applied Radar, Inc, and Pulse Radar, Inc. [5, 6, 8] developed dedicated vehicles with radar systems for detection of voids under pavements and measuring pavement thickness at highway speeds. These GPR dedicated vehicles operated air-coupled antennas at 1-GHz. Geophysical Survey Systems, Inc. (GSSI) marketed two models of the radar antennas for pavement applications [34]; model 1048 air-launched horn antenna operated at 1-GHz frequency and Model 1045 ground-coupled antenna operated at 400/500 MHz range. These GPR systems were used in most state DOT studies starting in the mid-1980's through 1990's until July-October 2002 when the federal restrictions on the use of these devices took effect. More discussions on these developments and their consequences on GPR technology implementation for pavement evaluation are included in the following sections and Chapter 3.

<u>GPR Data Analysis Software</u>

In addition to the field data acquisition software, special software packages have been developed for further analysis of GPR data to generate the desired outputs. Radar image interpretation and data analysis methodology is a key part of GPR application for calculating layer thickness and/or dielectric properties. In the 1990's concentrated efforts were made to enhance the GPR data interpretation by several independent pavement investigators and researchers, such as Scullion, Saarenketo, Maser, Lytton, and Olhoeft [12, 18, 20, 21, 26, 51]. For illustration, the algorithm described by Maser in 2001 paper [16] for GPR scan data analysis and results are presented.

Data Analysis The pavement layer thickness analysis is carried out by computing the arrival times and amplitudes of the reflections from the different layers [16]. The reflected waveform contains a record of the properties and thickness of the layers within the pavement. Layer thickness is calculated from the arrival time of the reflection from the top and bottom of each layer as follows:

$$\text{Thickness (in.)} = (5.9\ t)/\sqrt{\varepsilon} \qquad (6)$$

where time (t) is measured in nanoseconds and ε is the relative dielectric permittivity of the pavement layer. Computation of the surface layer dielectric permittivity can be made by measuring the ratio of the radar reflection from the pavement surface to the radar amplitude incident on the pavement. The incident amplitude on the pavement is determined by measuring the reflection from a metal plate on the pavement surface, since the metal plate reflects 100% of the incident energy. For example, using this data, one obtains the asphalt dielectric constant, ε_a, as follows:

$$\varepsilon_a = [(A_{pl} + A)/(A_{pl} - A)]^2 \qquad (7)$$

where A = amplitude of reflection from asphalt, and A_{pl} = amplitude of reflection from metal plate (= negative of incident amplitude). A similar analysis can be used to compute the dielectric constant, ε_b, of the base material. The resulting relationship is:

$$\varepsilon_b = \varepsilon_a\ [(F - R2)/(F + R2)]^2 \qquad (8)$$

where $F = (4\sqrt{\varepsilon_a})/(1 - \varepsilon_a)$ and R2 = the ratio of reflected amplitude from the top of the base layer to the reflected amplitude from the top of the asphalt. The above equations serve as the basis for analysis of the data collected during this project [16].

Test Sites and GPR Equipment Table 2 shows the GPR equipment used at each of the two highway test sites. Figures 4 (a) and (b) show the GPR equipment used. The typical pavement construction for each of these sites consisted of 3 to 5 inches of asphalt over 8 to 10 inches of concrete and 3 lanes in each direction [16]. Cores were used for groundtruthing and field calibration.

Table 2. Test sites and GPR equipment used [16]

Highway	Location	State	Length	GPR Equipment
I-495	Long Island Expressway in Nassau County	New York	9 miles	Pulse Radar, Inc.; 1-GHz horn antenna 18 inch above pavement surface
I-90	Illinois Tollway in Chicago, MP 0 to MP 15	Illinois	15 miles	GSSI; 1-GHz horn antenna 18 inch above pavement surface

Each GPR system was set up to generate approximately 1 scan per foot travel. These scans were continuously digitized and stored on the on-board computer. Markers placed in the data during the survey at mile markers and at other reference locations are used for ground control of the radar distance measurements. GPR data was collected at normal driving speed, which ranged from 45 to 55 mph. The GPR survey van was followed by a shadow vehicle, which typically was equipped with a truck mounted attenuator. The shadow vehicle assisted the survey vehicle in maintaining lane alignment during the survey. No lane closures or traffic disruptions were required to conduct this work. In order to provide condition data, multiple parallel survey lines were collected in each lane—one in each wheel path and one along the centerline.

Figure 5 shows samples of the raw GPR data taken from each project. The I-495 data also reveals the joints and the bottom of the concrete. The I-90 data samples, however, do not reveal these features. Absence of the reflection from the bottom of the concrete is likely due to the similarity of dielectric constants between the concrete and the sub-base layers. This is frequently observed in concrete pavement on granular base. The absence of joint indications suggest that the dowel bar length may be too short or too widely spaced to be picked up by the GPR at the sampling rates used in this project. The analysis procedures discussed above have been applied to the raw data in order to calculate the layer thickness and concrete condition.

On I-495 site asphalt thickness at four stations was measured using cores along a calibration run behind a lane closure. Since there was no traffic, the GPR data was collected at a lower speed and the GPR data could be precisely identified at the core locations. Asphalt thickness was calculated from the GPR data for the calibration survey, and the calculated asphalt thickness was compared to the core data. The results of this comparison are reasonably accurate, as shown in Figure 5 (c). The GPR thickness calculations were all within 5% of the core thickness. Based on this result, it was concluded that no calibrations would be necessary, and that the analytic procedure would meet the accuracy specifications of the project. Thickness data from 89 cores were collected from I-90 site and correlated with the GPR data. The average difference between GPR and core data was –0.1 inches, and the average absolute error was 0.4 inches.

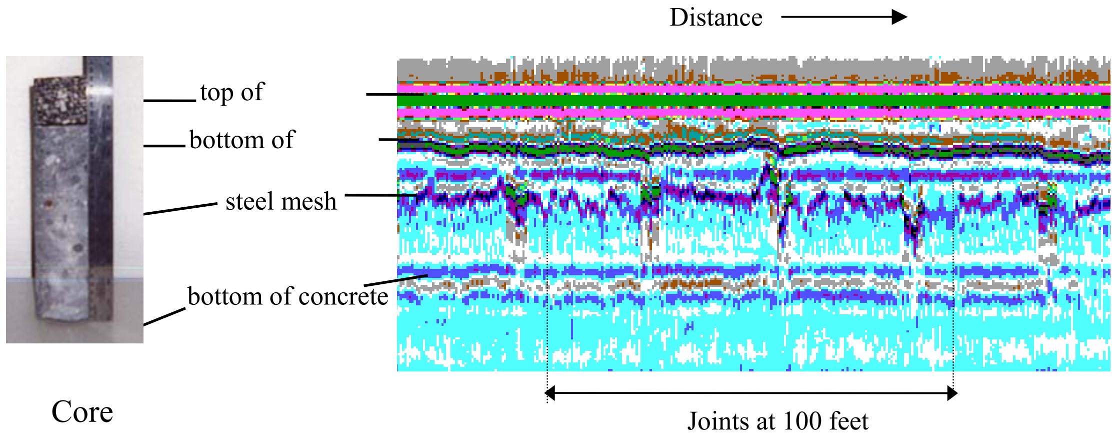
(a) GPR equipment used at I-495 site

(b) GPR equipment used at I-90 site

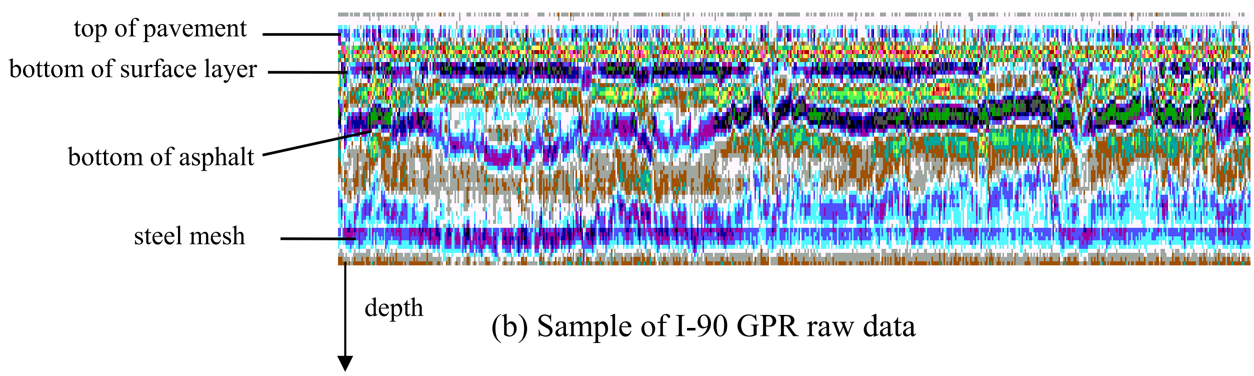
Figure 4. Equipment used for GPR data collection [16]

GPR was shown to be an effective and accurate means for characterizing asphalt overlay thickness on composite pavement structures. This thickness data is useful in determining bridge clearances, material removal quantities for rehabilitation purposes. The GPR capability is particularly valuable on high-density roads where lane closures for this purpose are prohibitive. GPR data can also be used to assess the condition of the concrete under the overlay for estimating repair requirements during rehabilitation [16].

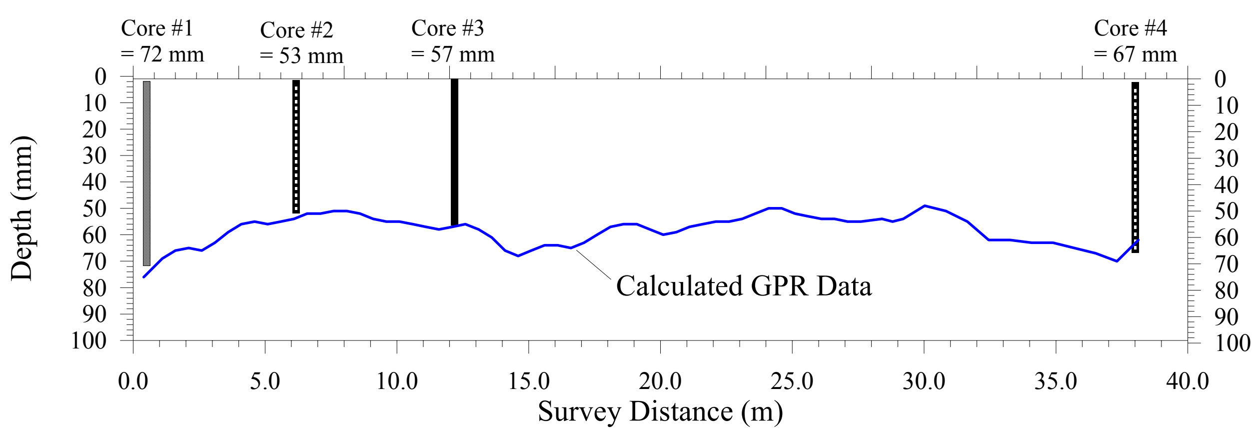
(Note: The above case studies were presented in Maser's paper at the 2001 International Pavement Symposium which was jointly organized in Auburn by the University of Mississippi, Auburn University, and Mackenzie University.)



(a) Sample of I-495 GPR raw data



(b) Sample of I-90 GPR raw data



(c) Plotted results of core calibration test (I-495)

Figure 5. Samples of GPR data and thickness results [16]

2.2 TxDOT Studies for GPR Implementation

Historical Overview

The Texas Department of Transportation (TxDOT) has a long history in using and implementing non-contact and non-invasive GPR equipment for nondestructive evaluation of the structure of pavements. This has been well documented by Bertrand [36] and Scullion [37]. A summary of the following key milestones and achievements is based on their referenced reports.

- In the mid 1980's the Lufkin District of TxDOT performed an extensive experiment to evaluate the effectiveness of the GPR for the detection of stripping in the asphalt concrete pavement layers. A GPR service provider conducted the GPR survey on a selected roadway and gave TxDOT a map of suspected areas where stripping in the asphalt layers was detected. The TxDOT staff collected many core samples and compared with the GPR results. The results of this evaluation were negative. TxDOT decided not to pursue the use of GPR as a non-destructive test for stripping in asphalt layers.
- In the late 1980's The Center for Transportation Research (CTR) at the University of Texas at Austin and TxDOT requested that the FHWA bring their GPR system to Austin and attempt to locate the voids beneath the jointed concrete slab. The research test slab was constructed with two known voids between the concrete and the base material. This slab was previously used, under a research project with TxDOT, for evaluating the use of the falling weight deflectometer as a joint load transfer measurement tool. The FHWA personnel and their GPR system were not able to locate either of the voids. TxDOT decided against actively pursuing the use of GPR for the evaluation of voids beneath concrete pavements. (Note: The same test slab, constructed during 1983-84, is shown in Figure 6. The test slab was also used in 1986 for the FHWA pavement equipment evaluation study, as described by Uddin et al. [8] and Benson et al. [10].)
- During the 1970's and 1980's several factors limited the successful use of GPR for pavement evaluations. There was no software available to help technicians interpret the captured GPR return signals. GPR analysis required a highly trained individual to manually look at the captured GPR signals and subjectively decide what the anomalies represented in terms of pavement distress. The data interpretation of these initial systems was done by individuals with little or no background in pavement evaluation. Early GPR data collection

systems simply provided a gray-scale strip chart of the returned signals that had to be subjectively interpreted.

(Note: This research facility is now known as the JJ Pickle Research Center.)

Figure 6. The CTR/TxDOT research test slab at Balcones Research Center in Austin, Texas

- In 1984 TTI purchased a non-contact GPR system from Pulse Radar Inc. of Houston. TTI installed their GPR system on its own data collection vehicle. TTI began the development of MS-DOS based GPR data collection and GPR data analysis software packages, using the test data and experience gained from operating the TxDOT and TTI GPR systems. Many data processing features were programmed and tested during this phase of the GPR development effort. A standard data file format was designed to access data from any GPR manufacturer's antenna system as long as an analogue signal is available to use with the analysis software. Additionally, integration of a distance signal was necessary so that GPR data could be related back to the distance traveled on a pavement's surface. Video capture systems were added to both the TxDOT and the TTI GPR data collection systems. Having images of the pavement's surface helped the analyst interpret the GPR signal anomalies.
- During the early 1990's through the mid 1990's, TxDOT actively evaluated the potential use of GPR for pavement applications. This effort was conducted both through in-house research and under multiple research projects with the Texas Transportation Institute (TTI) at the Texas A & M University. In 1990 TTI purchased a GPR antenna from Pulse Radar Inc

of Houston. The first generation of data collection and data processing software, developed by TTI, and GPR was successfully demonstrated to be able to measure the layer thickness of asphalt pavements. GPR's use to detect stripping in asphalt layers was also validated.

- Around 1994 TxDOT purchased two non-contact GPR systems from its first GPR system from Penetradar of Buffalo, New York. The two initial TxDOT GPR antenna systems were never fully implemented outside of the research arena. Performance specifications were developed around TTI' Pulse Radar unit.
- The TTI/Texas DOT's GPR systems use 1-GHz air-coupled non-contact antennas. This frequency is optimum for most pavement applications, providing a balance between the depth of penetration and the resolution needed to detect thin near surface layers (minimum 1 inch). The radar antenna is attached to a fiber glass boom and suspended about 5 feet from the vehicle and 14 inches above the pavement. This particular GPR unit can operate at highway speeds (e.g., 70 mph posted speed); it transmits and receives 50 pulses per second, and can effectively penetrate to a depth of around 24 inches. A brief description of the analysis methodology developed by TTI is presented in the next section.
- TTI and TxDOT developed a special data collection feature for GPR antennas to ensure accuracy and repeatability of GPR traces during normal routine operation, as well as long-term signal stability. A single metal plate GPR trace was captured and stored on the computer's hard drive. The trace, the reference trace, is normally captured after annual verification of calibration has taken place. The trace is collected with the GPR antenna mounted to the housing vehicle under normal operating conditions. Prior to data collection the technician recalls this reference trace and views it on the data collection computer screen display. At the same time the data collection system displays the current GPR trace. The technician views and aligns the real trace to the reference trace. If the two traces cannot be aligned, then the GPR system is not functioning properly, and data should not be collected.
- TTI and TxDOT developed a performance based specification for the future purchase of GPR antenna systems. It was found that the manufacturer's performance claims were insufficient indicators of the actual GPR systems performance. This fact, coupled with the state's purchasing mandate of the lowest bidder, necessitated the development of these specifications. The performance specifications for the non-contact GPR systems included long and short-term stability tests as well as signal to noise ratio tests. The GPR antenna

system's velocity factor was calculated from the short term stability test. The performance specification is also used for monitoring a GPR system's characteristics over time.

- During the late 1990's TxDOT purchased three new GPR systems from Pulse Radar Inc of Houston using the TTI performance specifications. The cost for these new GPR systems was $60,000 each which included a 1 year warranty. Adding this to a vehicle with the associated data collection hardware put the cost of the entire system between $80,000 and $100,000. Two of these antenna systems are still in operation today. One of the three units was lost while being sent to the manufacturer for repair. In 2000, TxDOT purchased three GPR systems from Wavebounce Inc. TTI also purchased one Wavebounce GPR system in 2000. The TxDOT and TTI non-contact GPR data collection for high-speed applications can capture quality traces at 10 foot per trace at 70 mph. The system is able to collect traces at 5 feet per trace at 60 mph. If a trace per foot of travel is required the operational speed of the vehicle must be reduced below 30 mph.
- TxDOT awarded a multi-year implementation research project to TTI at a cost of over $800,000 once it was proven that multiple GPR units could produce very similar results, that the systems were reliable enough to be used on a daily basis, and the software for data collection and analysis was stable. TTI purchased two housing vehicles, three additional non-contact GPR systems from Wavebounce and all additional hardware necessary to implement a GPR system under this project. All of this equipment was transferred to TxDOT for statewide implementation. TTI developed training CD's for both the GPR data collection and analysis. The COLORMAP software for color scan image processing has been a significant product of this effort [38].
- The Association of American State Highway and Transportation Officials (AASHTO) established a Technical Advisory Group on GPR implementation and promotion to other state DOTs. The Technical Advisory Group used information from the TxDOT GPR experience to plan the nationwide GPR implementation effort. This effort produced the draft AASHTO specifications PP 40-00 on application of GPR to highways [39].
- After the 2002 federal restrictions on the output power of 700-MHz to 2-GHz unintentional radiators which included GPR antenna systems, TxDOT initiated a research project with the University of Houston to develop Federal Communication Commission compliant GPR systems for about $200,000. The University of Houston concept was to replace the single GPR antenna with a dual antenna system. One GPR antenna could operate below the 700-

MHz frequency and the other could operate above the 2-GHz frequency. This effort has shown several implementation hurdles. However, TxDOT is reportedly considering a research implementation project to complete the development effort and expand its GPR fleet.

- In early 2002 TxDOT awarded a $250,000 research project to TTI for creating a software package that could be used to integrate the FWD and GPR data for project analysis. TxDOT currently operates 15 FWD units. The newly developed PAVECHECK software can read individual FWD and GPR data files and process them [40].
- Use of the high-speed non-contact GPR technology on concrete pavements in Texas has not been very successful. Layers of steel within the continuously reinforced concrete pavements tend to reflect too much of the GPR signal. The cement stabilized base material is also too similar in dielectric property to that of the concrete, so that the layer interface cannot be detected. Layer thickness measurements are impossible without the interface reflection.

After the 2002 federal restrictions on 1-GHz GPR devices, the GPR systems owned by TxDOT, universities, and mining companies are exempt these restrictions. These older systems could be used for operation as "grandfather" devices if registered properly before October 2002 deadline, as discussed in detail in Chapter 3.

TTI Data Analysis Software for TxDOT and TTI GPR Systems [37, 38, 40]

The 1-GHz air-coupled GPR units, operated by TTI/TxDOT, were acquired before 2002 federal restrictions on the output power of ultrawide band radiators. A typical GPR unit is shown in the top part of Figure 7. The unit transmits and receives 50 electromagnetic pulses per second, and can effectively penetrate to a depth of around 24 inches. This system sends discrete pulses of radar energy into the pavement and captures the reflections from each layer interface within the structure. At each interface within a pavement structure a part of the incident energy is reflected and a part is transmitted. A typical plot of captured reflected energy versus time for one pulse is shown in the bottom part of Figure 7, as a graph of volts versus arrival time in nanoseconds. To understand GPR signals it is important to understand the significance of this plot. The reflection A_0 is known as the end reflection; it is internally generated system noise which will be present in all captured GPR waves. The more important peaks are those that occur after A_0. The reflection A_1 is the energy reflected from the surface of the pavement and A_2 and A_3 are reflections from the top of the base and subgrade respectively. These are all classified as positive reflections, which indicate an interface with a transition from a low to a high dielectric material. These amplitudes of reflection and the time delays between reflections are used to calculate both layer dielectrics and thickness. The dielectric constant of a material is most influenced by moisture content and density. An increase in moisture will cause an increase in layer dielectric; in contrast an increase in air void content will cause a decrease in layer dielectric.

In the mid 1990's TTI researchers conducted a series of laboratory dielectric measurements on a range of base materials from around Texas, as well as HMA mixes at a range of air void contents [20]. This data is used in the interpretation of GPR images. A range of typical dielectrics has been established for most paving materials, Hot Mix Asphalt (HMA) layers normally have a dielectric value between 4.5 and 6.5, depending on the coarse aggregate type. Measured values significantly higher than 6.5 would indicate the presence of excessive moisture. Lower values could indicate a density problem or that an unusual material, such as lightweight aggregate, has been used. The examples below illustrate how changes in the pavement's engineering properties would influence the typical GPR trace shown in Figure 7.

1) If the thickness of the surface layer increases, then the time interval Δt_1 between A_1 and A_2 would increase.
2) If the base layer becomes wetter, then the amplitude of reflection from the top of the base A_2 would increase.
3) If there is a significant defect within the surface layer, then an additional reflection will be observed between A_1 and A_2.
4) Large changes in the surface reflection A_1 would indicate changes in either the density or moisture content along the section.

Two software packages are used; RADAR2K is the program used to collect GPR traces and store them in a standard file format. The COLORMAP system is used to process and report the information. Figure 8 shows an example of color coded GPR scan image. Limited processing of GPR can be performed in the field but it is typically done in the office. In RADAR2K the GPR data is normally collected in a distance mode where the operator specifies the data collection interval, typically between 1-ft and 10-ft intervals depending on the application.

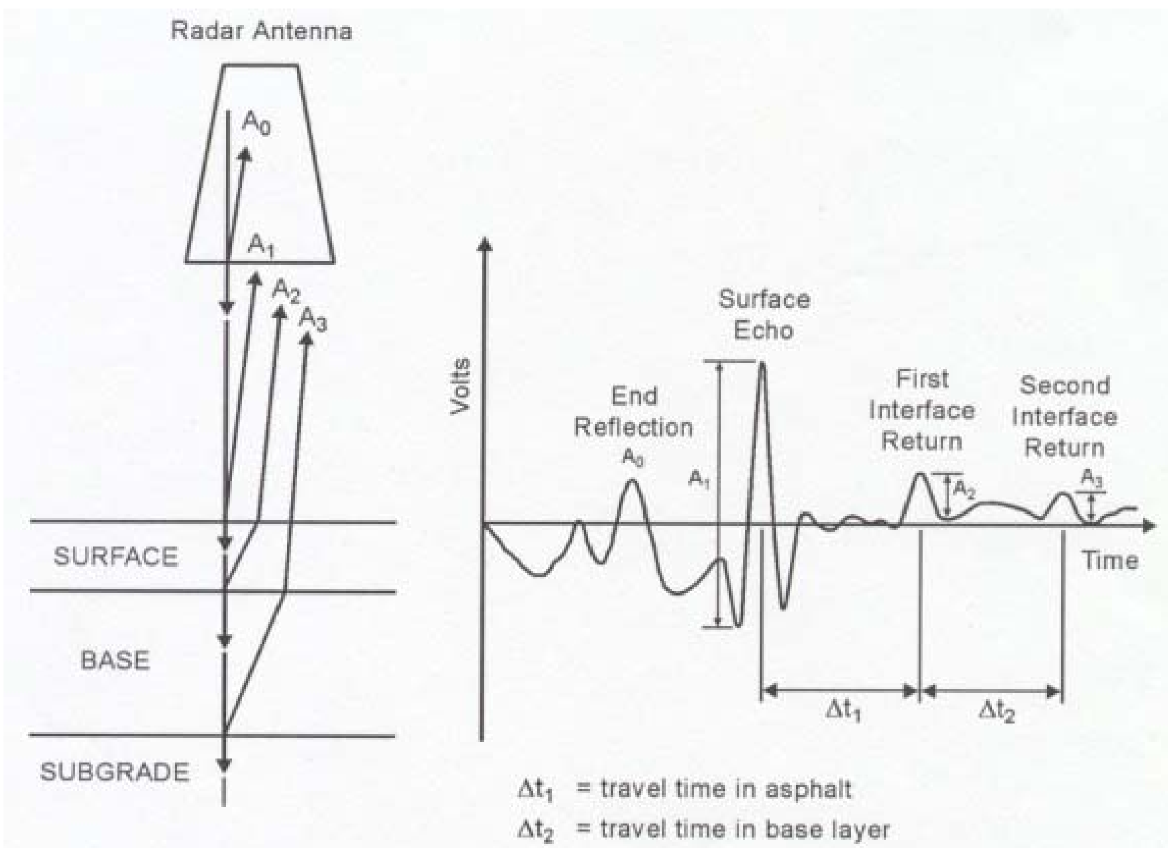


Figure 7. GPR Equipment and principles of operation [37]

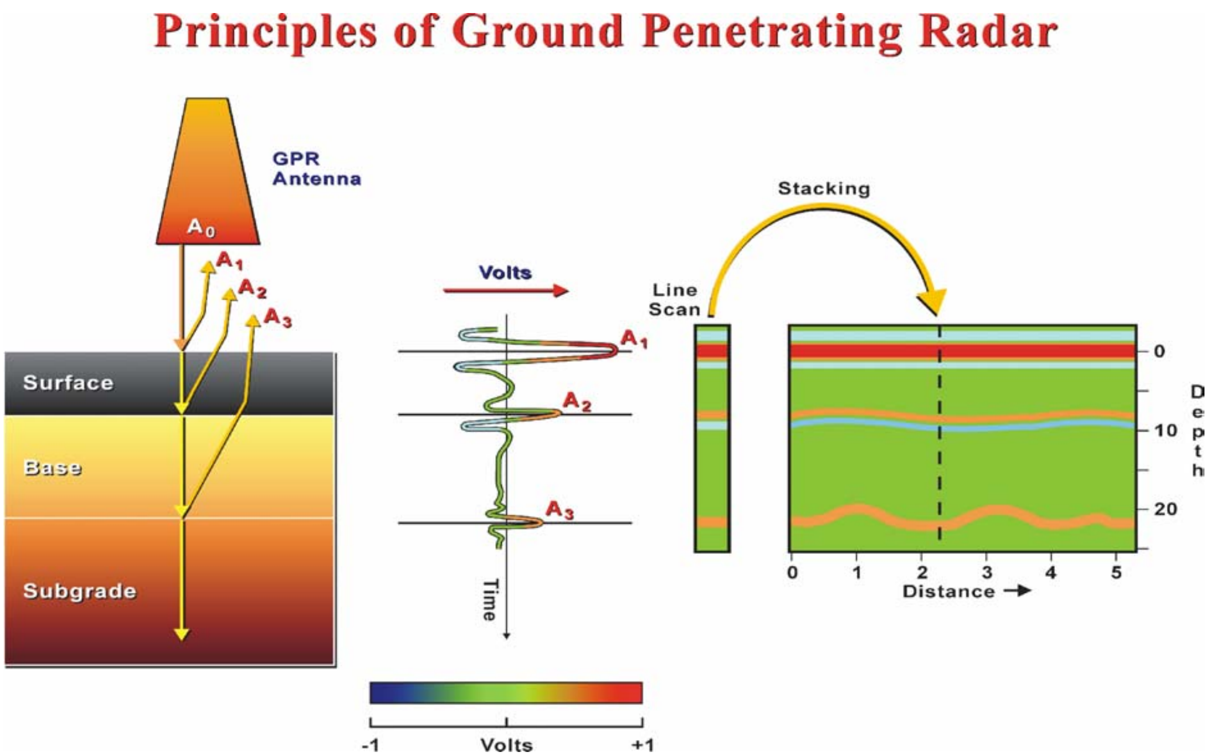


Figure 8. Color coded GPR scan image [37]

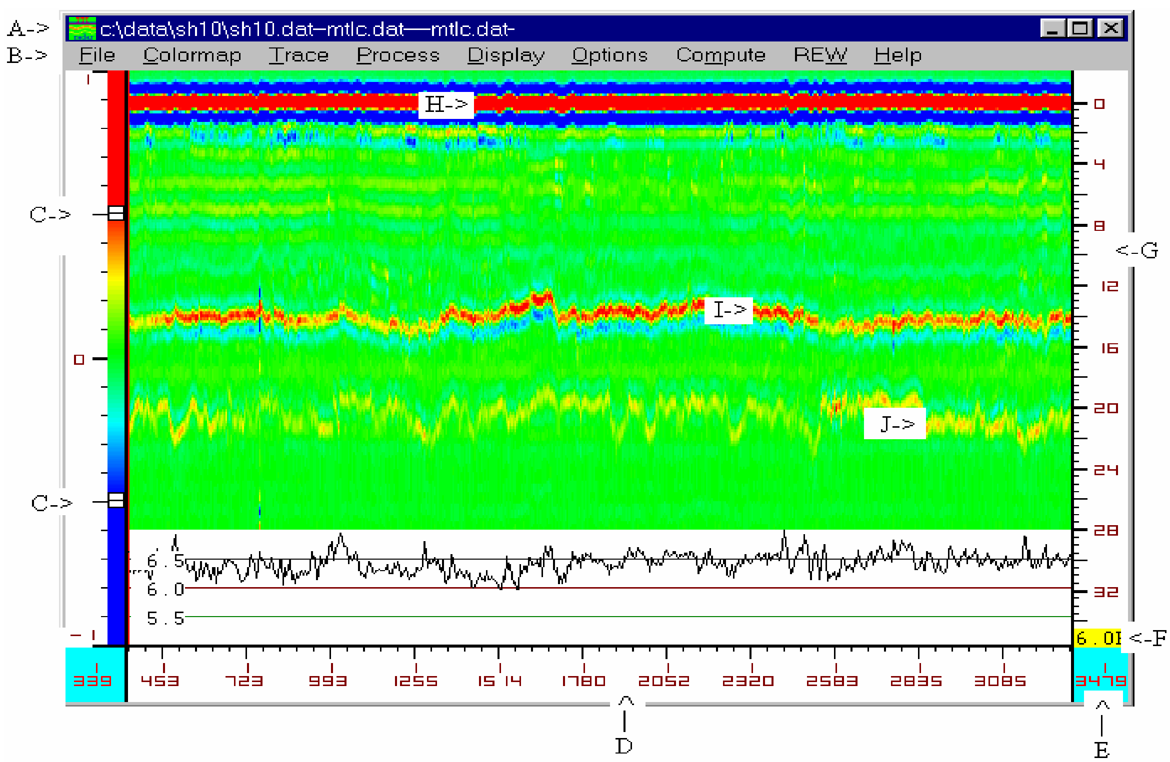


Figure 9. An example of GPR image generated by the COLORMAP processing software [37]

One very useful component of the GPR system is the use of synchronized video. This is collected using a camera which captures right-of-way images through the vehicle's windshield. A synchronized video image also shows the distance and trace number information. This same location information is stored with each GPR trace. A desktop computer is used to process the GPR data and a video system to display the video images. The GPR images show the operator the subsurface condition; these can be compared with the distresses observed on the surface. The video images are also very important for locating areas where validation cores should be taken. On most GPR surveys in Texas one or two validation cores are taken to verify subsurface condition, the video images helps to locate the exact location. Also as GPR data can be collected at highway speed it is possible to collect 200 to 300 miles of data in one day. Often processing of this data occurs 2 to 3 weeks after collection and often the person processing the data may be different from the person who collected it.

In 2005 TTI started the transition to digital images. These have the advantage that they can be integrated with the GPR images so that both right-of-way images and GPR scan traces can be displayed on the same monitor. Recent efforts have also integrated other items such as Falling Weight Deflectometer and road profile data. The latest developments in this area are described by Scullion [37].

<u>Layer Thickness Calculation</u> The information obtained from the GPR trace (Figures 7 and 8) can be used to calculate the thickness of the surface and base layers and the dielectrics of each layer. To do this it is necessary to measure the amplitude of reflection from each reflection (in volts) and the time delay between reflections (nanoseconds). The amplitude A_1 (reflection from pavement surface) as shown in Figure 7 is measured from max to min peak, this measurement is performed automatically within the processing software. For example this value is typically around 4 volts. One additional piece of information that is required is the amplitude of reflection from a large metal plate. In Figure 7 it is observed that the antenna is positioned directly over a large (4ft by 4 ft) metal plate. This is the 100% reflection case where all of the energy being transmitted by the antenna is reflected. The 100% reflection is defined to be A_m. For example, A_m is often around 10 volts. Comparing this 100 % reflection to the partial reflection A_1 from the pavement surface is the start of the computational process. In this case 40% of the incident energy (4 volts) is reflected at the surface. The remaining 60% is transmitted into the pavement.

The equations to calculate thicknesses and dielectrics are summarized below [37]:

$$\varepsilon_a = \left[\frac{1 + A_1 / A_m}{1 - A_1 / A_m}\right]^2 \tag{9}$$

Where ε_a = the dielectric of the surface layer

A_1 = the amplitude of surface reflection, in volts

A_m = the amplitude of reflection from a large metal plate in volts (this represents the 100% reflection case)

With A_1 = 4 volts and A_m =10 volts the surface dielectric values would be computed to be 5.4.

$$h_1 = \frac{c\ (\Delta t_1)}{\sqrt{\varepsilon_a}} \tag{10}$$

where h_1 = the thickness of the top layer

c = speed of EM wave in air (5.9 in./ns two way travel)

Δt_1 = the time delay between peaks A_1 and A_2, (in ns)

$$\sqrt{\varepsilon_b} = \sqrt{\varepsilon_a}\left[\frac{1 - \left[\frac{A_1}{A_m}\right]^2 + \left[\frac{A_2}{A_m}\right]}{1 - \left[\frac{A_1}{A_2}\right]^2 - \left[\frac{A_2}{A_m}\right]}\right] \tag{11}$$

where ε_b = the dielectric of base layer

A_2 = the amplitude of reflection (volts) from the top of the base layer

$$h_{base} = \frac{c\,(\Delta t_2)}{\sqrt{\varepsilon_b}} \tag{12}$$

where h_{base} = thickness of base layer

Δt_2 = time delay (ns) between A_2 and A_3

Using these equations it is possible to calculate both layer thickness and dielectrics for each GPR trace collected along the section under test. The use of the thickness information is obvious to DOT personnel for either quality control of new construction or structural evaluation of existing structures. The COLORMAP data analysis system permits the computation of the following:

1. Layer dielectrics (up to 3 layers)
2. Layer thicknesses (up to 3 layers)
3. Base moisture content (from correlation with base dielectric)

This system also has the capability of correcting for antenna bounce, and performing signal deconvolution so that the thickness of thin layers (< 1.5 inches) can be calculated. COLORMAP color-codes and stacks GPR traces so that the operator can look at a long length of highway on a single screen, this permits easy identification of layer interfaces and layer defects. This software has the capability of providing graphic or summary statistics of layer thicknesses. By determining the thicknesses of 3 different layers on the top of the subgrade the data is readily available for backcalculating modulus values. Figure 9 shows typical results for approximately 3,000 ft of a thick flexible pavement. This is taken from a section of newly constructed thick asphalt pavement over a thin granular base.

<u>FWD Data Analysis Using GPR-Derived Layer Thickness</u> The key aspect of structural evaluation is the calculation of layer moduli from FWD deflection bowls. To obtain an acceptable solution it is critical to input correct pavement layer thicknesses for the test section. These are most frequently obtained from the existing plan sheets and/or from localized coring. While the thickness obtained for the base may be reasonable it is known that the values used to the surface layer are often not correct. The major concern is that the thickness in the surface layer is not constant and it varies substantially along a project. It is important to realize that the computed layer moduli are highly dependent on all input thicknesses especially for the surface layer. The TTI studies found that a 10% error in estimating surfacing thickness would result in a 20 to 30% error in calculated base modulus. In many instances the error in estimating surface thickness is well over 10%.

In the early 1990's several studies were conducted to determine GPR's ability to measure pavement layer thicknesses. It was found that the accuracy was 5% in asphalt layer thickness from GPR data when no calibration core was used, which could be improved to around 3% by calibrating the GPR software analysis with the use of a calibration core. For base layer 10-20 % accuracy is reported. GPR has been found to have the capability of locating buried areas of stripping in asphalt layers, which is a major problem on Texas highways. Several old asphalt mixes constructed with river gravels have been found to be prone to stripping and most have been buried beneath one or more asphalt overlays. TTI recently developed the PAVECHECK software that can read individual FWD and GPR data files and process them for backcalculation of layer modulus values using MODULUS program [37].

2.3 Overview of GPR Applications on Asphalt Pavements

A synthesis of literature review on GPR applications for asphalt pavements is presented in this section. Most of the studies were conducted in the US; however, many other GPR related published papers were contributed from Germany, France, Finland, Sweden, Switzerland, UK, and Italy. Most of the cited papers date back from the mid-1990's [16-24; 41-66] and recent information is acquired from the Internet sources or personal contacts through e-mail and/or telephone [67-87].

According to the study objectives, focus has been on the review of studies and other sources related to:

- GPR equipment used in most studies or available to date commercially
- Enhancements in GPR data analysis and level of automation in radar image interpretation
- Determination of thickness of asphalt layer and sublayers
- Subsurface condition assessment of asphalt and sublayers

GPR Equipment Used in Most Studies

Most of the references cited in this section reported using GSSI's GPR systems with 1-GHz or 2-GHz horn antennas and SIR-20, SIR-10, SIR-8 and other GSSI data acquisition systems. Other GPR equipment used in these references include Pulse Radar and Penetradar from the US, RAMAC/GPR from Sweden, and IDS GPR from Italy. Table 3 lists the GPR equipment, country of origin, country of use, and all the related references from this information was extracted. The table does not include certain references that did not identify the specific GPR model used [24, 44, 53, 56, 58, 59, 60]. A summary table of most references and their summary findings are included in Appendix A. The referenced asphalt pavement studies in the US were conducted in the following states: California, Florida, Georgia, Idaho, Illinois, Kansas, Kentucky, Minnesota (Mn Test Road sections), New Jersey, New Mexico, New York, North Carolina, Texas, Virginia, Washington, and Wyoming. Most of these studies were conducted at highway speeds using 1-GHz horn antenna GPR equipment dating back to pre-2002 period.

Table 3. GPR equipment used and described in references reviewed for this report

GPR Manufacturer (country)	GPR Antenna EM Operating Frequency /Model	Country of Use	Related References (owners)
GSSI (USA)	2-GHz horn, Models 4105	USA	47, 48, 65, 70, 71, 72, 73, 74, 76 (Geovision, Fugro, FLDOT, JILS-FWD)
GSSI (USA)	1-GHz horn, Models 4108 or 4108F	USA , Finland, Mexico	26, 45, 50, 63, 64, 70, 74, 75, 76, 77, 79 (Infrasense, Fugro, Geovision, EPIC, RoadScanners)
GSSI (USA)	2.5-GHz horn; Models 4205 (Obsolete) 1.5-GHz ground-coupled	USA, France, Switzerland	41, 46, 48, 49, 61, 76, 78 (RoadScanners, Geovision, Wavetech)
GSSI (USA)	900 MHz ground-coupled	USA, Switzerland	41, 63, 76 (Geovision)
GSSI (USA)	400/500-MHz ground-coupled	USA, France, Finland	45, 50, 76, 78 (Geovision, Wavetech)
Pulse Radar (USA)	1-GHz horn	USA	17, 21, 36, 37, 42, 43, 52, 57, 83, 84 (TTI/TxDOT, Florida DOT)
Wavebounce (USA)	1-GHz horn	USA	78, 83, 84 (TxDOT, Wavetech)
Penetradar (USA)	1-GHz horn, Model PS 24	USA	55, 83, 84 (TTI/TxDOT, North Carolina DOT)
Mala Geoscience (Sweden)	RAMAC/GPR 1-GHz horn 1.2, 1.6, 2.3-GHz ground-coupled	Sweden USA	54 85 (Rutgers University using 1.2 GHz)
IDS (Italy)	600-MHz, 1.6-GHz ground-coupled (in trailer, following FWD)	Italy	80, 81, 82 (University of Pisa)
3D-Radar (Finland)	1-GHz	Finland	69, 70 (RoadScanners)

It is important to note that at the time of this report, the GSSI horn models 4108F (1-GHz) and 4105 (2-GHz) are the only federally approved GPR "air-launched" antennas for sale and use in the US. The only other usable GPR horn antenna models are the old devices (GSSI 1-GHz model 4108, Pulse Radar, Wavebounce, and Penetradar) from pre-federal regulation days, if they were properly registered with the Federal Communications Commission prior to October 2002. Mala Geoscience of Sweden [85] reports that their three ground-coupled GPR antennas (1.2 GHz, 1.6 GHz and 2.3 GHz) are also certified by the Federal Communications Commission. This issue of federal certification requirement has made significant impact on GPR applications for highways in the US; it is discussed in detail in Chapter 3.

GPR Data Analysis Enhancements

Since the availability of increased desktop computing power and object-oriented programming in the mid 1990's, refinements in GPR image display and more complex data interpretation methodologies have been pursued by GPR manufacturers, owners, and service providers. A detailed description of the GPR data analysis software evolution including COLORMAP by TTI/TxDOT [36, 37] is provided in section 2.2. An example of enhanced data analysis programs developed and used by Maser [16] are also included in section 2.1. These include PAVLAYER for pavement layer assessment and DECAR / winDECAR for bridge deck assessment. Papers published by Wells and Lytton [21] and Olhoeft and Smith [26] show their enhanced data analysis methods. Some patented GPR data analysis programs are: GSSI's RoadScan system that includes Road Structure Assessment Module [34, 67], Lytton's SIDARS software [21, 62], and RoadDoctor [69, 70]. Non-contact horn antennas are used for most pavement applications at highway speeds.

As shown in Table 3, many GPR service providers and owners use GSSI GPR systems for highway pavements. The JILS-FWD's integrated GPR equipment includes GPR data acquisition RADAN software and 2-GHz horn antenna from GSSI [67, 71]. The Florida DOT has recently purchased a GSSI GPR system of two 2-GHz horn antennas with a full suite of GSSI software for $100,000 [72]. Additionally, the Florida DOT also acquired three ground-coupled antennas (900, 400, and 100 MHz). Figure 10 shows a sample out put generated by the GSSI software. Many GPR owners and service providers using the GSSI's GPR equipment and patented RADAN field data processing software [67] also use the RoadDoctor GPR data analysis software [69]. Figure 11 shows a sample screen display. This software combines data from GSSI GPR and FWD and synchronize with video, core, and other pavement information.

GPR Determination of Pavement Layer Thickness

TTI Studies As previously stated, The TTI studies found that a 10% error in estimating surfacing thickness would result in a 20 to 30% error in base modulus backcalculated from FWD deflection data. In many instances the error in estimating surface thickness is well over 10%. Several studies were conducted to determine GPR's ability to measure pavement layer thicknesses. It was found that the accuracy was 5% in asphalt layer thickness from GPR data when no calibration core was used, which could be improved to around 3% by calibrating the GPR software analysis with the use of a calibration core. For base layer thickness 10-20 % accuracy is reported [37].

North Carolina DOT Study Corley-Lay and Morrison [55] used Penetradar GPR 1-GHz horn antenna at 50 scans/sec on 13 in-service pavement sites in North Carolina, which were included in the general pavement study of the Long-Term Pavement Performance (LTPP) program. They reported the following results in their 2001 paper:

- Large variability in the GPR-calculated thickness compared to the historic LTPP data
    - Asphalt layer thickness within 1 inch of the LTPP inventory data
    - Base thickness from GPR generally less (1.1 inch) than that in the LTPP database
    - Variability of both aggregate base and cement treated base decreased with total pavement thickness
- Asphalt layer thickness: Coefficient of variability (CV) between 15-22 % for asphalt layer thickness ranged of 3.5 to 11.0 inches; lower CV of 17 % for thin (6-inch or less) asphalt layers
- Aggregate base layer thickness: CV between 25-38 % for untreated base layer thickness range of 5.0 to 12.2 inches
- Cement treated aggregate base layer thickness: CV between 21-34 % for cement treated base layer thickness range of 5.5 to 9.3 inches
- Cement treated subgrade layer thickness: CV of 44 % for an average layer thickness of 6.3 inches (one test site only)
- Effect on overlay thickness requirement: Sensitivity analysis of the effect of variability of layer thickness (± 1 standard deviation) on backcalculated modulus values indicated about 0.15 inch change in overlay thickness predictions

Virginia and Kentucky Studies Al-Qadi et al. [60] studied extensively several GPR antennas (500 MHz – 2 GHz horn; 900 MHz ground-coupled) on many miles of asphalt highway sections; the average error in asphalt thickness ranged from 3.7 % to 13.8 %. Willet et al. [64] used GSSI's 1-GHz horn antenna and showed that by adding more calibration cores the predictions of layer thickness got closer to the actual core values. When comparing surface layer thickness between GPR, calibrated with multiple core data, and actual measured cores one may expect GPR results to fall between the following ranges [64]:

1. Asphalt surfaces less than 50.8 mm (2 in.);
   - ±10.32 to ± 0.40% corresponding to ± 5.08 to ± 0.25 mm (± 0.20 to ± 0.01 in.)
2. Asphalt bases of 203.2 to 228.6 mm (8 to 9 in.);
   - ± 2.73 to ±1.34% corresponding to ± 6.10 to ± 3.05 mm (± 0.24 to ± 0.12 in.)
3. Concrete slabs 228.6 to 304.8 mm (9 to 12 in.);
   - ± 14.24 to ± 0.05% corresponding to ± 42.16 to ± 0.25 mm (± 1.66 to ± 0.01 in.)

Other Studies Maser [16, 18, 58, 66, 75] conducted numerous studies using mostly 1-GHz GPR data (from GSSI Model 4108 and Pulse Radar GPR) for asphalt pavement layer thickness on highways and bridge decks. The following summary findings are based on his reports:

- Asphalt thickness within 0.1 inch of the core thickness in 2003 paper [58]
- Asphalt thickness calculations within 5% for one project without calibration cores; on another project the average difference between GPR and core thickness data was –0.1 inch, and the average absolute error was 0.4 inch, as described in 2001 paper [16]
- Asphalt thickness within 7 % accuracy confirmed with cores for 2-20 inch thick pavements in 1995 paper [17]
- Granular base thickness accuracy within 12 % accuracy for 6-13 inches thick base layers confirmed with test pits in 1995 paper [17]
- Asphalt thickness within 0.11 inch of the core thickness with core calibration and within 0.32 inch without core calibration in 1992 paper by Maser, Scullion and Briggs [18]

Comparison with Core Thickness Most GPR studies extract cores and measure its thickness for calibration of GPR results or for groundtruthing. The above literature review shows that an accuracy of up to 0.1 inch in asphalt thickness has been reported. Can core thickness be measured with that accuracy and good repeatability? This is more questionable especially on older deteriorated pavements that may have rutting on surface and/or stripping or intrusion in base materials. These observations lead to some concern about the accuracy and precision of thickness measured from cores when calibrating or groundtruthing. It is important to make 3-5 thickness measurements of a core and calculate an average, as well as to take an average of three measurements inside the core hole if possible.

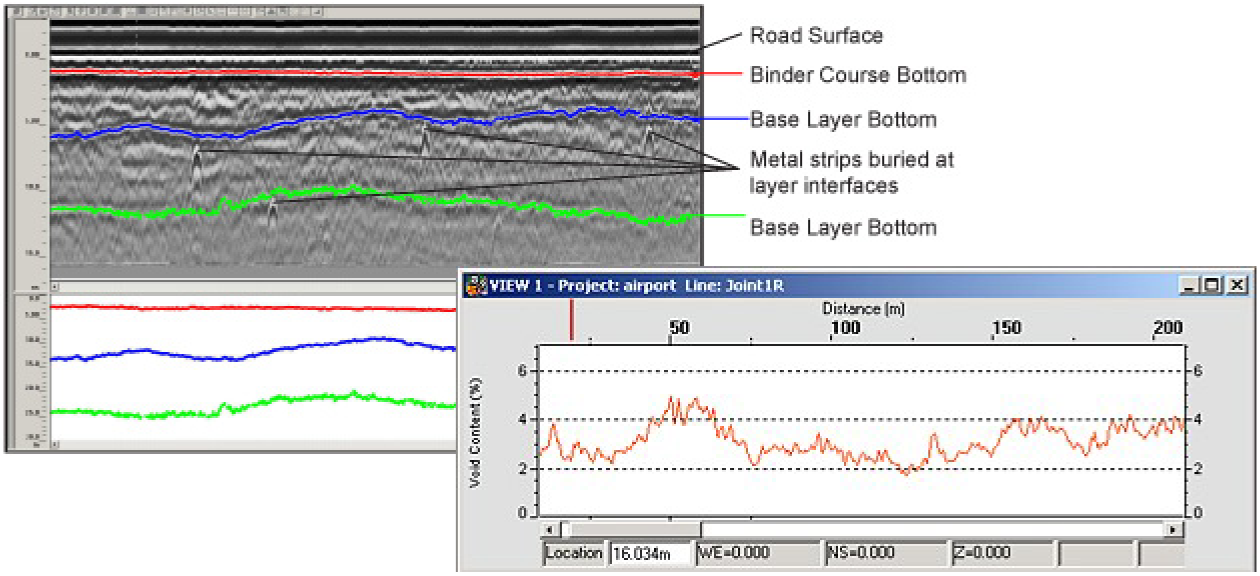


Figure 10. Example outputs generated by the patented GSSI GPR data analysis software [34, 67]

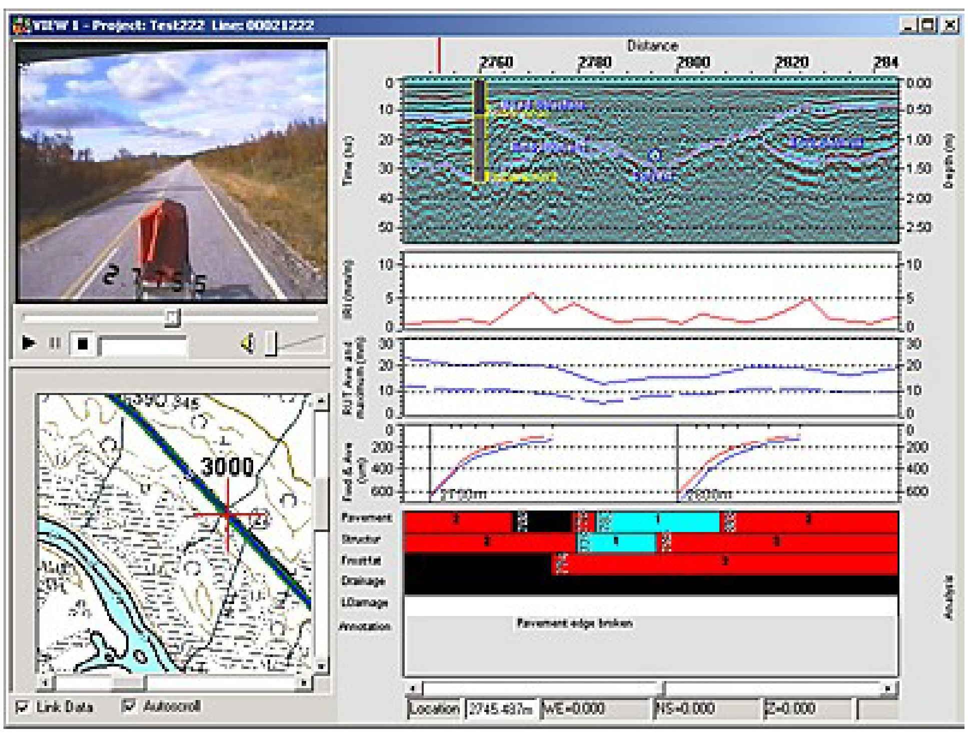


Figure 11. Example outputs generated by the patented RoadDoctor software [69, 70]
(courtesy of Timo Saarenketo)

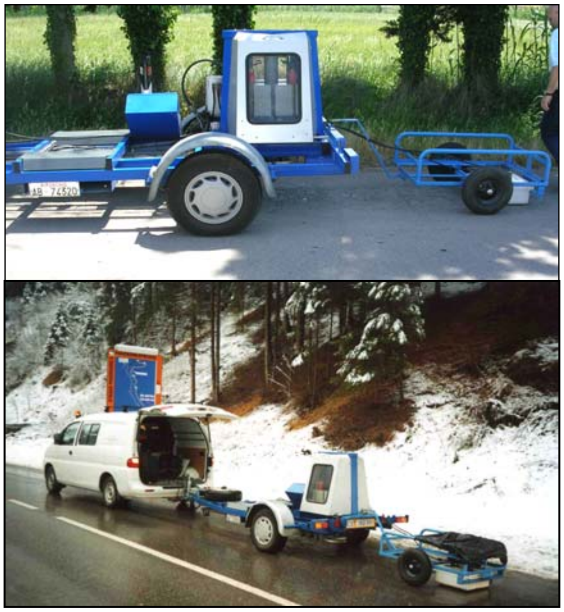


Figure 12. University of Pisa integrated FWD -GPR testing system [80]

Figure 13. Pusle Radar Inc.'s GPR van used in the study [21]

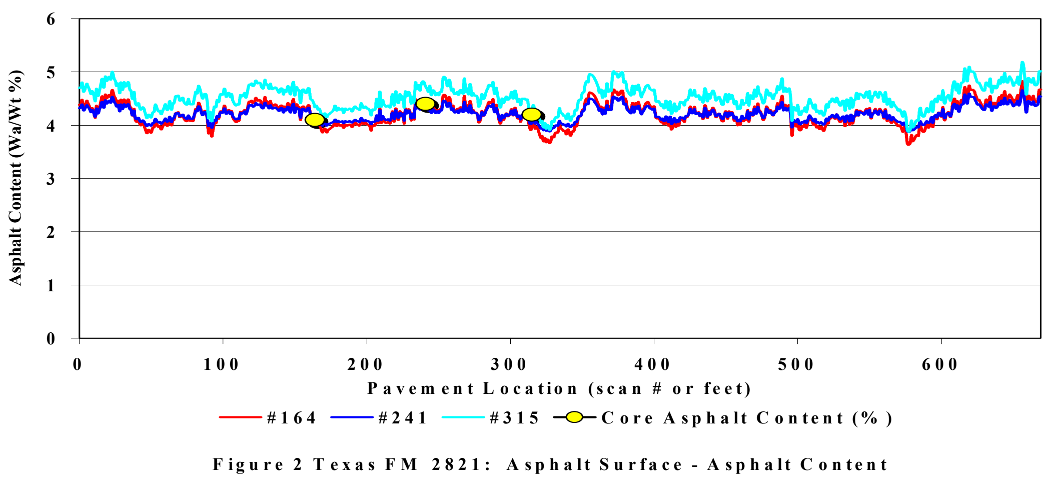


Figure 14 (a). Asphalt pavement - % asphalt pavement - on a 700-ft section [21]

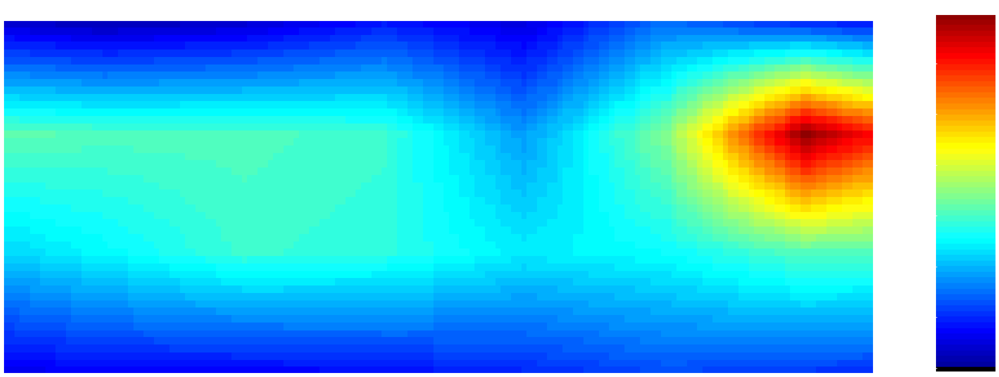


Figure 14 (b). Asphalt pavement - spatial distribution of % air content of asphalt mix [21]

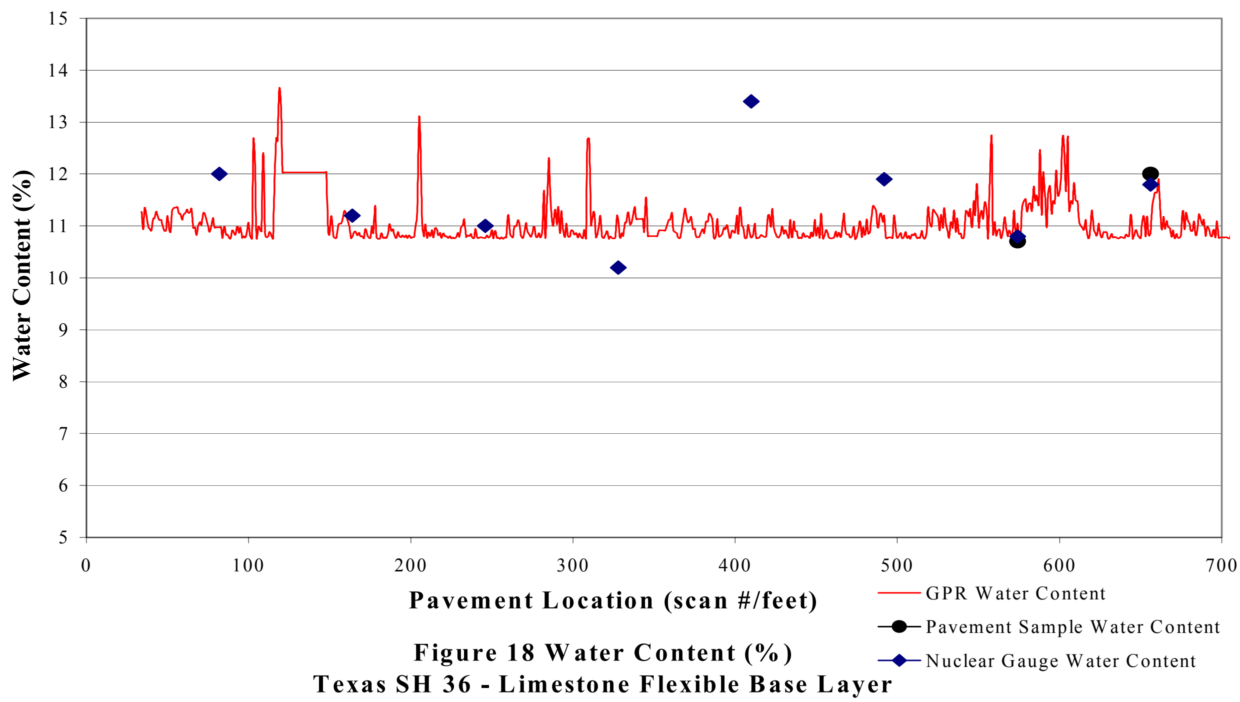


Figure 15. Water content profile of aggregate base course after construction, Texas SH36 [21]

Integration of GPR with FWD Deflection Testing Presently, the integration of GPR thickness data with FWD deflection data files is facilitated by many users of GPR which include the following:

- Briggs [68], over the last 14 years, has trained many state DOTs in the use of Dynatest's ELMOD program for the analysis of FWD data. The ELMOD program can utilize GPR derived data to assign individual pavement layer thicknesses to each evaluation point. The layer thickness information must be converted from the native GPR file format into a simple ASCII flat file with a .gpr extension. The GPR thickness data file has five fields per line: Station, H1, H2, H3, H4, H representing the thickness each layer up to a total of 4 (not counting the subgrade). The Station variable must use the same linear referencing system and units as the corresponding .fwd file. If there are less than five layers (including the subgrade), zeros are entered for the absent layers. If the GPR and FWD test points are not coincidental, ELMOD will utilize the GPR thicknesses for the point nearest the FWD test point. This GPR thickness data file is used with the ELMOD backcalculation program versions 4 or 5 to analyze FWD deflection data.

- Scullion's review report [37] describes the recently developed PAVECHECK software for reading individual FWD and TxDOT/TTI GPR data files and processing with the MODULUS backcalculation program.
- Maser's GPR data analysis program, PAVLAYER, produces tabular (spreadsheet) output of layer thickness vs. station. This output file can be integrated with any modulus backcalculation using FWD data [75].
- GSSI's RoadScan GPR system [67] generates a simple comma delimited ASCII output file that can be easily integrated with any FWD data collection and analysis software. For example, this system is fully integrated with JILS-FWD and described in more detail in Chapter 3.
- Saarenketo's RoadDoctor software [69, 70] fully supports the GSSI's GPR output data file and integrates with the FWD data file (Figure 11); and it is used and/or recommended by many users and service providers [73, 74, 76, 78, 79].
- Losa at University of Pisa [80] uses an integrated system of FWD and GPR. The GPR is towed directly by the FWD at a fixed distance in order to measure thickness of pavement in the same location as that of the FWD plate, as shown in Figure 12. The data files are processed for deflection analysis and modulus backcalculation using station-specific layer thickness produced from the IDS 600-MHz and 1.6-GHz ground-coupled antennas.

Enhanced GPR Assessment of Asphalt Layer and Sublayers

Enhanced applications of GPR data for assessment of asphalt and sublayers include:

- Locating buried areas of stripping in asphalt layers [21, 24, 37]
- Asphalt mix composition and properties of paved asphalt, such as asphalt content, mix density, air void content, permeability [21, 37, 62, 77, 86]
- Unbound base and subgrade soil composition and properties, such as water content, dry unit weight, porosity, and percent air [21, 62]

Lytton's GPR Studies Lytton's patented GPR analysis method [62] is described by Wells and Lytton in their 2001 paper, as summarized here. The SIDARS (System Identification Analysis of Radar Signals) software, is a method of analyzing and graphically displaying the composition of pavement layers, and a related analytical and graphical method for detecting, measuring, and displaying the shape, size, depth, volume, and location of voids beneath a pavement surface layer. The SIDARS method uses the reflected signal from either ground-coupled or air-launched antennas to determine the thickness and relative dielectric constants of several pavement layers and then uses a further analysis to determine the volumetric concentrations of solids and fluid in the mixture that makes up each layer. After calibrating to a core of the material which represents ground truth, asphalt layers are measured for their thickness, asphalt content, total unit weight, voids in the mineral aggregate, and percent air, among others. Cured concrete pavements are measured for their thickness, evaporable water content, dry and total unit weight, and porosity. Unbound base courses are measured for their thickness and the same volume and weight compositions as subgrade soils including water content, dry unit weight, porosity, and percent air. Void detection measures the thickness of air filled voids as thin as 0.10 inch both accurately and repeatably [21].

Figure 13 shows the GPR van used in their study was built by Pulse Radar, Inc. and had four 1 nanosecond (1-GHz) air-launched antennas mounted across the front. Coordinated readings from each of the four antennas were used to provide a cross-sectional view of the pavement layers that are penetrated by the signal. Figures 14 (a), 14 (b) and 15 show some results of analyzing the GPR data by the patented software for asphalt, concrete and base course layers measured on various pavements in California, New Mexico, and Texas [21]. *(Note: The above case studies were presented in Wells and Lytton's paper at the 2001 International Pavement Symposium which was jointly organized in Auburn by the University of Mississippi, Auburn University, and Mackenzie University.)*

<u>NCAT Study of GPR Evaluation for Compacted Asphalt Mix Properties</u>   West [86] is conducting a GPR study for nondestructive evaluation of asphalt mix properties at the National Center for Asphalt Technology (NCAT)- Auburn University. The 1-GHz horn antenna GPR system, and all data interpretation software are being provided by EPIC [77]. Independent core and laboratory test results are being used to evaluate the accuracy of GPR results and outputs of asphalt content, density, and permeability [86]. The study is still in progress and detailed results are not available at the time of this report.

NJ DOT Study of GPR- Based Overlay Thickness Design

Zaghloul et al. [87] conducted a study of asphalt layer thickness evaluation by GPR for highways including SPS sections in New Jersey. Overlay thickness values were also compared using as-built thickness data and GPR-based layer thickness data of the existing pavements. Key findings are:

- Improved reliability in layer thicknesses using GPR
  - Mean asphalt layer thickness was 10 in. over 10 in. granular base
  - Cores were needed to achieve reasonable GPR results (only asphalt layer)
  - CV of asphalt layer thickness = 8 – 20 % (from thin to thick pavements)
- Overlay thickness analysis using 1993 AASHTO method; Example SPS Sec 502:
  - 4.3 in. overlay from as-built thickness (50% reliability)
  - 5.2 in. overlay thickness from GPR data (85% reliability)
- GPR based asphalt overlay thickness generally higher than that from the as-built record (Figure 16)

No benefit-cost evaluation or savings from extended life was reported.

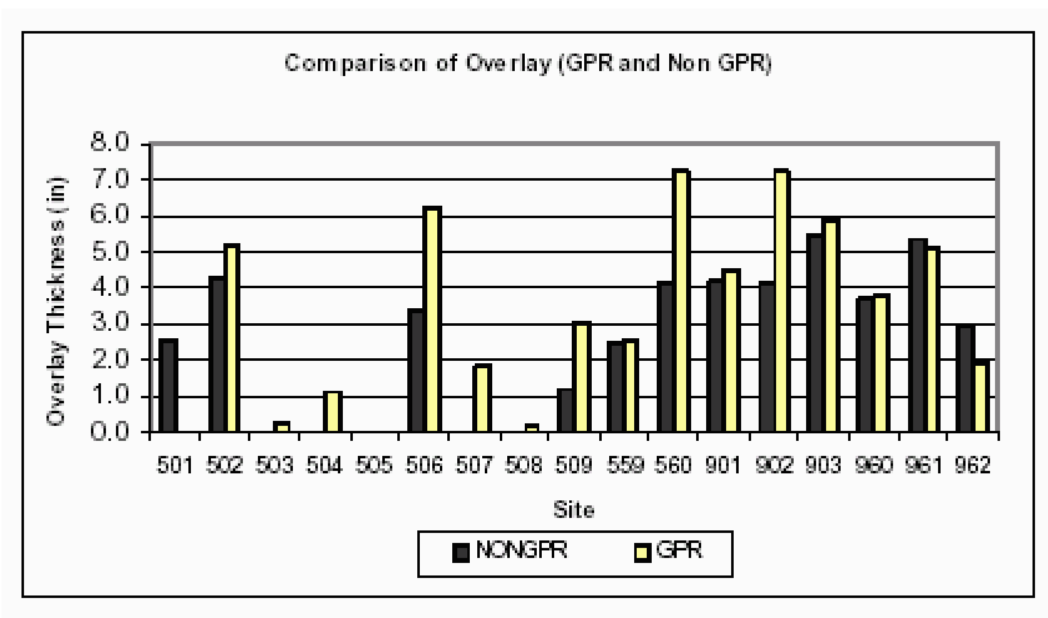


Figure 16. Required asphalt overlay thicknesses for SPS-5 and SPS-9 sections [87]

2.4 Summary

This chapter has presented an in-depth review of GPR theory, data processing and analysis methodologies, limitations, operational issues, and applications for calculating thickness of asphalt pavement layers and properties of layer materials. An increase in moisture content increases the material dielectric constant, which is the key property used for GPR data interpretation. Layer thickness estimates are reasonably accurate within 5 % of asphalt thickness measured by cores. Accuracy improves if some cores are used for calibration of initial GPR results. One DOT study shows higher variability (CV of 21-38 %) in the thickness data calculated for base layers at and even higher CV of 44 % for lime treated subgrade. In another study it is shown that reliability of asphalt layer thickness increased with GPR survey. In this study the overlay thickness generally increased with GPR based thicknesses compared to the as-built thickness data. No published data was found on benefit/cost evaluation using GPR. Integration of GPR data with FWD deflection data files is already being routinely done for production use by most GPR users. Furthermore, there is no proven fully automated GPR data analysis program at this time. Therefore, it is obvious that the available FCC certified or "grandfathered" GPR technologies and their experienced users are key elements for successful implementation of GPR in field studies of pavement thickness evaluation for project-level and forensic applications.

3. IMPACTS OF 2002 FCC RESTRICTIONS ON GPR

3.1 Background and Final FCC Regulations

Federal Communication Commission (FCC) in the USA had a major concern on the performance of cell phones and GPS units in the presence of radio signal interference caused by ultrawide band radiator radar devices. In an experiment, reported by Olhoeft in 2000 at the Colorado School of Mines, this issue was discussed which encompasses GPR and all electromagnetic transmissions in the ultrawide band above 9 kHz [51]. A GSSI 500 MHz short pulse antenna was setup in a 6 x 6 x 3 m high underground in the interior of a large building. The GPR signal interference with a cell phone operating at a frequency of 900 MHz outside the building was demonstrated. Key findings were:

(1) With the radar off, the cell phone had a signal strength in the room about 1/6th of that outside the building.

(2) With the radar on and the antenna coupled to the tiled concrete floor, the cell phone can not acquire service within about 1 m of the radar antenna, but once acquiring the service outside that range, had no trouble keeping it.

(3) With the cell phone off, the radar scan was less noisy and good interpretation can be made for the concrete thickness, rebars in the concrete, and detection of sewer pipe beneath the floor.

(4) With the cell phone in standby, the radio frequency noise masked the sewer pipe.

(5) The active cell phone conversation made the rebar detection marginal, and concrete thick ness determination impossible.

The FCC Part 15 regulations of 15 July 2002 required all radar devices in the United States operating in ultrawide band to register. The rulings did not affect working with devices less than 960 MHz or in the higher frequency range of 3.1 – 10.6 GHz. Road GPR working in 1 - 2 GHz range for pavement evaluation was a great concern for GPR industry, operators, and users. Through the efforts of users and manufacturers [36, 37, 66, 67] the following two significant results were achieved [66].

1) The FCC issued a ruling in July 2002 specifically permitting continued operations of all existing GPR devices.
2) On 13 February 2003, the FCC adopted an amendment to the Part 15 rules to specifically allow for the operation of new GPR systems

3.2 Post FCC Regulation ─ GPR Technology Status

Existing GPR devices were allowed to be "grandfathered" by 15 October 2002, such as 1-GHz Pulse Radar equipment. The FCC allowed the users of the existing GPR from pre-FCC ruling to register with the FCC for continued use. However, concern was there for the sale of GPR device in the 1-Ghz or higher frequency range sale after that date because all post-FCC ruling devices must be certified and licensed by the FCC. The GPR industry was discouraged by the FCC to use the term "air-coupled" in equipment specifications due to Federal Aviation Administration's concerns [36]. The non-contact air-coupled antennas are now termed "horn" or air-launched antennas. The main problem created by the FCC regulation was with old 1-GHz horn antennas, which were mostly used for pavements and their data interpretation was enhanced during the 1990's. The FCC regulation limited the amount of electromagnetic energy (output power) radiated from transmitters operating between 700 MHz and 2 GHz. Some previous GPR manufacturers such as 1-GHz Pulse Radar went out of business.

GSSI [34, 67] has enhanced their technology to address this FCC certification issue and got FCC approvals by designing new GPR equipment that comply with the FCC regulations and still capturing up to 1 scan per foot at normal highway speeds. At this time the following new GSSI equipment with its new 1-Ghz and new 2-GHz horn "air-launched" antennas are the only horn models certified and approved by the FCC for nationwide sale and use [67].

1) Currently, GSSI model SIR-20 GPR system is the most widely used in the United States and abroad. GSSI's new 2-GHz air-launched horn antenna model 4105 has been developed specifically for FCC compliance. It is claimed to provide higher resolution than the 1-GHz antenna. The depth of penetration will be less than that from the 1-GHz antenna (Table 4).

2) The FCC certified 1-GHz horn antenna model 4108F, developed by GSSI, has lower radiated output power than the non-FCC version model 4108 [67]. Consequently, the model 4108F is more susceptible to Radio Frequency (RF) interference than the older 1-GHz horn antenna model 4108 from GSSI and other "grandfathered" 1-GHz GPR devices. This may limit the thickness resolution of deeper layers in the case of the new 1-GHz antenna.
3) These older GPR devices from pre-FCC ruling days can be used only by their owners, such as the older Pulse Radar equipment operated by the TxDOT, Florida DOT, and consultants if they were properly registered with the FCC by 15 October 2002.

FCC Compliant Antenna Specifications

Table 4 shows the GSSI specifications for FCC compliant 1- and 2-GHz horn antennas [67].

Table 4. FCC Compliant horn antenna specifications; courtesy of GSSI [67]

SIR-20 System Specifications	Model 4108F	Model 4105
Operating Frequency, Hz	1 GHz	2 GHz
Bandwidth, Hz	1 GHz (approximately)	2 GHz (approximately)
Scan rate (using SIR-20 data acquisition system	Up to 500 KHz	Up to 500 KHz
Number of samples per scan	128,256,512,1024,2048	128,256,512,1024,2048
Depth penetration	36 inches (0.9 m)	30 inches (0.75 m)
Antenna type	Horn (air-launched)	Horn (air- launched)
Antenna height above pavement recommended	17 – 18 inches	17 – 18 inches
Weight	16 lbs	16 lbs
Power source (from vehicle)	12 VDC or 120 AC	12 VDC or 120 AC
Noise to signal ratio, %	Conforms to TTI specs *	Conforms to TTI specs *
Range resolution depends on samples/scan and desired working depth		

* as reported by GSSI [67]

The RAMAC/GPR system from Sweden [81] is the only other GPR with FCC-certified 1.2-GHz, 1.6-GHz and 2.3-GHz ground-coupled antennas that can be sold and used in the US. Other GPR antenna models manufactured in Europe, such as 3-Radar from Finland [69, 70] and IDS GPR from Italy [78, 79] are not FCC certified and, therefore, not approved for use in the US.

<u>Some Cautionary Observations</u>

The 2-GHz antenna has been in use for only a few years. The depth of penetration of the 2-GHz antenna is slightly less than the 1-Ghz antenna. As previously stated, the newer FCC compliant 1-GHz antenna is more noisy and susceptible to RF interference than the pre-FCC "grandfathered" antennas. Figure 17 shows a field comparison of the scanned images on an asphalt pavement using new 1-GHz antennas (bottom image) and old 1-GHz antenna (top image). The data on the top is from a 1-GHz model 4108 antenna (non FCC compliant). The data on the bottom is from a 1-GHz model 4108F antenna (FCC compliant). In the new antenna image (bottom) the top asphalt layer is easy to interpret for layer thickness. However, the reduction in output power of the FCC compliant 1-Ghz model 1408F antenna may limit the depth of penetration and the ability to obtain deeper sublayer thickness as compared to the pre-FCC 1-GHz antenna [67].

3.3 Post FCC Regulation ─ GPR Technology Applications in USA

<u>FCC Compliant GSSI Horn Antenna Models and GPR Data Acquisition System</u>

As reported by Parrillo [67], GSSI's 1-GHz and 2-GHz air-launched horn antennas are tested for noise and repeatability under the TTI GPR antenna performance specification [67]. These specifications are based on test data of GPR reflections from a large metal plate related to:

- Noise to signal ratio
- Signal stability
- Long term signal stability
- Variations in time calibration factor
- End reflection test
- Symmetry of metal plate reflection

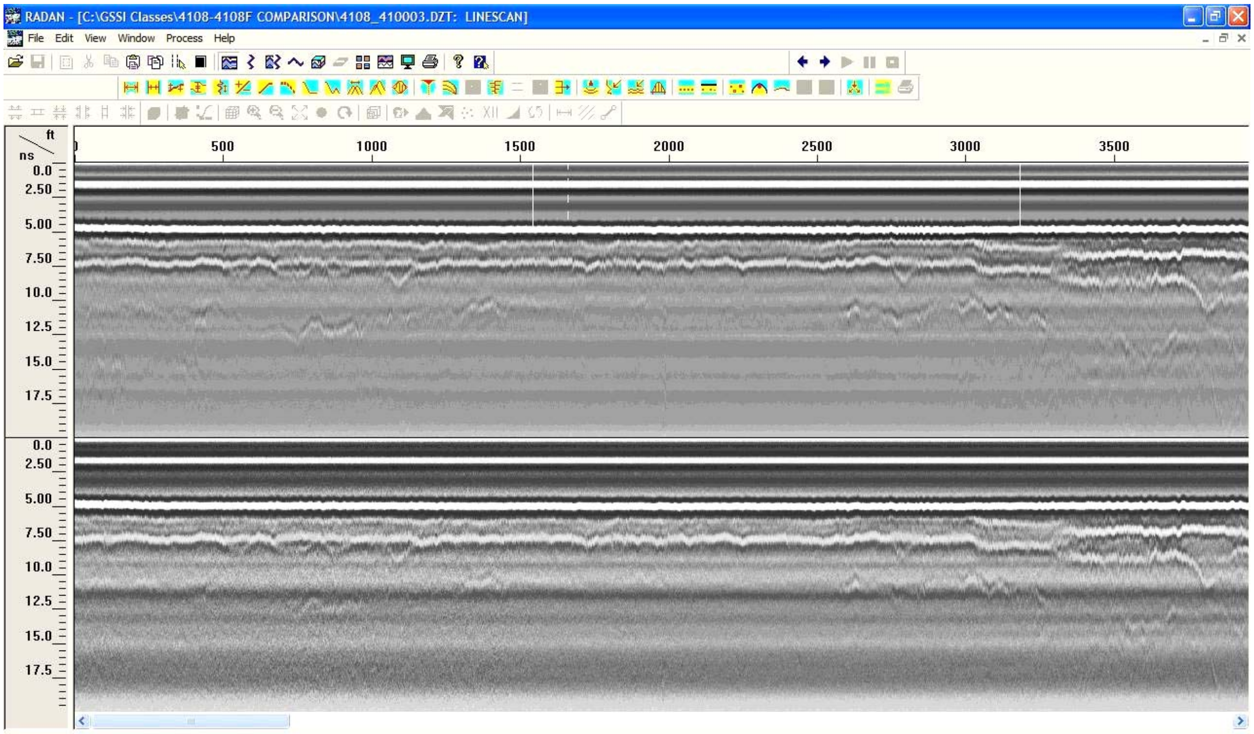


Figure 17. The scanned images on an asphalt pavement using new FCC compliant 1-GHz antennas (bottom) and old non-compliant 1-GHz antenna (top); courtesy of GSSI [67]

The following capabilities of the GSSI GPR systems for pavements are provided by Parrillo [67].

1. The GSSI's RADAN data software processes radar and DMI data with reliability. The SIR-20 data acquisition system supports an optional GPS connection and reads data from any GPS unit capable of sending the NMEA GGA command.
2. The output file from the RoadScan system is a simple generic comma delimited ASCII file that may be easily used by any software application capable of opening an ASCII file.
3. The RoadScan system has been integrated with Foundation Mechanics JILS truck-mounted FWD for simultaneous collection of FWD and GPR data so that accurate pavement layer thickness can be obtained at each FWD location. Figure 18 shows the system [71]. The GPR pavement thickness data is stored with the FWD data in a single database.
4. GSSI's radar format is fully supported by the RoadDoctor program available from RoadScanners in Finland [69, 70]. Using RoadDoctor, the GPR data may be combined and synchronized with video, FWD, core and a variety of other data (Figure 11).

Figure 18. JILS 20T FWD (back in the vehicle) integrated with GSSI RoadScan GPR and 2-GHz model 4105 horn antenna [71]

Experience with FCC Approved Antennas

Table 3 provides a list of all current “grand fathered” 1-GHz horn GPR units and GSSI’s FCC compliant 2-Ghz and 1-GHz horn antennas. Several GPR service providers have been using GSSI’s 2 GHz horn antenna systems. They include: Fugro from Texas [74], Geovision from California [76], Wavetech from Alabama [78], and RoadScanners from Finland [70]. TTI/TxDOT [36, 37], Infrasense Inc. from Massachusetts [75], EPIC from Louisiana/Alabama [77], and others have been using 1-GHz “grandfathered” horn antennas.

The following GPR studies have been conducted recently in the last few years. (Note: The results of Louisiana and NCAT studies have not been published at the time of this report.)

Georgia DOT Hammons et al. [24] published a research report in 2005 on a comprehensive study for the Georgia DOT to map subsurface asphalt stripping using several technologies. The field evaluation included Infrasense Inc.’s “grandfathered” 1-GHz GSSI horn antenna GPR system and data analysis software. The study is described in detail in section 1.2.

Louisiana DOTD The Louisiana DOTD and Louisiana Transportation Research Center have contracted out the following two recent studies involving GPR applications, according to Gaspard and Mix [73]:

- Post Katrina Pavement Evaluation in New Orleans Area Testing and evaluation of about 300 miles of highways and roads in New Orleans and surrounding areas which were devastated by Hurricane Katrina in October 2005. Both FWD and GPR have been used on these flexible and rigid pavement sections in conjunction with the ELMOD modulus backcalculation and structural evaluation software. Daleiden of Fugro from Austin - Texas, the study contractor, reports using both 1-GHz and 2-Ghz horn GSSI antennas [74] and that the data analysis is still in progress.

- GPR Evaluation of Voids Beneath Concrete Slabs, Lafayette, Louisiana This study required a GPR survey of about 500 sq ft of reinforced concrete slabs to identify large voids that may have developed beneath reinforced concrete slabs, either bridge deck approach slabs or something similar in construction. The GPR survey has been conducted by Geovision; the results are not available at this time.

NCAT Study According to West [86], a GPR study for evaluation of asphalt mix properties is currently in progress at NCAT - Auburn University. The 1-GHz horn antenna GPR system and all results are being provided by EPIC using EPIC's proprietary data interpretation software [77]. The GPR results and outputs include two-dimensional maps of asphalt content, density, and permeability. The NCAT researchers are evaluating the accuracy of the GPR results for 11 NCAT test sections built with a variety of asphalt mixes by comparing with independent cores and laboratory test results [86].

Florida DOT – 2005 Procurement of GPR During the pre-2002 period a Pulse Radar 1-GHz unit was owned and operated by the DOT in Florida using the TERRA software [57]; its status is not known now [72]. Some GPR projects were contracted out using EPIC's GPR and data analysis software [72].

Recently, in 2005 the Florida DOT purchased a GSSI GPR system consisting of two FCC compliant 2-GHz horn antennas with a full suite of GSSI software for $100,000 [72]. As reported by GSSI [67], the TTI performance specifications were used by the Florida DOT for the GPR procurement; and the GSSI's 2-GHz horn antennas passed these specifications. This new GPR system with two 2-GHz horn antennas is being used for inventory and project level work in Florida with the main output of asphalt thickness. Additionally, the Florida DOT also acquired three ground-coupled antennas (900, 400, and 100 MHz) from GSSI. These GPR units are being implemented for forensic studies [72].

3.4 Summary

It is important to note that at the time of this report, the GSSI horn antenna models 4108F (1-GHz) and 4105 (2-GHz) are the only FCC compliant GPR horn antennas for sale and use in the US. In 2005 the Florida DOT has acquired GSSI GPR SIR-20 system with two 2-GHz FCC compliant horn antennas and all related GSSI software packages. The only other usable GPR antenna models are the old “grandfathered” GPR antennas (GSSI 1-GHz model 4108, Pulse Radar, Wavebounce, and Penetradar) from pre-FCC regulation days, if they were properly registered by their owners with the FCC prior to October 2002 deadline. Mala Geoscience of Sweden [85] reports that their three ground-coupled GPR antennas (1.2 GHz, 1.6 GHz, and 2.3 GHz) are also certified by the FCC.

4. CAIT SURVEY OF GPR TECHNOLOGY FOR ASPHALT PAVEMENTS

4.1 Background

A technology evaluation survey of GPR manufacturers, users, and owners was conducted mostly though e-mail communications. The CAIT survey form, developed for this study for GPR technology evaluation, is included in Appendix B. The survey form requested for unbiased expert responses to survey questions based on the evaluator's reputation and research/consulting experience in GPR testing and data interpretation. The survey involved the following nine evaluation criteria followed by comments on enhanced data analysis beyond layer thickness and a request for some references:

1. GPR Equipment Robustness and Durability
2. Field Data Collection and Processing
3. Operating Restrictions
4. Office Data Processing
5. Data Quality and Usefulness
6. Cost of Equipment, Operation, Data Analysis
7. Cost-Effectiveness Estimate
8. User Preference
9. Overall Ranking
10. Comments

Table 5 lists the names of all survey responders, affiliation, and user category. Full contact info for all survey responders is provided in Appendix C. Total 14 responses were received including the feedback from Bertrand [83] and Scullion [84]. Bob Briggs of Dynatest [68] declined to respond because GPR services are contracted out by Dynatest; he only provided detailed feedback on the GPR thickness data file format used with the ELMOD modulus backcalculation program. No formal survey response was given by Gaspard and Mix of Louisiana DOTD [73]; however, they provided lots of information related to their recent GPR projects and contacts of GPR users and service providers. Randy West of NCAT [86] provided telephone feedback.

The composition of the 14 responders in the survey group and other significant data are:

- 3 GPR equipment manufacturers, 9 consultants-service providers, 2 academic/researcher, and 2 current DOT experts and 1 former DOT expert.
- Number of years of experience in GPR equipment ranges from 0.5 to 24 years (with 10 or 71 % of the group having 5 or more years of experience).

- Number of years of experience in GPR data analysis ranges from 0.5 to 24 years (with 9 or 64 % of the group having 5 or more years of experience).
- Number of years of experience in GPR data analysis for asphalt pavements ranges from 0.5 to 20 years; and 1 to 20 years of experience in using GPR data for FWD analysis.

Table 5. List of GPR technology evaluation survey responders who used CAIT's survey form

Eval. No.	GPR Expert [Reference]	Years of GPR Experience		Affiliation	Professional Category of Evaluator			
		Equipment	Data Analysis		Manufa -cturer	Consulting /Service Provider	Academic/ Researcher	DOT/ Agency
1	Tom Scullion [84]	18	18	TTI		X	X	
2	Carl Bertrand [83]	15	15	Note 1		X		X
3	Robert Parrillo [67]	3	3	GSSI	X			
4	Gary Sanati [71]	4	4	Note 2	X			
5	Charles Holzschuher [72]	0.5	0.5	Florida DOT				X
6	Kenneth Maser [75]	15	15	Infrasense, Inc		X		
7	Jerry Daleiden [74]	20	2	Fugro Consult		X		
8	Francisco Romero [76]	10.5	10.5	GEOVision		X		
9	Carl D. Rascoe [78]	24	24	WaveTech		X		
10	Robert Emfinger [77]	7	11	EPIC		X		
11	Victor Torres-Verdin [79]	3	3	EIO Civiles		X		
12	Timo Saarenketo [70]	21	18	RoadScanners		X		
13	James E. Cook [85]	5	5	MALA USA, Inc Mala Geoscience	X			
14	Massimo Losa [80] Note 3	21	18	Univ of Pisa			X	

Note 1: Carl Bertrand is currently with Spectral Measurements LLC; formerly with TxDOT.
Note 2: Gary Sanati is with Foundations Mechanics, Inc., manufacturer of JILS-FWD.
Note 3: Victor Torres-Verdin of Evaluación Integral de Obras Civiles is from Mexico; Timo Saarenketo is from Finland; Massimo Losa and Laurent D'Onofrio are from University of Pisa, Italy.

The survey form describes the study objectives and provides the following instructions.

Instructions: Please provide your best expert answers to the following criteria (as many as you can) so that we can evaluate the GPR equipment and data analysis technology for its potential routine use on flexible/asphalt/bituminous surfaced highway pavements. Please read each criterion carefully, add comments, and indicate if you can provide your best published or unpublished related references. Thank you very much for your scholarly contribution.

4.2 Synthesis of GPR Survey Responses

Tables 6 though 9 summarize the responses related to evaluation criteria 1, 5, 8, 9, and 10. For other criteria, discussions are provided on the responses related to key GPR implementation issues for asphalt pavement evaluation.

1. GPR Equipment Robustness and Durability

1.1 Equipment specifications See Table 6 summary for GPR model, frequency, and antenna type. All models of 1-GHz and 2 GHz horn antennas are air-launched. Maximum depth of asphalt pavement evaluation depends on the antenna frequency and user's experience as shown in Table 7. The reported thickness range is 18 – 40 inches.

Table 6. GPR Survey responses to equipment criteria 1.1

GPR Manufacturer (country)	GPR Antenna Model and Frequency	FCC Registration	Owners/Users
GSSI (USA)	2-GHz horn, Model 4105	Certified	JILS-FWD [71], Florida DOT [72], Fugro [74], Geovision [76]
GSSI (USA)	1-GHz horn, Models 4108F	Certified	Fugro [74], Geovision [76]
GSSI (USA)	1-GHz horn, Models 4108	Grandfathered	Infrasense [75], EPIC [77], Geovision [76]
GSSI (USA)	1.5GHz ground-coupled 400/500-MHz ground-coupled	Grandfathered No need	Geovision [76], Wavetech [78]
Pulse Radar (USA)	1-GHz horn	Grandfathered	TTI [84], TxDOT[83]
Wavebounce (USA)	1-GHz horn	Grandfathered	Texas DOT [83], Wavetech [78]
Penetradar (USA)	1-GHz horn	Grandfathered	TTI [84], TxDOT [83]
MalaGeoscience (Sweden)	RAMAC/GPR 1.2 GHz, 1.6 GHz, 2.3 GHz; ground-coupled	Certified	Mala USA and Rutgers University [85]
IDS (Italy)	600-MHz ground-coupled 1.6-GHz ground-coupled	Non-FCC	Losa - University of Pisa [80]

Note: 1-GHz non-FCC model and 2.2-GHz horn antennas used by RoadScanners in Finland [70]; 1-GHz non-FCC model horn antenna used in Mexico [79]; Rutgers University in New Jersey, is using 1.2 GHz MalaGeoscience ground-coupled antenna for soil moisture study 85].

1.2 Tow vehicle requirements and safety on road Responses are summarized in Table 7.

1.3 Field automation & instrumentation reliability Continuous data collection and good to excellent reliability is reported by all (no comment by one responder). GSSI provides 2 years warranty. Most testing in Texas was done with old Pulse Radar system; the system may no longer available [84].

1.4 Versatility (Applicable for 4-inch or thicker pavements) Very versatile for asphalt pavements. Resolution of layers using 1-GHz horn antenna reported down to: 1 inch [78, 87], 1.5 inch [75, 77], and 3 inch [80]. Resolution of minimum layer thickness depends on antenna frequency. Higher 2.2-GHz frequency identifies each sublayer in asphalt [70].

Table 7. Responses to evaluation criterion 1.2 Towing vehicle and safety requirements
* Maximum depth of asphalt pavement evaluation

Number	GPR Expert [Reference]	GPR Antenna and FCC Registration	Maximum Depth *	1.2 Tow Vehicle and Safety on Road
1	Tom Scullion [84]	1-GHz horn Grandfathered	24 in.	No problem; data collection at highway speed
2	Carl Bertrand [83]	1-GHz horn Grandfathered	24 in.	Single vehicle with warning light at posted speed with sample at 10 ft; 5 mph for samples every 5 ft; moving traffic control for sample per ft at 30 mph
3	Robert Parrillo [67]	1- & 2-GHz horn Certified 200 MHz......1.5 GHz ground-coupled	Depends on antenna	At highway speed; any vehicle with class III trailer hitch; front or rear; 12 V power
4	Gary Sanati [71]	2-GHz horn Certified	25 in.	System mounted on FWD van; no trailer
5	Charles Holzschuher [72]	Two 2-GHz horn Certified, 100,400,900 MHz ground-coupled	18 in.	Chevy van self-contained with top strobe package
6	Kenneth Maser [75]	1-GHz horn Grandfathered	30 in.	Antenna suspended from rear; no special safety requirements
7	Jerry Daleiden [74]	2-GHz horn Certified, 1-GHz horn Grandfathered	--	Strapped back to SUV; no unusual safety issues
8	Francisco Romero [76]	All GSSI antennas	20 - 40 in.	Horn antenna operated at highway speed; ground-coupled with attenuator truck above 15 mph and with lane closure below 5 mph
9	Carl D. Rascoe [78]	GSSI/Wavebounce; 1.5-GHz, 400-GHz ground-coupled	12 - 36 in.	Typically any vehicle with 2 inch hitch
10	Robert Emfinger [77]	1-GHz horn Grandfathered	24 in.	Self-contained vehicle
11	Victor Torres-Verdin [79]	1-GHz horn (non-FCC)	40 in.	Mounted on Ford E-150 van (no GPR towing)
12	Timo Saarenketo [70]	1-GHz, 2.2- GHz horn (non-FCC)	35 in.	Horn antenna mounted in front of a van; no towing; in front it is better protected
13	James E. Cook [85]	RAMAC/GPR 1.2-, 1.6-, 2.3-GHz; ground-coupled	20 in.	No towing; can be configured to any vehicle (Note 1)
14	Massimo Losa [80]	600-MHz, 1.6-GHz ground-coupled (non-FCC)	40 in.	No towing vehicle; pulled by FWD trailer

Note 1: RAMAC/GPR 1.2-GHz, 1.6-GHz, 2.3-GHz FCC-certified mono-static dipole antennas are configured for ground coupling. They can probably work within 2 inch of the ground. However, results are best when ground-coupled [85]. Data collection speed will be less compared to highway speeds of GPR systems with horn antennas.

2. Field Data Collection and Processing

2.1 Level of automation Setup with wheel mounted DMI and used by most users including TTI/TxDOT (DMI needs calibration).

GPS is optional with GSSI models and can be integrated through GSSI's RADAN data acquisition software [67]. Scanning and data capture is generally semi-automated requiring operator's input on data acquisition computer. TTI unit scans 40 traces per second. Field data processing is limited.

2.2 Special education and training Required. Response for training duration varies from minimum 2 days for a GPR operator to 6 months for a good data analyst. Minimum education level is another preference.

2.3 Crew (for GPR and tow vehicle) Generally 2 (driver and GPR operator)

2.4 Productivity and data quality (Comparison with field) Accuracy of scan is mostly reported good, and repeatability error is very low. Less than 1 % repeatability error is reported [75].

Scan rate can be 1 per foot at most operating speeds; 10 per foot reported by one responder. Scan rate is adjustable by operators using GSSI data acquisition software. Number of scans per surveyed lane mile depending on the speed can be up to 5000. Lower scan rate may be desirable for network-level survey.

3. Operating Restrictions

3.1 Environmental effects Environmental operating constraints are rainfall, freezing weather, Good quality data can not be collected when there is standing water, snow or de-icing salts on the pavement.

3.2 Traffic interference and safety Normally no traffic control required for data collection at highway speed. Local agency guidelines are followed when operating at lower speed, such as an arrow board truck on the back for traffic safety. Some applications, such as forensic investigations, may require lower speed.

3.3 Operating speed, mph (During scanning) Most responders use GPR up to posted highway speed. Speed can not be more than 60 mph on Interstate highways in Florida [72].

3.4 Signal interference sources and noise problems The GPR scanning in the field can be sensitive to noise interference from passing vehicles, radio and CB transmissions, RF signals near airports, cell phones, and other facilities producing radio signals (radio stations, hospitals, military facilities, microwave and cell towers, and high energy transmission lines, etc.). Cell phones, operating at 900 MHz, may not work in the vicinity of GPR and may interfere with GPR scanning quality.

4. Office Data Processing

4.1 Special education and training required; staff size Special dedicated software and training is required including basic knowledge of PC Windows operating system. GSSI includes 3 days training in GSSI's equipment price. Two persons minimum and 3 persons are preferable. Considerable training and pavement evaluation experience is essential, as well as periodic professional development opportunities in related conferences and refresher courses.

4.2 Versatility of data processing computer equipment Modern desk top computer or laptop with Windows operating system is essential. One responder recommends Windows XP and up to 1GB memory for computational needs. A large hard risk storage and a good graphics card are specified by another responder.

4.3 Ease of data processing (Fully automated electronic data processing available? If not what level of automation; explain.)

It depends on the software and requires training. There is no fully automated data analysis software, and old pavement structures are too complicated for automated analysis. Manual interpretation is necessary to identify the relevant layers and material types. Responses for productivity vary. One responder cautions against too much automation and gives the following specific comments [76]:

- Some dedicated software packages are not available commercially, such as Infrasense' software.
- Penetradar sells software which has many automated features that can not be overridden; their GPR is not FCC compliant and the software may not work with other FCC compliant systems.

Other GPR users (such as TTI/TxDOT and EPIC) have developed their own dedicated programs for specific GPR systems which may not be available commercially. The

University of Pisa's software is fully automated but manual data processing produces better results.

The most popular GPR data analysis program is RoadDoctor; it is recommended by most responders in the consulting-service provider category both in the US and abroad.

4.4 Extent of data coverage (per mile scan) and time Depends on the project and objectives (for example, only pavement thickness or all layers plus defects). New construction is relatively easier to process and GPR data analysis is more time consuming for old pavements. Wide variations are shown in productivity estimates, such as:

- One file may take 5 minutes to several hours.
- Only 30 minutes for 10 miles if only pavement thickness required on a good road.
- About 7-10 lane miles per day; 10-15 lane miles per day by one analyst.
- 100 miles per day; 200 miles per day; up to 300 miles per day.

5. Data Quality and Usefulness

5.1 Data analysis and permanent record of GPR scans See Table 8 for responses.

- Name of software and name of developer
- Scan image quality (Black & White or Color)
- Processing productivity

5.2 Ease of interpretation of GPR scanning outputs See Table 8 for responses.

(Rating scale 1-10 for ease of interpretation, 10 being the easiest & fastest, 1 – slowest).

Depends on pavement structure; easier on thin asphalt than for concrete [72].

Outputs include mostly: ASCII file, Excel spreadsheet, 2-D graphs. One responder produced 3-D contour reports and full lane analysis.

5.3 Accuracy of thickness results (Comparison with cores and/or boring)

See Table 8 for responses. Most agree on 2-5 % accuracy of asphalt thickness; 5 % with no validation core. Base/subbase thickness accuracy depends on material and environment and the ability to interpret layer interfaces; 5-10 % accuracy for base layer, and around 10-20 % for subbase.

5.4 Repeatability error (For thickness of asphalt and sublayers) Highly repeatable if data collected in the same path; less than 1 % repeatability error noted by most responders.

Comment A careful review of Table 8 shows that each responder is knowledgeable only about in-house or self-developed GPR data analysis software; and this factor applies to their stated experience related to (a) ease of interpretation and (b) accuracy of thickness of asphalt and other layers. The only exception is the RoadDoctor software which is also available commercially and being used by several consultant-service providers.

Table 8. Responses to evaluation criterion 5. Data Quality and Usefulness

* (Rating scale 1-10 for ease of interpretation, 10 being the easiest & fastest, 1 – slowest)

GPR Expert [reference]	5.1 Software (Developed by)	Scan Image Quality, Processing Production	* 5.2 Ease of Interpretation Rating (1-10)	5.3 Accuracy of Thickness Results from GPR (comparison with coring/boring)		
				Asphalt	Base	Subbase
Tom Scullion [87]	COLORMAP (TxDOT/TTI)	Color automated	9	5 %, no validation core 2-3 %, with validation core	5 % with clear base interface; no guarantee	Same as base
Carl Bertrand [88]	GPR_ANA (in-house)	Color N/A	3	5 %, no core 3 %, with reference core	5 %, no core 3 %, with reference core	Only Base/subbase interface
Robert Parrillo [67]	RADAN- RSAM (GSSI)	Excellent Fast; point and click	1	5 % typical	Depends on material and environment	Depends on material and environment
Gary Sanati [71]	RADAN (GSSI)	No comment	9	5 %; need for a consistent method of core thickness	10 %	20 %
Charles Holzschuher [72]	Easy Tracker (GSSI)	Good Production unknown	5 (Depends on structure)	to be determined	N/A	N/A
Kenneth Maser [75]	winDecar (Infrasense, Inc)	Good Productivity varies	Depends on data	within 5 - 10 %	within 5-10 %	No results
Jerry Daleiden [74]	RADAN (GSSI)	B & W	Insufficient experience	good	Depends on distinctions between unbound layers	Same as base
Francisco Romero [76]	RoadDoctor recommended	No comment	No comment	Better than 5 % with a verification program	7 - 10 % with a verification program	15 - 20 % with a verification program
Carl D. Rascoe [78]	RoadDoctor (RS) RADAN (GSSI)	Color 7-10 miles / day	7	2 -5 %	10 %	20 %
Robert Emfinger [77]	EasyPlot (EPIC)	Color	10	± ¼ inch	± ¼ inch	No comment
Victor Torres-Verdin [79]	RoadScan (GSSI)	B & W > 1000 scans / hour	6	high	moderate	No comment
Timo Saarenketo [70]	RoadDoctor (RoadScanners)	B & W grey scale is the best	9	5 %, with cores 10 %, without cores	10 %	10 - 20 %
James E. Cook [85]	REFLEX (Dr. Sandmeier)	B & W and Color	No comment	± 1/8 inch	± ¼ inch	± ¼ inch
Massimo Losa [80]	IDSGRED (IDS, Italy)	Any 2 Colors	7	0.6 inch	1 inch	1.2 inch

6. Cost of Equipment, Operation, and Data Analysis The following items were included in the survey form.

6.1 Cost of owning/leasing GPR equipment

6.2 Cost of field operation (Based on number of scans per lane mile)

6.3 Cost of office data processing and analysis

6.4 Total field operating and office processing cost at 50 % annual use (from 6.2 and 6.3)

However, most of the responders did not answer the cost queries due to: (a) equipment cost variations depending on specific requirements of hardware and software options, (b) significant range of costs for field operations of data collection, office data processing, desired outputs, and length and scope of the project, (c) requirements for comparison of GPR results with independent coring and/or other evaluation method, and (d) cost for providing GPR data collection and analysis services generally considered privileged and confidential information.

Based on some responses, purchase cost of FCC-certified GPR equipment in the US varies significantly from $ 48,000 to around $100,000 depending on antenna type, hardware options, and software options. The cost data for pre-FCC regulation period is not relevant.

Cost for providing GPR data collection and analysis services is generally considered confidential; however, the following estimates are given by only 3 consultant-service providers from the US:

- $ 20-40 per lane mile for field data collection (depending on the survey volume per day).
- $100-150 per lane mile for office data processing and analysis (depending on the required outputs); $ 45 per lane mile is another estimate.

More discussion follows in Section 4.3.

7. <u>Cost-Effectiveness Estimate</u> The following items were included in the survey form.

7.1 Total owning & operating cost / Total number of lane miles surveyed and analyzed (from items 6.1, 6.2, and 6.3)

7.2 B/C Ratio: (Savings from enhanced FWD deflection data analysis due to accurate GPR-derived thickness data / Total cost of GPR data collection and interpretation)

Only Maser [75] provided the following estimates based on his long history as a GPR service-provider:

- Benefit/coat ratio is about 20-30 (based on a study for one DOT).
- GPR survey is not cost-effective for a very small section due to large mobilization cost.

8. User Preference See Table 9 for responses, generally found very effective.

Rating based on applications of data for asphalt pavement layer thickness, use with FWD data, and cost-effectiveness. (Rating scale 1-10, 10 being the best/most favorable and 1 being poor and not effective)

9. Overall Ranking See Table 9 for responses, not that effective for small sections.

Rating for 1 to 10 mile or longer 2-lane highway. (Rating scale 1-10, 10 being the highest rank and 1 being the worst)

Table 9. Responses to evaluation criterion 8, 9, and 10

Number	GPR Expert [reference]	8. User preference Rating (1-poor to 10-best)	9. Overall ranking Rating (1-worst to 10-highest)	10. Comments (see explanation below the table)						
				1	2	3	4	5	6	7
1	Tom Scullion [87]	10	9					Good, routine		
2	Carl Bertrand [88]	8	8							
3	Robert Parrillo [67]	10	10	Excellent	Excellent	Good	Fair	Good	Good	Fair
4	Gary Sanati [71]	9	9	Yes	Yes	Yes	Yes	Yes	Not sure	Not sure
5	Charles Holzschuher [72]	8	8	High	Yes	Yes	N?A	?	?	?
6	Kenneth Maser [75]	10	Not effective for small sections	V. Good	V. Good	V. Good	Good	Good	Good	Fair
7	Jerry Daleiden [74]	8	8	Good	Good	Depends	Depends	Effective	No data	Depends
8	Francisco Romero [76]	8 - 10	8 - 10	Excellent	Excellent	Excellent	V. Good	V. Good	Good	Site-specific
9	Carl D. Rascoe [78]	8	8	Possible	Possible	Possible	Possible	Possible	Possible	Possible
10	Robert Emfinger [77]	10	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11	Victor Torres-Verdin [79]	9	9	V. High	V. High				V. Low	Moderate
12	Timo Saarenketo [70]	9	9	Good Routine 1-4	Good	Good	Good	Good	Harder	Yes
13	James E. Cook [85]	None	None	High	High	High	High to Moderate	Moderate	Unknown	Unknown
14	Massimo Losa [80]	9	9	V. Good	Poor	Good	Good	Poor	None	None

10. Comments Table 9 summarizes responses to comments 1-7 for potential advanced application of GPR are.

1. Potential for determination of asphalt and other layers
2. Potential for thickness of asphalt layer(s)
3. Potential for thicknesses of asphalt and base layers
4. Potential for thicknesses of asphalt, base, and subbase
5. Potential for asphalt degradation
   (identify - stripping, asphalt content…etc.)

6. Potential for asphalt layer debonding
7. Potential for stabilized base/subbase layer degradation
8. Other: New 1-Ghz FCC certified (post FCC ruling) is not as effective as old antennas [74].

   All potential applications (comments 1 – 7) are possible with GPR; however, be cautious because GPR is site dependent [78].

4.3 Evaluation of Benefits and Costs

There are no recent published study on benefits and costs associated with statewide implementation of GPR and its applications with FWD testing. GPR surveys are certainly not cost-effective for small sections due to large mobilization cost and investment in proper training and data analysis expertise.

If pavement layer thickness results, determined from GPR data and used in conjunction with modulus backcalculation of FWD deflection data, suggest a recommendation of overlay thickness that sufficiently improves the performance of the pavement then that will warrant the use of the GPR. This could be manifested in one of two ways. If a recommended overlay thickness is less than that obtained without the use of GPR data then it can be shown that a saving in construction cost to the state would offset the cost of using the GPR. Conversely, if a recommended overlay thickness is more than that obtained without the use of GPR data then it can be shown that the reduction in pavement life resulting from an insufficient overlay thickness will result in greater cost to the state than the cost of routinely using the GPR.

All cost data related to the GPR testing, data interpretation, and overlay thickness design should be identified and compared with the savings which will be resulting from:

- Reduced number of cores required for accurate modulus backcalculation.
- Savings in construction cost due to possible reduction in overlay thickness.
- Benefits from improved performance or longer life that will also result in reduced user costs.

If possible, a realistic and reliable benefit/cost study should be performed in a future pilot study of GPR and FWD testing in Mississippi. The detailed data of pavement assessment, design, and cost from the pilot section should be used to estimate a benefit and cost ratio. The benefit is in the form of potential savings from improved pavement assessment and overlay or rehabilitation design. If one can reduce overlay thickness and associated costs by 10 %, that will directly result in 10 % reduced costs or benefit to the agency. This can show to the state that the benefit can offset the cost of using GPR for routine testing alongside FWD.

<u>CAIT's Analytical study of GPR Benefits and Costs</u> An analytical study was conducted for this project assuming accuracy of GPR based layer thickness ± 10 % of as-built record. Overlay thickness and benefit/cost ratios were calculated using the 1993 AASHTO overlay pavement design procedure. Assumptions and key findings are presented here for asphalt overlay design scenarios [88].

- <u>Assumptions</u>
    - 4-lane, 10 mile long asphalt highway
    - High truck volume trafficked highway
    - (27,500 vehicles per day with 20 % truck traffic at standard axle load equivalency of 1.0)
    - 35 million ESALs in 17.5 years (annual 2 million ESALs, 0% growth)
    - 95 % Reliability, 0.45 overall SD, design loss in PSI = 2.0, Poor condition pavement
    - 1-in. overlay cost (HMA material cost) = 80,000 / mile (+ 4 % for edges, $ 50/ton)
    - Assumed in-place M_r values (keeping constant); only layer thicknesses vary

      A (pavement) from as-built record of layer thicknesses;

      B (+ 10 % more) and **C** (– 10 %) from more accurate GPR data
    - GPR survey& analysis cost = about $ 5,000 for 10 miles @ $ 120 /lane mile; $ 10,000 maximum for 10 miles (excluding mobilization costs)

- <u>Results</u>

  Figure 19 shows the results of the overlay design study.
    - **B:** about 1 in. less thickness than the as-built data; $ 80,000 / mile savings or $ 0.8 million saved for 10 miles

- **C:** 1 in. more overlay thickness than the as-built data; 17.5 years life (life for underestimated **A** overlay layer thickness is only 5 years; or another overlay of 2.5 in. needed after 5 years);
  Cost savings for **C** = $ 2 million for 10 miles
- Benefit/cost ratio = 80 -200 (using $10,000 for cost of GPR survey)

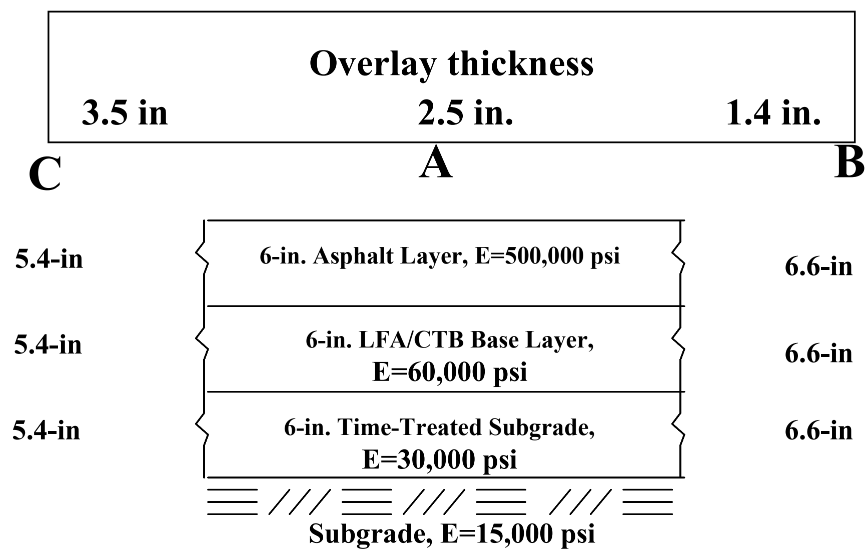


Figure 19. Overlay thickness results for ± 10 % more accurate GPR based layer thicknesses

- If pavement overlay thicknesses are the same then what is the GPR benefit? Numerous benefits are expected from subsurface condition assessment at an additional GPR cost of maximum $10,000 for 10 miles. These benefits are not available from FWD tests alone or from a few cores.
- Examples of GPR benefits:
  1. Removal of uncertainties associated with in situ layer thicknesses
  2. More accurate information on widened lanes and for no record of thin overlays
  3. Differences in asphalt layers based on composition, density, air voids
  4. Stripping assessment in asphalt mix layers; reduced layer coefficient
  5. Variations in treated base and subbase layers
  6. Based on these additional value-added subsurface data, a totally different overlay/rehabilitation design strategy may develop with longer pavement life

4.4 Discussion and Summary

The GPR technology survey, conducted in this study, shows the following highlights of experiences shared by the survey responders:

- Most users including Texas DOT/TTI have experience of GPR testing at highway speeds using 1-GHz horn antenna from pre-FCC ruling for maximum 24-inch thick pavements [37]. Experience with FCC certified 2-GHz horn antenna is limited; however, it is claimed for use up to 25 inch maximum asphalt thickness.
- Reasonable good accuracy for asphalt layer thickness has been reported within 2-5 % of constructed thickness. Accuracy is improved if some coring is used for calibration.
- The thickness accuracy of pavement sublayers depends on the reflection from the bottom of the layer. With significant reflection and transition in material properties, base layer thickness can have 5 % accuracy. In general base layer thickness has been reported within 5-10 % accuracy, and subbase layer accuracy has been reported within 10-20 %.
- None of the available GPR horn antennas, including FCC-certified GSSI's 1-GHz and 2-GHz and all other "grandfathered" GPR equipment, has been successfully used for (a) evaluating asphalt pavements deeper than 24 inch, (b) discriminating an asphalt treated drainage layer from surface asphalt layer, (c) identifying cement stabilized base, and (d) characterizing lime-treated subgrade. These issues are important for any future study of GPR for asphalt pavement evaluation in Mississippi.
- About 80-200 benefit/cost ratio was estimated for asphalt overlays as a result of ± 10 % more accurate GPR based layer thicknesses.

5. ADAPTING GPR FOR PAVEMENT EVALUATION IN MISSISSIPPI

5.1 Asphalt Highway Pavement Structures in Mississippi

Typical Asphalt Highway Pavements

Due to scarcity of rock materials in Mississippi, traditional unbound granular or flexible base materials are generally not used in pavement construction. Instead, stabilized bases are constructed using locally available soils treated with cement, lime, or lime-flyash. Historically, cement-treated base (CTB) and lime-flyash (LFA) base has been used on numerous asphalt highway projects. In the mid to late 1990's several asphalt pavements showed signs of early failures due to (a) saturated base/subbase/subgrade problems and (b) problems with LFA base performance resulting from slow strength gain due to saturation at an early age. Many such problematic pavement sections were evaluated in forensic studies by MDOT using trench examination and FWD testing for in situ modulus values. It was also observed that newer Superpave asphalt mixes showed higher permeability and possibility of migration of portions of rainwater through the pavement and into the base/subbase and subgrade [89].

In the MDOT state study 122 [89] these asphalt pavements were investigated extensively with respect to backcalculated modulus values from FWD deflection data. The study showed high variability in LFA base modulus and granular subbase modulus values (up to 71 %) and always 15-25 higher coefficient variability than the subgrade in most sections. Some other sections showed no significant difference in LFA base or untreated base/subbase layer and the underlying subgrade. The study confirmed the problems with the constructability and poor performance of LFA base once it is allowed to saturate. During the past few years MDOT has adopted a policy to chemically treat the top 6 inches of subgrade soils on all highway projects [90]. It can be lime, lime/flyash, or cement depending on soil types. This policy should ensure better bearing capacity of the subgrade. For any nondestructive pavement assessment project using FWD data, 6-inch thickness is usually assumed for the chemically-treated subgrade layer.

Asphalt layer generally consists of a surface wearing course above asphalt binder course(s) with different mix compositions and asphalt contents. More recently, a drainage layer (asphalt treated aggregate) is being constructed below asphalt layer on 4-lane highway projects [91]. These new construction strategies should reduce some of the problems experienced in the past due to saturation of base, subbase, and subgrade.

Based on these studies and pavement construction practices, typical asphalt highway pavement structures constructed in Mississippi are described in Table 10 [89, 90]. Hot-mix asphalt (HMA) layer generally consists of a surface wearing course above an asphalt binder course with different mix compositions and asphalt contents. A drainage layer constructed below the asphalt layer will add another 4 inches in the pavement structure [91], as described in the following section.

Table 10. Typical asphalt highway pavement structures in Mississippi [89, 90, 91]

Note 1: Layer 1 is surface asphalt layer (combined wearing and binder courses).

Note 2: Cement-Kiln-Dust (CKD) was used with LFA on experimental sections of US45ALT.

Pavement structure (Layer Thicknesses) Note 1				Highway, (Year of Study)	County	Total Thickness above subgrade
Layer 1 Hot Mix Asphalt	Layer 2 Base	Layer 3 Subbase	Layer 4 Top of Subgarde			
6.5 in. HMA	6 in. LFA	-	-	US 45, Project 97-0002-03-070-10, (1997)	Noxubee	12.5 in.
2.5 in. HMA	6 in. LFA	9 in. Granular	-	SR6 W, Project 26-0070-05-012-10, (1997)	Pontotoc	17.5 in.
10.5 in. HMA	6 in. CTB	-	-	MS 6 E (LTPP section)	Lafayette	16.5 in.
5.7 in. HMA	8.6 in. LFA	-	6 in. Lime-treated	SR 25 S, SS131 Study (average core thicknesses)	Rankin	20.3 in.
7.5 in. HMA	6 in. LFA/ CKD	6 in. Granular	6 in. Lime-treated	US 45 ALT N, CKD Study (1998) Note 2	Monroe	25.5 in.
3.0 in. Overlay 10.5 in. Old HMA	6 in. CTB	-	6 in. Lime-treated	I-55 N, Polymer-modified asphalt study (1998)	Grenada, Yalobusha	25.5 in.
10.0 in. HMA	4 in. Drainage 6 in. CTB	-	10 – 14 in. Lime-treated	US 45-ALT, candidate for GPR study (2006)	Lownes	30 - 34 in.

Typical total thickness of asphalt highway pavement structure above the subgrade ranges from 13 – 34 inches, as shown in Table 10. Some of the uncertainties in modulus backcalculation results arise from assumed (design) thicknesses of pavement layers, particularly base, subbase, and lime-treated subgrade layers. A better estimation of thickness of all pavement layers representing in situ conditions close to each FWD test station will significantly improve the accuracy of in situ modulus values and overlay thickness design.

Candidate Asphalt Pavement Section for Future GPR Evaluation

The MDOT Research Division has identified the following asphalt pavement section (30-34 inches thick) for a pilot GPR study [91].

Going from top to bottom of the pavement (U.S. Highway 45-A) in Lownes County:

10 inch of HMA consisting of: (asphalt surface wearing and binder courses)

2" thick HMA with 12.5 mm crushed gravel aggregate - polymer modified

5" thick HMA with 19 mm crushed gravel aggregate – top 2.5 " lift polymer modified

3" thick HMA with 25 mm crushed gravel aggregate

4 inch thick drainage layer: MDOT #57 crushed limestone aggregate with 2.5% asphalt binder content. This is passing 1.5 in. and retained # 8 sieve predominantly course aggregate material.

6 inch soil cement layer (CTB layer)

Cement content varies from 5 to 6 % depending on borrow pit. The MDOT Central laboratory uses 300 psi of 4-inch Proctor size specimens for base course application.

10 – 14 inch lime treated subgrade layer)

The original thickness of lime treated subgrade was 10 inch, but in certain segments of the road it was increased to 14 inch. That was done in one lift, so the bottom part may have lesser densities. The MDOT Central laboratory requires a soaked CBR of 20 to determine the amount of lime to be added to the soil.

The subgrade is a clay soil (gumbo).

This pavement section is very thick (30 – 34 inches) compared to other typical asphalt highway pavement with 13 – 26 inch total thickness above the subgrade, as shown in Table 10.

5.2 GPR Technology Specifications and Cost Issues

As shown in Table 3 and Tables 6-8, many GPR service providers and owners use GSSI GPR systems for highway pavements. The JILS-FWD's integrated GPR equipment includes GPR data acquisition RADAN software and 2-GHz horn antenna from GSSI [67, 71]. The Florida DOT has recently purchased a GSSI GPR system of two 2-GHz horn antennas with a full suite of GSSI software at a cost of over $100,000 [72].

Based on the review of GPR theory and analysis method and GPR survey results, it is obvious that two major factors will influence the decision to select appropriate antenna frequency and to use one or more GPR antennas. These factors are: (1) resolution needed in layer thickness and (2) depth of penetration required or total pavement thickness. For pavements thicker than 24 inches where all pavement layers need to be assessed, it may not be possible by using only one high frequency (1 GHz or 2 GHz) antenna. A second lower frequency 400 or 500 MHz ground-coupled antenna may be critical to assess lime-treated subgrade layer at a depth of 24 or 30 inches. These factors should be considered when selecting appropriate GPR antenna for determining pavement layer thickness and condition of layer materials.

A detailed specifications document should be prepared to procure GPR testing service for a potential pilot test site that must include the TTI performance specifications for antenna acceptance. The specification must also state the antenna to be FCC complaint or “grandfathered”. In the scope of the pilot study the concern should be to invite bids on $ per lane mile for the length of the site and scope of testing including the typical cross section of the selected pavement structure and required outputs of each layer thickness and condition.

5.3 Selecting Appropriate GPR Antenna

From theoretical perspectives 1-GHz antenna has the ability to resolve up to one-inch thickness. 1-GHz antenna signals penetrate approximately 24 inches. This review and the technology survey results show that GPR users have experience with 1-GHz horn antenna for pavement depth 24-36 inches [37, 42, 70]. Penetration depth depends on the dielectric properties of pavement layers which are significantly influenced by moisture and temperature changes. Experience with 2-GHz horn antenna is limited; however, it is claimed for use up to 30 inch maximum asphalt thickness [67].

On the other hand, ground-coupled antennas are all mono-static dipole antennas configured for ground coupling only. They can normally work non-contact within 1-2 inch above the ground. However, results are best when ground coupled. Some times a ground-coupled unit is combined with an air-coupled antenna in countries that have very thick pavement structures. Such as Finland where the pavement structure can be over 1 m thick (due to frost protection layers). The ground-coupled antenna measures deeper layers and air-launched measures upper layers. GSSI recommends its ground-coupled antenna only in that mode and not 1-2 inch above ground [67].

Only some of the reviewed references show limited data for comparisons of thicknesses of base and subbase layers below the asphalt layers, particularly for thicker than 24-inch pavements. Degradation of lime-flyash stabilized base/subbase layers and lime treated subgrade below the structural pavement layers is known on highway pavements in Mississippi. Careful considerations should be given to the selection of GPR antennas for a pilot field study due to the expected high variability in lime treated layers and relatively thicker than 24-inch asphalt pavements, such as the 30-34 inch thick candidate pavement section described in Table 10.

For future pilot field study, the effectiveness of antenna frequency to penetrate full pavement depth should also be considered so that reliable information on GPR-derived thicknesses of base and other sublayers are collected and compared to measurements of independent core and/or borehole depth. For very thicker pavements (30 inch or more) a higher frequency antenna (1 or 2 GHz) may be beneficial to get reliable information for pavement layers above the subgrade and a lower frequency (400 or 500 MHz) antenna to penetrate to lower layers, such as the lime treated subgrade used in Mississippi. The specification must state the antenna to be FCC complaint or “grandfathered”.

A careful review of Table 8 shows that each responder is knowledgeable only about in-house or owner developed GPR data analysis software, and that applies to their stated experience related to (a) ease of interpretation and (b) accuracy of thickness of asphalt and other layers. The only exception is the RoadDoctor software which is also available commercially and being used by more than one consultant-service providers. However, data from other different sources must be properly formatted for use as input to the RoadDoctor software, which makes it harder to use by a highway agency.

5.4 Plan for Phase II Study

There is adequate experience available with data interpretation methodologies and FCC certified or “grandfathered” GPR antenna technologies for reliable and reasonably accurate field assessment of layer thicknesses of asphalt pavement. It has been established that GPR provides site-specific information; and the depth of penetration and layer resolution depends on the horn antenna frequency. It is shown that a benefit/cost ratio of 80-200 can be achieved by using GPR for measuring accurate layer thicknesses.

Next, if a decision is taken by MDOT to approve a phase II and conduct a pilot study then a detailed bid document should be prepared for GPR testing services for the selected pilot test site with the following information:

- Scope and specifications to procure GPR testing service by a service provider alongside FWD testing by MDOT. A detailed specifications bid document should include; (a) a typical pavement structure of the potential pilot test site, (b) the TTI performance specifications for antenna acceptance, (c) a statement that the antenna should be FCC complaint or “grandfathered”, and (d) details of required graphics and spreadsheet output results.
- GPR testing plan. To ensure site-specific data quality, MDOT should specify one pass of GPR scan at highway speed and a second pass at a lower speed during side-by-side testing with FWD to cover 30-50 % scans at exact locations of FWD tests. This replicate data can also be used to verify repeatability errors.
- Randomly selected locations of about 6-12 cores extraction by MDOT in each layer of asphalt, asphalt treated drainage layer, stabilized sublayer, and lime-treated subgrade. (Up to 4 -6 cores can be used for GPR calibration, the rest can be used for independent evaluation of the GPR thickness results. Some of these can be used using independent tests to verify and fine-tune typical dielectric constant and EM wave velocity values.)
- FWD evaluation of structural assessment by MDOT using GPR-surveyed thickness profile data and the ELMOD program for modulus backcalculation and overlay thickness design. Comparisons of these results should be made with the overlay designs using only construction data and limited core data for layer thicknesses.
- A database of all costs and calculated benefits of reduced agency construction cost and user costs. This will help to calculate a benefit/cost ratio considering GPR operation costs.

- Assessment of GPR evaluation and lesson learnt to: (1) enhance structural evaluation of pavements in Mississippi and (2) assess performance of GPR in the field (reduced coring, repeatability, 1-GHz vs. 2-GHz, additional costs and savings.
- Upon successful results and validation of improved pavement evaluation and resulting potential cost savings, the MDOT may consider implementing the GPR technology for routine use.

6. CONCLUSIONS AND RECOMMENDATIONS

An extensive literature review of the GPR technology for asphalt pavement layer thickness evaluation was conducted using online library resources of the university, interlibrary loan services, TRB reports and papers, and additional Internet searches. Over 60 references were studied for GPR applications and the reliability of their interpreted results. Additionally, a detailed GPR technology evaluation survey form was developed. This survey form and /or telephone interviews and e-mail communications were used for obtaining inputs of GPR experts on pavement evaluation, manufacturers, service providers, and DOT agencies.

The study consultants also prepared their expert review reports with special emphasis on the studies conducted in Texas and provided survey feedbacks. Several models of GPR were evaluated by the consultants during the 1990's and implemented for the TxDOT on asphalt pavement evaluation projects to provide thickness data of asphalt layer and sublayers. The layer thickness results have been used for reliable backcalculation of pavement layer modulus values.

6.1 Conclusions

The following conclusions are based on the literature review of published reports, Internet sources, related information collected through the GPR survey form and personal contacts by CAIT, and reports of study consultants.

1) GPR technology provides a nondestructive measurement tool for the structural evaluation of AC pavements. The data collection is fast using a van mounted horn antenna and usually does not involve traffic control. The data analysis is at best semi-automated and is dependent on the software being used. Structural anomalies are relatively easy to detect but detailed analysis requires expertise in both GPR signal analysis and pavement materials.

2) The GPR data acquisition equipment including the antenna is generally considered reliable, accurate, and repeatable by most survey responders and in published reports. Typical GPR equipment costs \$ 48,000 to 100,000 depending on specific requirements of antenna, vehicle installation, and data analysis software options.

3) Currently only GSSI produces FCC certified horn antennas in the operating frequencies of 1-GHz and 2 GHz for pavement evaluation. These antennas are compliant with the FCC Part 15 regulations of 15 July 2002 for radar devices operating in the ultrawide band. Older GPR devices operating around 1 GHz were given the opportunity to be "grandfathered" by the FCC prior to 15 October 2002.

4) At present GSSI model SIR-20 is the most widely used GPR system in the United States and abroad. Its new 2-GHz air-launched horn antenna model 4105 has been developed specifically for FCC compliance, which provides better quality and less noisy scans. GSSI has stated that its 1-GHZ and 2-GHz FCC certified horn antennas have been tested for noise and repeatability under the TTI performance specifications. The TTI specifications have been recently used by the Florida DOT to purchase GSSI's 2-GHz horn antennas.

5) It is known that the FCC certified 1-GHz horn antenna GSSI model 4108F has smaller radiated output power, which results in more noisy scan data when compared to the data generated by the older "grandfathered" 1-GHz horn antenna models. The older GPR devices from pre-FCC ruling days can be used only by their owners, such as the older Pulse Radar equipment operated by the TxDOT and consultants, as well as the older GSSI model 4108 used by consultants, if these devices have been properly registered with the FCC prior to 15 October 2002.

6) The GSSI's Radan scanning data software processes radar and DMI data, and it is generally considered reliable. The generated ASCII data output file can be easily used by FWD analysis program or any other software. GSSI's SIR-20 system supports an optional GPS signal capture connection and fully supported by the RoadDoctor software from RoadScanners. Some service providers/re-sellers provide additional capabilities of collecting GPS location positioning data and synchronizing with GPR data, as well as on-vehicle digital image or video captures, and FWD data. Examples are: the Road Doctor software from Road Scanners and the TxDOT GPR system software. Foundation Mechanics, Inc has integrated their truck-mounted JILS-FWD with SIR-20 GPR system and 2-GHz antenna.

7) Fast collection of the field data is possible because the GPR equipment is mounted on the survey van and it can be operated at the posted highway speed. For example, a 10-mile scan can be completed in a few hours including mobilization to the site and some stops if coring or FWD tests are required at the same time on selected stations. For network-level survey 200 miles or more have been scanned per day in Texas. This time estimate does not include GPR data analysis. Data analysis can take a few minutes to several hours depending on the complexity of the pavement structure and the anomalies to be detected.

8) Traffic control is generally not needed for routine continuous operation. Typical scanning rate can vary from 1 GPR scan per ft to one scan every 10 ft at the posted speed depending on the application and resolution required. Shorter scanning intervals will collect large data files and require automated signal interpretation.

9) The GPR scanning in the field can be sensitive to noise interference from passing vehicles, radio and CB transmissions, RF signals near airports, cell phones, and other facilities producing radio signals (radio stations, hospitals, military facilities, microwave towers, and high energy transmission lines, etc.). Cell phones, operating at 900 MHz, may not work in the vicinity of GPR and may interfere with GPR scanning quality.

10) Environmental operating constraints are rainfall, freezing weather, and standing water, as well as deicing salt on the pavement.

11) Most current software packages are user-driven and have color outputs with significantly improved data interpretation compared to older analysis programs used in the 1980's and early 1990's. Examples of currently used software include GSSI's Road Structure Assessment module for RADAN, COLORMAP developed by Texas DOT/TTI, Infrasense's PAVLAYER and winDecar, RoadScanners' RoadDoctor, EPIC's in-house software, and Lytton's patented software. There is no independently proven software for fully automated GPR data analysis.

12) In-house office data processing and analysis requires significant investment in training 2-3 dedicated persons on the selected software. Considerable training and pavement evaluation experience is essential as well as periodic professional development opportunities in related conferences and refresher courses.

13) A careful review of the GPR technology survey shows that each responder is knowledgeable only about in-house or self-developed GPR data analysis software, and that applies to their stated experience related to (a) ease of interpretation and (b) accuracy of thickness of asphalt and other layers. The RoadDoctor software, available commercially, is being used by some consultant-service providers. However, data from different sources must be properly formatted for input.

14) The interpretation productivity is site-specific. It depends on the pavement structure, pavement condition, and type of diagnostic information needed. Less than an hour has been reported for a 10-mile long pavement in good condition that requires only bound pavement thickness. Up to 30 minutes per 1-mile section has been reported for detailed data analysis time.

15) Reasonably good accuracy for asphalt layer thickness has been reported within 2-5 % of constructed thickness, 5 % with no validation core. Accuracy is improved if some coring is used for calibration. The 1-GHz units have been widely used and the maximum effective depth of penetration has been reported by TxDOT to be 24 inches, with the ability (with signal processing) to resolve surface layers down to one inch thickness. Experience with the 2-GHz equipment is limited; however, the depth of penetration will be less than the 1-GHz systems and the layer resolution should be better. The 2 GHz equipment can reportedly discriminate up to 1-in thickness; it has been used to evaluate up to 25-in thick pavements.

16) The thickness accuracy of pavement sublayers depends on the reflection from the bottom of the layer. If there is not a significant reflection as is sometimes the case for older pavements then GPR cannot be used to obtain base and subbase layer thickness. GPR reflections only occur if the layers are electrically different and if there is a clean transition from one layer to the next. When significant reflections are present in the GPR data the base layer thickness can have 5 % accuracy. In general base layer thickness has been reported within 5-10 % accuracy. Similarly, subbase layer accuracy has been reported around within 10-20 % accuracy.

17) More accurate pavement layer thickness will enhance the modulus backcalculation results from FWD defection data, which will also improve the accuracy of overlay

thickness design. Most users recommend the integration of FWD and GPR testing. Examples are PAVECHECK software developed by the TxDOT/TTI and RoadDoctor software that provides output for use with the ELMOD modulus backcalculation program. Dynatest's ELMOD version 5 program can read Dynatest's formatted ASCII data file for FWD stations and associated GPR layer thicknesses for up to four layers above the subgrade.

18) GPR data can also be used as a diagnostic tool to ascertain the condition of each of the layers in a given pavement structure. It requires specialized procedures in the data analysis software. GPR data interpretation has been used to identify asphalt stripping, air voids, moisture-related degradation in base and subbase layers. It has been found very useful for forensic investigations. It has also been used to locate areas of de-lamination of asphalt covered bridge decks.

19) Some of the uncertainties in modulus backcalculation results arise from assumed (design) thicknesses of pavement layers, particularly base, subbase and lime-treated subgrade layers. A better estimation of thickness of all pavement layers representing in situ conditions close to each FWD test station will significantly improve the accuracy of in situ modulus values.

20) Only some of the reviewed references show limited data for comparisons of thicknesses of base and subbase layers below the asphalt layers; only one study gives information on lime-treated subgrade layer thickness. In any future pilot field study on thicker pavements (30 inch or more), this factor should be considered to select appropriate antenna frequencies so that reliable information on GPR-derived thicknesses of base and other sublayers are collected and compared to measurements of independent core and/or borehole depth.

21) CAIT's analytical study for benefit/cost evaluation was conducted assuming the accuracy of GPR based layer thickness to be ± 10 % of the as-built record. Overlay thickness and benefit/cost ratios were calculated for a 10-mile long 4-lane asphalt highway section. A benefit/cost ratio of 80-200 was calculated.

6.2 Recommendations

The following recommendations are based on the favorable results of Phase I study as summarized in the conclusions:

1) GPR technology is strongly recommended for asphalt pavement evaluation in Mississippi by using a non-contact horn antenna. FCC certified 2-GHz and/or 1-GHz horn antenna and "Grandfathered" 1-GHz devices can be allowed to compete in a pilot field study if MDOT decides to contract out GPR services. Several service-provider companies have been identified including some companies in our region.

2) A Phase II study is warranted based on the results of this Phase I study. In Phase II detailed GPR specifications and cost estimates should be developed. The provisional AASHTO PP40-00 test standard as well the experience of neighboring states such as TxDOT, Louisiana DOTD, and Florida DOT can be used as good source for specifications and guidelines. Samples of bid specifications and cost data on recent GPR projects have been collected already to estimate a reasonable budget.

3) The Phase II study should consist of two parts:

    - Part 1 ─ A pilot field study on a selected site

      MDOT should assign a research team to develop objectives and scope of work, antenna and detailed job specifications, cost estimates for GPR testing contract, MDOT in-house costs (for FWD testing, coring and boring, required traffic control), and timeline. The study should include both 1-GHz and 2-GHz horn antennas, as well as a comparison of new vs. old 1-GHz horn antennas.

    - Part 2 ─ Independent evaluation and implementation of GPR

      The research team will conduct independent evaluation of GPR results for pavement layer thicknesses by comparing with cores and site observations, use the thickness profile data with FWD data to backcalculate modulus values of pavement layers and subgrade, and perform overlay design as well as benefit/cost analysis. The results will be used to justify routine implementation of GPR with FWD testing. The need for procuring in-house capability will be evaluated.

4) The pilot field study should be conducted involving side-by-side GPR and FWD testing on a selected highway section of a reasonable length of 10-15 miles. One candidate section selected by MDOT is Highway 45 Alt in Lownes County, Mississippi. This pavement section is 30-34 inch thick.

5) The field evaluation should include a comparison of the 1-GHz and 2-GHz horn antenna systems; concerns exist about the depth of penetration of the 2GHz systems. A lower frequency ground-coupled antenna may also be desirable considering the 30-34 inch thick pavement and the need to estimate the bottom lime-treated subgrade layer. One of the components of GPR will be a second scan at posted highway speed to assess repeatability errors and routine field productivity.

6) A minimum number of pavement cores should be required to validate layer thickness data derived from GPR for Phase II study. A precise standard procedure must be adapted for making multiple core thickness measurements and taking an average because very high (2-5 %) thickness accuracy of asphalt layer is desirable.

7) The identified test section is very thick (30-34 inches). Most highway pavements in Mississippi consist of a thick surface asphalt layer (wearing and binder courses) over an asphalt treated drainage layer paved above stabilized base/granular subbase that is constructed over lime-treated subgrade. Typical total pavement thickness range from 13 to 30 inches above the subgrade. The field pilot study should be able to evaluate the capabilities of the current technology with regard to layer resolution and depth of penetration. The extent of expected layer information from GPR and its use with FWD data analysis needs to be examined.

8) The degree of specialized skills and training needed for GPR data analyses requires the services of an expert in this area and dedicated analysis software. These issues should be considered in the Phase II budget estimate.

9) A two-day trip by Bob Briggs of Dynatest should be budgeted in Phase II for training of MDOT staff and research team to (a) create the Dynatest formatted GPR layer thickness data file, (b) using it with the ELMOD version 5 software for modulus backcalculation computations, and (b) training on selected set of real data collected in the pilot study.

10) All cost data related to the GPR testing, data interpretation, and overlay thickness design should be identified and compared with the savings which will be resulting from (a) reduced number of cores required for accurate modulus backcalculation, (b) savings in construction cost due to possible reduction in overlay thickness, (c) savings in reduced user costs due to longer life pavements. These cost data for the pilot section can be used to estimate a benefit and cost ratio and to show to the state that the benefit can offset the cost of using the GPR. In developing the GPR costs a comparison should be made of purchasing GPR equipment for collecting the data in house or via contracting-consulting services.

11) If GPR surveys can improve the reliability of pavement layer thickness and subsequently the analysis of FWD deflection data then improved overlay design and rehabilitation strategies can be produced that may result in substantial cost savings. This can result in achieving the objective of enhanced pavement assessment at reduced costs and longer life of appropriate rehabilitation strategies.

7. REFERENCES

[1] Hironaka, M.C., R.D. Hitchcock, and J.B. Forrest. "Detection of Voids Underground and Under Pavements." *Report No. CEL-TN-1449*, Naval Civil Engineering Laboratory, Port Hueneme, California, August 1976.

[2] Kovacs, A. and R.M. Morey. "Detection of Cavities Under Concrete Pavement." *Report No. CRREL 83-18*, Cold Regions Research and Engineering Laboratory, Department of the Army, July 1983.

[3] Steinway, W. J., J.D. Echard, and C.M. Luke. "Locating Voids Beneath Pavement Using Pulsed Electromagnetic Waves." *National Cooperative Highway Research Program Report 237*, Transportation Research Board, Washington, D. C., USA, 1981.

[4] Evaluation of a Ground Probing Radar Device for Detecting Voids Within and Beneath Concrete, State of California Department of Transportation, April 1985.

[5] Donohue Engineers & Architects, "Remote Sensing" brochure, Sheboygan, Wisconsin, 1983.

[6] Gulf Applied Radar, Equipment Bulletins-RODAR, Gulf Applied Research, Marietta, Georgia, 1987.

[7] Clemena, G.G., M.M. Sprinkel, and R.R. Long, Jr. "Use of Ground-Penetrating Radar for Detecting Voids Underneath a Jointed Concrete Pavement." Final Report, Virginia Highway and Transportation Research Council in Cooperation with the U.S. Department of Transportation, Federal Highway Administration, May 1986.

[8] Uddin, W., W.R. Hudson, G.E. Elkins, and K.T. Reilley. "Evaluation of Equipment for Measuring Voids under Pavements." *FHWA-TS-87-229,* Federal Highway Administration, McLean, Virginia, USA, 1987, pp. 488-502.

[9] Uddin, W., and W.R. Hudson. "Evaluation of NDT Equipment for Measuring Voids under Concrete Pavements Evaluation of Equipment for Measuring Voids under Concrete Pavements." *ASTM STP 1198,* Nondestructive Testing of Pavements and Backcalculation of Moduli (Second Volume), Philadelphia, USA, 1994, pp. 488-502.

[10] Benson, K.T., G.E. Elkins, W. Uddin, and W.R. Hudson. "Comparison of Methods and Equipment to Conduct Pavement Distress Surveys." Transportation Research Record 1196*,* Journal of Transportation Research Board, Washington, DC, 1988, pp. 40-50.

[11] Morey, R.M., J.M. Armaghani, R. Berntein, C. Bertrand, G.G. Clemena, G.P. Jayaprakash, P.A. Kopac, G.R. Olhoeft, G.J. Rix, G. Robson, and J. Springer. "Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities." *NCHRP Synthesis of Highway Practice 255,* National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C., USA, 1998.

[12] Saarenketo, T. and T. Scullion. "Road evaluation with ground penetrating radar." Journal of Applied Geophysics, vol. 43, 2000, pp. 119-138.

[13] Sirles, P.C. "Use of Geophysics for Transportation Projects." *NCHRP Synthesis of Highway Practice 357,* National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C., USA, 2006.

[14] Uddin, W. "Diagnostic Evaluation and Performance Study of Portland Cement Concrete Pavements in Mississippi." *Report No. FHWA/MS-DOT-RD-99-110*, Prepared by the University of Mississippi for the Mississippi Department of Transportation, August 1997, Published in November 1999.

[15] ASTM. "Standard Test Method for Determining Thickness of Bound Pavement Layers Using Short Pulse Radar." *D4748-98*, 1999 *Annual Book of ASTM Standards,* pp. 470-473.

[16] Maser, K.R. "Use of Ground Penetrating Radar Data for Rehabilitation of Composite Pavements on High Volume Roads." *Paper 01-157, CD Proceedings,* Second International Symposium On Maintenance And Rehabilitation Of Pavements And Technological Control, Auburn, Alabama, USA, 2001.

[17] Maser, K.R. "Evaluation of bridge decks and pavements at highway speed using ground-penetrating radar." *Proc. SPIE Vol. 2456*, p. 237-248, Nondestructive Evaluation of Aging Bridges and Highways, Steve B. Chase; Ed. 05/1995.

[18] Maser, K.R., T. Scullion, and R.C. Briggs. "Use of radar technology for pavement layer evaluation." Presented at International conference on Asphalt Pavements 02/1991, 1992.

[19] Saarenketo, T. "Using Ground Penetrating Radar and Dielectric Probe Measurements in Pavement Density Quality Control." *Transportation Research Record 1575*, Transportation Research Board, Washington, DC, 1997, pp. 34-41.

[20] Scullion, T. and T. Saarenketo. "Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials." *Transportation Research Record 1577*, Transportation Research Board, Washington, DC, 1997, pp. 37-44.

[21] Wells, Abigail K. and R.L. Lytton. "Ground Penetrating Radar For Measuring Pavement Layer Composition And Void Detection." *Paper 01-161, CD Proceedings,* Second International Symposium On Maintenance And Rehabilitation Of Pavements And Technological Control, Auburn, Alabama, USA, 2001, pp. 141-156.

[22] Zhao, Zhiyong and J.P. Mohsen. "Using Ground Penetrating Radar Technology To Locate Subsurface Voids Below Pavements." *International Journal of Pavements, IJP 2005*, Volume 4 Number 1-2, January-May 2005, pp. 63-71.

[23] Noureldin, A. Samy, Karen Zhu, Shuo Li, and Dwayne Harris. "Network Pavement Evaluation Using Falling Weight Deflectometer and Ground Penetrating Radar." *TRB 2003-000253*, 82nd Annual Meeting Transportation Research Board, Washington, D.C., USA, 2003.

[24] Hammons, M.I., K. Maser, and S. Nazarian. "Detection of Stripping in Hot Mix Asphalt." *Final Report*, Applied Research Associates, Prepared for Georgia Department of Transportation, March 2005.

[25] Hubbard, S. S., J. E. Peterson, Jr., E.L. Majer, P.T. Zawislanski, K.H. Williams, J. Roberts, and F. Wobber. "Estimation of permeable pathways and water content using tomographic radar data." *The Leading Edge*, 16, 1623-1628, 1997. http://cgiss.boisestate.edu/~billc/dielec.html

[26] Olhoeft, G.R. and S.S. Smith III. "Automatic processing and modeling of GPR data for pavement thickness and properties." *Proceedings of SPIE*-The International Society for Optical Engineering, v 4084, 2000, pp.188-193.

[27] Reppert, P.M., F.D. Morgan, and M.N. Tosoz. “Dielectric constant determination using ground-penetrating radar reflection coefficient.” *Journal of Applied Geophysics*, vol.43, 2000, pp. 189-197.

[28] Maierhofer, C. “Nondestructive Evaluation of Concrete Infrastructure with Ground Penetrating Radar.” *Journal of Materials in Civil Engineering*, ASCE, Volume 15, Issue 3, May/June 2003, pp. 287-297.

[29] Adcock, A.D., W.C. Dass, and J.W. Rish. “Ground-penetrating radar for airfield pavement evaluations.” *Proc. SPIE Vol. 2455*, p. 373-384, Nondestructive Evaluation of Aging Aircraft, Airports, Aerospace Hardware, and Materials, Tobey M. Cordell; Raymond D. Rempt; Eds. 07/1995.

[30] Arbeitsanleitung fuer den Einsatz des Georadars fuer die Gewinnung von Bestandsdaten des Fahrbahnaufbaus unter Beruecksichtigung zusaetzlicher Georadarmessungen insitu, Allied Associates Geophysical Ltd, Buero Deutschland, Dorsten (DEU), 2002/09. 4S+Anh., 2002.

[31] Jaselskis, E.J., J. Grigas, and A. Brilingas. “Dielectric Properties of Asphalt Pavement.” *Journal of Materials in Civil Engineering*, ASCE, Sep./Oct. 2003, pp. 427-434.

[32] Hothan, J. and M. Foester. “Gültigkeit der mit dem Ground Penetration Radar" (GPR) ermittelten Schichtdicken“ *Fachgebiet Konstruktiver Straßenbau*,Universität Hannover, October 2000.

[33] Zhou, C. and L. Liu. “Simultaneous inversion for velocity and attenuation.” Proceedings of SPIE-The International Society for Optical Engineering, v 4084, pp. 514-518, 2000.

[34] *GSSI Handbook*. Geophysical Survey Systems, Inc, North Salem, NH, USA, 2003. www.geophysical.com

[35] Bulyukozturk, O. “ Electromagnetic Properties of Concrete and Their Significance in Nondestructive Testing.” *Transportation Research Record 1574*, Transportation Research Board, Washington, DC, 1997, pp. 10-17.

[36] Bertrand, C. “ Texas Department of Transportation Experience Using Ground Penetrating Radar Systems.” *Spectral Measurements, LLC Report*, Prepared for Center for Advanced Infrastructure Technology – University of Mississippi (Mississippi Department of Transportation GPR Phase I Study), May 2006.

[37] Scullion, T. “Ground Penetrating Radar (GPR) Technology Review and Evaluation Report.” Prepared for Center for Advanced Infrastructure Technology – University of Mississippi (Mississippi Department of Transportation GPR Phase I Study), May 2006.

[38] Scullion, T. and Y. Chen. “COLORMAP Version 2 User's Guide with Help Menus.” *Research Report 1702-4*. Texas Transportation Institute, College Station, TX. Nov 1999.

[39] AASHTO. “Application of Ground Penetrating Radar (GPR) to Highways.” the draft *AASHTO specifications PP 40-00*.

[40] Liu, W. and T. Scullion. “PAVECHECK: Integrating deflection and GPR Data for Pavement Evaluation.” *TTI Report 4495-1*, Feb 2006.

[41] Hugenschmidt, J., M.N. Partla, and H. de Witteb. “GPR inspection of a mountain motorway in Switzerland.” Swiss Federal Laboratories for Materials Testing and Research,

EMPA, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland, Canton Uri, Building and Construction Department, 6460 Altdorf, Switzerland, 1998.

[42] Sener, J.C., R.M. Smith, M.D. Garz, G.A. Murgel, R.W. Hamilton, and D.R. Haws. "Pavement thickness evaluation by GPR survey in Idaho." *Proc. SPIE Vol. 3400*, Structural Materials Technology III: An NDT Conference, Ronald D. Medlock; David C. Laffrey; Eds., 03/1998, pp. 236-249.

[43] Kurtz, J.L., J.W. Fisher, G. Skau, J. Armaghani, and J.G. Morley. "Advances in ground-penetrating radar for road subsurface measurements." *Proc. SPIE Vol. 3066*, p. 11-21, Radar Sensor Technology II, Robert Trebits; James L. Kurtz; Eds. 06/1997.

[44] Gordon, M.O., K. Broughton and M.S.A. Hardy. "The assessment of the value of GPR imaging of flexible pavements." NDT Group, Department of Civil and Environmental Engineering, The University of Edinburgh, Crew Building, King's Buildings, Edinburgh EH9 3JN, UK, January 1999.

[45] Roimela, P., S. Salmenkaita, P. Maijala, and T. Saarenketo. "Road analysis: a tool for cost-effective rehabilitation measures for Finnish roads." *Proc. SPIE Vol. 4084*, Eighth International Conference on Ground Penetrating Radar, David A. Noon; Glen F. Stickley; Dennis Longstaff; Eds. 04/2000, pp. 107-112.

[46] Fauchard, C., X. Derobert, and P. Cote. "GPR performances on a road test site." *Proc. SPIE Vol. 4084*, Eighth International Conference on Ground Penetrating Radar, David A. Noon; Glen F. Stickley; Dennis Longstaff; Eds., 04/2000, pp. 421-426.

[47] Derobert, X., C. Fauchard, O. Coffec, P. Cote, E. Le Brusq, E. Guillanton, J.Y. Dauvignac, and C. Pichot. "Step-frequency radar applied on bituminous concrete." *Proc. SPIE Vol. 4084*, Eighth International Conference on Ground Penetrating Radar, David A. Noon; Glen F. Stickley; Dennis Longstaff; Eds., 04/2000, pp. 753-757.

[48] Saarenketo, T. and H. Vesa. "Use of GPR technique in surveying gravel road wearing course." *Proc. SPIE Vol. 4084*, Eighth International Conference on Ground Penetrating Radar, David A. Noon; Glen F. Stickley; Dennis Longstaff; Eds., 04/2000, pp. 182-187.

[49] Al-Qadi, I.L., A. Loulizi, and S. Lahouar. "Dielectric characterization of hot-mix asphalt at the smart road using GPR." *Proc. SPIE Vol. 4084*, Eighth International Conference on Ground Penetrating Radar, David A. Noon; Glen F. Stickley; Dennis Longstaff; Eds., 04/2000, pp. 176-181.

[50] Saarenketo, T., D. van Deusen, and P. Maijala. "Minnesota GPR Project 1998: testing ground penetrating radar technology on Minnesota roads and highways." *Proc. SPIE Vol. 4084*, Eighth International Conference on Ground Penetrating Radar, David A. Noon; Glen F. Stickley; Dennis Longstaff; Eds. 04/2000, pp. 396-401.

[51] Olhoeft, G.R. "Maximizing the information from ground penetrating radar." *Journal of Applied Geophysics*, vol.43, 2000, pp. 174-187.

[52] Fernando, E., W. Liu, and B. Dietrich. "Computer program for network level determination of pavement layer thicknesses." *Proc. SPIE Vol. 4084*, Eighth International Conference on Ground Penetrating Radar, David A. Noon; Glen F. Stickley; Dennis Longstaff; Eds. 04/2000, pp. 194-199.

[53] Hothan, J. and M. Foester. “Gültigkeit der mit dem Ground Penetration Radar (GPR).“ *ermittelten Schichtdicken*, Fachgebiet Konstruktiver Straßenbau,Universität Hannover, October 2000. (in German)

[54] Lenngren, C.A., J. Bergstroem, and B.M. Ersson. ”Using ground-penetrating radar for assessing highway pavement thickness.” *Proc. SPIE Vol. 4129*, Subsurface Sensing Technologies and Applications II, Cam Nguyen; Ed. 07/2000, pp. 474-483.

[55] Corley-Lay, J. and C. S. Morrison. “Layer thickness variability for flexible pavements in North Carolina.” *Transportation Research Record 1778*, Transportation Research Board, Washington, DC, 2001, pp. 107-112.

[56] Wu, R., X. Li, and J. Li, Continuous pavement profiling with ground-penetrating radar, Dept. of Electr. & Comput. Eng., Florida Univ., Gainesville, FL, USA, 2002. http://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=2198

[57] Choubane, B., E. Fernando, S.C. Ross, and B.T. Dietrich. “Use of Ground Penetrating Radar for Asphalt Thickness Determination.” *Proceedings of SPIE* - The International Society for Optical Engineering, v 5045, 2003, pp. 230-240.

[58] Maser, K.R., Technology for Quality Assurance of New Pavement Thickness, *TRB 2003* Annual Meeting CD-ROM Paper revised from original submittal, 2003.

[59] Loulizi, A., I.L. Al-Qadi, and S. Lahouar. ”Optimization of Ground-Penetrating Radar Data to Predict Layer Thicknesses in Flexible Pavements.” Journal of Transportation Engineering, ASCE, Volume 129, Issue 1, January/February 2003, pp. 93-99.

[60] Al-Qadi, I.L., S. Lahouar, and A. Loulizi. **“**GPR: From the State-Of-the-Art to the State-Of-the-Practice.” International Symposium (NDT-CE 2003), Non-Destructive Testing in Civil Engineering, 2003.

[61] Hugenschmidt, J. “Non-destructive-testing of traffic-infrastructure using GPR.” EMPA, Swiss Federal Laboratories for Materials Testing and Research, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland, 2003.

[62] Lytton, R.L. “System identification and analysis of subsurface radar signals.” U.S. patent 5,384,715 – 1995, 19 p.

[63] Al-Qadi, I.L., S. Lahouar. “Use of GPR for thickness measurement and quality control of flexible pavements.” *Proceedings of the Technical Sessions,* Asphalt Paving Technology: Association of Asphalt Paving Technologists, v 73, Asphalt Paving Technology 2004, pp. 501-528.

[64] Willett, D.A., K.C. Mahboub, and B. Rister. “Accuracy of ground-penetrating radar for pavement-layer thickness analysis.” *Journal of Transportation Engineering*, ASCE, v 132, n 1, p 96-103, January, 2006.

[65] Maser, K.R., T.J. Holland, R. Roberts, and J. Popovics. “NDE methods for quality assurance of new pavement thickness.” *International Journal of Pavement Engineering*, v 7, n 1, March, 2006, pp. 1-10.

[66] “Infrasense Update.” *Newsletter*, Infrasense, Inc., Spring 2004.

[67] Parrillo, Robert. “Personal communications.” Geophysical Survey Systems, May 2006.

[68] Briggs, Bob. “Personal communications.” Dynatest, Florida, May 2006.

[69] RoadScanners, Finland. http://www.roadscanners.com/

[70] Saarenketo, Timo. "Personal communications." RoadScanners, Finland, May 2006.

[71] Sanati, Gary. "Personal communications." JILS, May 2006.

[72] Holzschuher, Charles. "Personal communications." Florida Department of Transportation, May 2006.

[73] Gaspard, Kevin J. and Leslie Mix. "Personal communications." Louisiana Transportation Research Center / Louisiana Department of Transportation and Development, May 2006.

[74] Daleiden, Jerry. "Personal communications." May 2006.

[75] Maser, Ken. "Personal communications." May 2006.

[76] Romero, Francisco. "Personal communications." May 2006.

[77] Emfinger, Robert. "Personal communications." EPIC, May 2006.

[78] Rascoe, Carl. "Personal communications." WaveTech Consulting, May 2006.

[79] Torres-Verdin, Victor. "Personal communications." Mexico City, May 2006.

[80] Losa, Massimo. "Personal communications." University of Pisa, Italy, May 2006.

[81] IDS Ingegneria dei Sistemi. http://www.ids-spa.it/

[82] Angiò, C., Manacorda, G., Pinelli, G. and Benedetto, A. "GPR Auomatic Inspection of Road Pavement Layer Thickness." *Proceedings, MAIREPAV03*. University of Minho, Portugal, 2003, pp.641-650.

[83] Bertrand, C. "Personal communications." Texas Transportation Institute, May 2006.

[84] Scullion, T. "Personal communications." Spectral Measurements LLC, May 2006.

[85] MALA USA, Inc. "Personal communications." MALA Geoscience, May 2006. http://www.malags.com/

[86] West, Randy. "Personal communications." NCAT, Auburn University, May 2006.

[87] Zaghloul, S., K. Helali, R. Ahmed, Z. Ahmed. and A.A. Jumikis. "Implementation of a Reliability-Based Backcalculation Analysis." *Transportation Research Record 1905*, Transportation Research Board, Washington, DC, 2005, pp. 97-106.

[88] Uddin, W. "Asphalt Overlay Design for GPR Benefit-Cost Study." *CAIT-TM-WU-06-01*, Center for Advanced Infrastructure Technology, University of Mississippi, June 2006.

[89] Uddin, W. "Improved Asphalt Thickness Design Procedures for New and Reconstructed Highway Pavements." *Report No. FHWA/MS-DOT-RD-99-122*, Final Report - Sponsored Research Study SS122, The University of Mississippi, for the Mississippi Department of Transportation, , November 1999.

[90] George, K.P. and W. Uddin. "Subgrade Characterization Study for Highway Pavement Design." *Report No. FHWA/MS-DOT-RD-00-131,* Final Report - Sponsored Research Study SS 131, The University of Mississippi, for the Mississippi Department of Transportation, December 2000.

[91] Barstis, W. "Personal communications." Mississippi Department of Transportation, May 2006.

APPENDIX A

Summary of GPR References on Asphalt Pavement Evaluation

Summary of GPR References on Asphalt Pavement Evaluation

[1]University of Mississippi Inter Library Loan

Reference	Author, year, publisher	Location of study, city, state, country	GPR equipment, frequency, brand	Asphalt/Bituminous pavement structure	Key results for layer thickness, success or failure	Comments
16	Maser, K.R. 2001 Intl. Pavement Symposium, Auburn CD proceedings	I-495 (NY, 9 miles), I-90 (Illinois, 15 miles) I-95 (Connecticut, 4 miles) USA	Air-launched horn antenna, 1GHz Pulse Radar and GSSI 45-55 mph	Composite pavements, (3-5in) asphalt over (8-10 in) concrete	1. I-495: GPR asphalt thickness within 5 % of core thickness 2. I-90: Avergae difference of -0.1 in. between GPR asphalt thickness and core 3. I-95: Deteriorated concrete slab condition evaluated	Uddin pdf
17	Maser, K.R. 1995 SPIE vol. 2456	USA (Texas, Florida, Kansas, Washington, Wyoming, Minnesota), UK, Denmark, Germany	Air-launched horn antenna, 1GHz Pulse Radar	Asphalt (51 – 508mm) Granular base (152-330mm)	1. The PAVLAYER software applied for accuracy study 2. ±7% accuracy for asphalt thickness and ±12% for base layers, confirmed with cores 3. Used antenna essential for thin layer thicknesses	ILL[1] pdf
18	Maser, K.R., T. Scullion, and R.C. Briggs 1992 International conference on asphalt pavements	SH-30, SH-19, SH-105, SH-21, Texas, USA	Air-coupled horn antenna, 1GHz Pulse Radar	Top course asphalt (1-2 in), bottom course asphalt (6-7mm), Base course (6-10in) LTPP sections	1. Accuracy and repeatability for asphalt thickness confirmed (standard error 0.32in. without and 0.11in. with core calibration 2. 0.99in. standard error for base course 3. Small (0.25in.) overestimation of asphalt thickness	ILL print
21	Wells, A.K. and R.L. Lytton, 2001 Intl. Pavement Symposium, Auburn CD proceedings	Various highways in California, New Mexico, and Texas, USA	Air-coupled antenna, 1GHz (4 antennas in front of van) Pulse Radar	Various cross asphalt and concrete pavement cross sections, SIDRAS analysis of GPR data	Successful evaluation and color plots of: 1. Asphalt: layer thickness, asphalt content, unit weight, air voids 2. Concrete: thickness, water content, unit weight, porosity; void detection beneath concrete slab (0.1 in. air filled) 3. Unbound base/subbase: thickness, water content, unit weight, porosity 4. (same for subgrade)	Uddin pdf
26	Olhoeft, G.R., and S.S. Smith III 2000 SPIE vol. 4084	Not available (Analytical)	GSSI SIR-8 Air-launched horn antenna, 1GHz	Asphalt pavement	1. Algorithm for automatic processing and modeling of GPR data developed 2. Statistical accuracy better than ASTM's coring and short-pulse-radar methods	ILL print

Summary of GPR References on Asphalt Pavement Evaluation (continued)

Ref	Author, year, publisher	Location of study, city, state, country	GPR equipment, frequency, brand	Asphalt/Bituminous pavement structure	Key results for layer thickness, success or failure	Comments
41	Hugenschmidt, J., M.N. Partl, and H. de Witte 1997 Journal of applied Geophysics	National Motorway N2 (Gotthard motorway), Switzerland	GSSI model H4205 with 2.5GHz horn antenna, GSSI model 3101D with 900 MHz antenna, GSSI SIR system 10A	Asphalt (0.16-0.2m), Subbase (rock)	1. Valuable for detecting extent of pavement damage, confirmed through cores and visual inspection 2. Suitable tool for rehabilitation quality control 3. 900MHz better for higher penetration depth	Internet search pdf
42	Sener, J.C., R.M. Smith, M.D. Garz, G.A. Murgel, R.W. Hamilton, D.R. Haws 1998 SPIE vol. 3400	SH-16, US-20, SH-44, I -84/EB, I-84 B/EB, US-95, Idaho USA	RODAR system 1GHz air-coupled horn antenna ROAD RADAR system 1GHz ground-coupled and 3GHz air-coupled antennas	Asphalt surface course, Base course	1. Surface course thickness reasonably accurate, confirmed with cores 2. Base course thickness deviates significantly from core results 3. Project level surveys more accurate than network level for both systems used	ILL pdf
43	Cowdery, J.M., J.L. Kurtz 1999 SPIE vol. 3704	University of Florida Electronic Communication Laboratory, Florida, USA	1GHz air-launched system Pulse Radar	Asphalt, Base layer	1. A signal processing technique for analyzing surface interfaces developed and demonstrated 2. Can analyze large amount of data accurately and quickly	ILL pdf
44	Gordon, M.O., K. Broughton, and M.S.A. Hardy 1999 NDT and E International Vol. 31, No. 6	Laboratory tests	1GHz, 900MHz	Asphalt (100mm) Subbases (Gravel, Concrete sand, Silica sand)	1. Thickness of thin layers can be impossible to interpret directly 2. Subbase material has no effect on initial response from the surface	ILL pdf
45	Roimela, P., S. Salmenkaita, P. Maijala, and T. Saarenketo 2000 SPIE vol. 4084	Finnish National Road Administration, Finland	GSSI SIR-10 H 1 GHz horn antenna, 400/500 MHz ground coupled antenna	Asphalt, base course, subgrade	1. Horn antenna accurate for asphalt and base course thicknesses 2. 400/500MHz can interpret road structure thickness and detect defects 3. Core sampling still necessary	ILL print

Summary of GPR References on Asphalt Pavement Evaluation (continued)

Ref	Author, year, publisher	Location of study, city, state, country	GPR equipment, frequency, brand	Asphalt/Bituminous pavement structure	Key results for layer thickness, success or failure	Comments
46	Fauchard C., X. Derobert, and Ph. Cote 2000 SPIE vol. 4084	LCPC circular pavement fatigue test track France	GSSI SIR 10 A+ 2GHz horn antenna used 0.5-2GHz	Asphalt layers, binders, bitumen and asphalt bound granular materials	1. Best contrasts from interface between base course and surfacing layers 2. 2GHz profiles not able to detect very thin asphalt surfacing (~2.5cm), confirmed with coring 3. Numerical inversion based on CMP had promising results for thickness but not confirmed	ILL pdf
47	Derobert, X., C. Fauchard, O. Coffec, and Ph. Cote 2000 SPIE vol. 4084	LCPC circular pavement fatigue test track France	GSSI system 1.5 GHz, 2GHz LEAT antennas Ultra wide band (458MHz – 10GHz)	Thin asphalt surfacing, bound and unbound granular material	1. Design of a step frequency radar technique for thin pavements proposed and tested 2. Possibility to detect thin layers better than classical GPR, confirmed through laboratory experiments	ILL print
48	Saarenketo, T., V. Heikki 2000 SPIE vol. 4084	Highway 9241, Simo Network level at Kemi and Karstula, Northern and central Finland	GSSI, 1.5GHz ground-coupled, and 1GHz air-coupled horn antennas	Gravel wearing course	1. Can be used for thickness and quality control but not as accurate as for asphalt thickness 2. 25mm average difference from core thickness 3. Thickness values statistically reliable 4. No significant difference between used antennas	ILL print
49	Al-Qadi, I.L., A. Loulizi, and S.Lahouar 2000 SPIE vol. 4084	Virginia Smart Road, Montgomery co., Virginia, USA	GSSI system Air-coupled antenna 750 – 1750 MHz	Wearing surface, Intermediate HMA, Open graded drainage layer, subbase, Geosynthetics	1. A method for calculating the complex dielectric constant of HMA developed and tested 2. Will be used to predict changes in dielectric properties at the smart road	ILL print
50	Saarenketo, T., D.V. Deusen, and P. Maijala 2000 SPIE vol. 4084	T.H. 23, T.H.71, Willmar, Minnesota Mn/Road Mainline test section, NW of Minneapolis/St.Paul, Minnesota, USA	GSSI SIR-10H 1GHz air-coupled horn antenna, 1.5GHz and 400MHz ground-coupled antenna	Asphalt layer (146mm) Unbound base (102mm)	1. Surface reflection method reliable to estimate dielectric values and thickness of asphalt 2. Beneficiary in detecting stripping, confirmed with cores and FWD	ILL print

Summary of GPR References on Asphalt Pavement Evaluation (continued)

Ref	Author, year, publisher	Location of study, city, state, country	GPR equipment, frequency, brand	Asphalt/Bituminous pavement structure	Key results for layer thickness, success or failure	Comments
52	Fernando, E., W. Liu, and B. Dietrich 2000 SPIE vol. 4084	US-1, Martin co., Florida, sections of Florida SR roads, USA	Pulse RODAR IV	Asphalt Base course	1. Computer program (TERRA) for analyzing GPR data developed 2. Asphalt thickness prediction verified using cores (0.3in absolute error) 3. TERRA may be used with confidence for asphalt thickness but coring still required	ILL print
53	Hothan, J. Foester, M. 2000 University of Hanover	Nienburg, Lemgo, and Koblenz, Germany	GPR1: Horn antenna (900, 1000, 2500 MHz), GPR2: Regular antenna (900, 1200 MHz), GPR3: Regular antenna (500, 900, 1500 MHz)	Wearing course: 2.5-4cm Asphalt binder: 4-6.5cm Asphalt base: 21.5 cm Gravel subbase: 8cm Frost protection: 30cm	1. Transitions between main pavement sections well identified by all systems 2. 2.5GHz antenna can detect asphalt layers > 3 cm with good accuracy 3. Asphalt thickness accuracy ± 2cm 4. Base thickness accuracy ± 3cm	Author word
54	Lenngren, C.A., J. Bergstroem, and B. Ersson 2000 SPIE vol. 4129	Central Regional Road Administration, Central Sweden	RAMAC/GPR 1GHz antenna	Asphalt (50-100mm) base course, subbase, subgrade	1. Interface between lower layers easy to distinguish 2. Improved backcalculation of elastic moduli, 3. Contributes to less coring and improved core sampling	ILL pdf
55	Corley-Lay, J., and C.S. Morrison 2001 Transportation Research Record	13 General Pavement Study (GPS) sites in North Carolina, USA	Penetradar Model PS 24 series B antenna, 1GHz	Asphalt layer (89-292mm) Aggregate base course, Treated/untreated subgrade	1. Lower coefficient of variation (CV) for thin asphalts, 15 – 22% 2. CV decreases with increasing average thickness for base course 3. Asphalt thickness predicted within 1in. of actual 4. Base layer overestimated by average of 28mm	UM Library print
56	Wu, R., X. Li, and J. Li 2002 IEE Proc. Sonar Navigation, Vol. 149	Not available (Analytical)	Air-launched system, 1GHz	Not available	1. A new algorithm for motion compensation and time delay estimation presented 2. Computational efficiency and estimation accuracy outperforms scan-by-scan approach 3. Demonstrated with numerical and experimental examples	ILL pdf

Summary of GPR References on Asphalt Pavement Evaluation (continued)

Ref	Author, year, publisher	Location of study, city, state, country	GPR equipment, frequency, brand	Asphalt/Bituminous pavement structure	Key results for layer thickness, success or failure	Comments
57	Choubane, B., E. Fernando S.C. Ross, and B.T. Dietrich 2003 SPIE vol. 5045	SR24, Fairbanks, US441, Micanopy, US441, Gainesville SR5, Brevard co. SR15, Volusia co. , I-10, Madison co., I-75, Hamilton co. Florida, USA	Pulse Radar, Inc. Air-launched antenna, 1GHz	Asphalt (Marshall and superpave mixes) 50 – 300 mm thick	1. Prediction error less for Marshall sites (1 – 20 mm) 2. Predicted thicknesses comparable to core for layers <180mm thick 3. Improved prediction for superpave sites after calibration with cores	ILL pdf
58	Maser, K.R. 2003 Transportation Research Board	I-93, Thornton, NH FAA Tech Center, Atlanta city, NJ FHWA ALF, Mc Lean, VA, US50 and US99, Sacramento, CA, SR180,Mendota, CA	GSSI air-launched horn antenna 1 GHz, Ground-coupled antennas in a CMP mode	Asphalt surface, Base course	1. Both systems meet accuracy specification of 0.1in for asphalt thickness, confirmed with cores 2. More area coverage with less effort by horn antenna 3. CMP method less effective for asphalt thicknesses <3.5in	ILL pdf
59	Loulizi, A., I.L. Al-Quadi, and S. Lahouar 2003 Journal of Transportation Engineering, ASCE	Experimental site in Bedford county, Virginia , USA	Not available	HMA (90mm) Base course (100-200mm), Subgrade	1. A new method for predicting layer thickness based on an optimization procedure developed and validated 2. 3.6% error between measured and predicted thicknesses of HMA 3. Able to resolve thin layers but requires long computer time and gives multiple solutions for same layout	Internet search pdf
60	Al-Qadi I.L., S.Lahouar, A. Loulizi 2003 International symposium of non destructive testing in civil engineering	Route 288 (new) in Richmond, and I-81 (0ld) in Virginia, USA	Impulse GPR system Air-coupled horn antenna (500-2000MHz), ground coupled antenna (900MHz)	HMA (SM-9.5D superpave)	1. For new pavements, static dielectric constant effectively estimated with air-coupled system (average error 6.7%) 2. For old pavements, combination of both systems in a modified CMP method has better results than time domain technique 3. Confirmed using core thicknesses	Internet search word
61	Hugenschmidt, J. 2003 Swiss Federal Laboratories for Materials Testing and Research	Sections of Swiss motorway and Swiss alpine roads, Switzerland	GSSI SIR-20 GSSI model 4205 horn antenna, Mobile, 30-50km/hr, Frequency not given	Not available	1. Relations between reflections and physical structures hard to identify for roads repaired several times 2. In some cases asphalt bottom reflection not identifiable without core 3. Accuracy and reliability sufficient for many applications	Internet search word

Summary of GPR References on Asphalt Pavement Evaluation (continued)

Ref	Author, year, publisher	Location of study, city, state, country	GPR equipment, frequency, brand	Asphalt/Bituminous pavement structure	Key results for layer thickness, success or failure	Comments
63	Al-Qadi, I.L., S. Lahouar 2004 Asphalt paving technologies	Virginia Smart Road Test Facility, Route-288, I-81, Virginia, USA	SIR-10B Air-coupled horn antenna, 1GHz Ground-coupled antenna, 900MHz	HMA wearing course HMA base Subbase	1. Acceptable thickness results for "thick" layers 2. Signal processing techniques can enhance accuracy for thin layers 3. Recommended air-coupled antenna for network level, and a combined system for project level HMA thickness	UM Library print
64	Willet, D.A., K.C. Mahboub, B. Rister 2006 Journal of Transportation Engineering	University of Kentucky campus parking lot, I-75, I-64, KY-17, Paris pike, Kentucky, USA	SIR-10B Air-launched horn antenna, 1GHz	Asphalt surface course (1 - 8.66 in) Base course Subgrade	1. Promising results for asphalt thickness 2. Four calibration cores considered optimum to minimize error rates 3. Challenge remains for thin layers due to "double reflection" effect	Internet search pdf
65	Maser, K.R. International Journal of Pavement Engineering, 2006	Several case studies	GPR and impact echo	Asphalt and concrete	1. Asphalt thickness accuracy within 2.5cm 2. Concrete thickness accuracy within 4cm	Internet search pdf
87	Zaghloul, S., K. Helali, R. Ahmed, Z. Ahmed. and A.A. Jumikis Transportation Research Record 1905, 2005, pp. 97-106	New Jersey DOT studies on highway sites including LTPP- SPSS sites in New Jersey, USA	GPR and cores; 1000 mile network GPR survey and 50 miles of project-level GPR survey	Asphalt and concrete highway pavements; mean asphalt thickness of 10 in over 10 in granular base	1. Asphalt core comparison important for reliable layer thicknesses from GPR data (CV of asphalt layer 8-20 %) 2. Improved reliability in layer thickness using GPR data 3. GPR based asphalt overlay thickness generally higher than that from the as-built data	TRB Annual meeting CD proceedings TRR 1905 publication

APPENDIX B

GPR Technology Survey Form

CAIT's Ground Penetrating Radar (GPR) Study for Mississippi DOT: Phase I -Technology Evaluation

Objectives: (1) Conduct literature review and interviews with manufacturers and users on the use of GPR and its limitations for asphalt pavement layer thickness evaluation. (2) Establish candidate GPR testing and interpretation methods that can provide reliable asphalt layer and sublayer thickness data at highway speeds for use with the FWD deflection data to enhance MDOT's modulus backcalculation program. (3) Plan a field study based on favorable results of Phase I.

Thickness of asphalt highway pavements in Mississippi range generally from 24 to 40 inch including minimum two asphalt layers, a treated base layer, subbase layer, and 6-in lime stabilized subgrade.

We are requesting you to provide your unbiased responses on the following evaluation form based on your known reputation and research/consulting experience in GPR testing and data interpretation.

Instructions: Please provide your best expert answers to the following criteria (as many as you can) so that we can evaluate the GPR equipment and data analysis technology for its potential routine use on flexible/asphalt/bituminous surfaced highway pavements. Please read each criterion carefully, add comments, and indicate if you can provide your best published or unpublished related references. Thank you very much for your scholarly contribution.
(*Note: I will send a complimentary copy of CAIT's Phase 1 report once approved by the Mississippi DOT.* *Waheed Uddin*).

Title & Name of Expert: Telephone: E-mail: Date:

Affiliation ________________________ (Equipment manufacturer/Consulting-Service Provider/Academic or Research)
Cross out the category not applied

Number of years of experience using GPR for pavement evaluation **with**:
(a) Equipment ____(b) Data analysis ____(c) Asphalt pavement layering and layer thickness determination ___
(d) GPR derived layer thicknesses used for FWD data analysis to calculate in situ modulus values ___

GPR Technology Evaluation Survey Form 1

GPR Evaluation Criteria	Response
1. GPR Equipment Robustness and Durability	
1.1 Equipment specifications Maximum depth of asphalt pavement evaluation, in = ____	GPR Model: Country: Operating frequency: Antenna (air or ground coupled):
1.2 Tow vehicle requirements and safety on road	
1.3 Field automation & instrumentation Reliability	
1.4 Versatility (Applicable for 4-in thin or thicker pavements)	
2. Field Data Collection and Processing	
2.1 Level of automation (Setup, scan, interpretation)	Setup (with GPS, DMI)? Scanning and data capture: Field data processing:
2.2 Special education and training required	
2.3 Crew (for GPR and tow vehicle)	
2.4 Productivity and data quality (Comparison with field) (Scan rate per foot ________ at operating speed ______ mph)	Accuracy of scan and data capture: Repeatability error: Number of scans per lane mile:

Please return to: Waheed Uddin by e-mail. cvuddin@olemiss.edu or fax at 662-915-5523 Subject: Expert Survey for GPR Evaluation

GPR Evaluation Criteria	Response
	Number of scans per lane mile:
3. Operating Restrictions	
3.1 Environmental effects (rain, visibility, wind….etc.)	
3.2 Traffic interference and safety (Arrow board truck for traffic control?)	
3.3 Operating speed, mph (During scanning)	
3.4 Signal interference sources and noise problems	
4. Office Data Processing	
4.1 Special education and training required; staff size	
4.2 Versatility of data processing computer equipment	
4.3 Ease of data processing (Fully automated electronic data processing available? If not what level of automation; explain.)	
4.4 Extent of data coverage (per mile scan) and time	
5. Data Quality and Usefulness	
5.1 Data analysis and permanent record of GPR scans (Name of software: ________ Developed by:)	Scan image quality (B&W or color): Processing productivity (scans/hour): Usefulness for analysis:
5.2 Ease of interpretation of GPR scanning outputs (Rating scale 1-10 for ease of interpretation, 10 being the easiest & fastest)	List of outputs: Steps in scan analysis: Ease of interpretation (1-10):
5.3 Accuracy of thickness results (Comparison with cores and/or boring)	Asphalt layer thickness accuracy: Base layer thickness accuracy: Subbase layer thickness accuracy:
5.4 Repeatability error (For thickness of asphalt and sublayers)	
6. Cost of Equipment, Operation, and Data Analysis	
6.1 Cost of owning/leasing GPR equipment (Model:____________________)	Purchase cost: $ Leasing cost: $ per year
6.2 Cost of field operation (Based on number of scans per lane mile)	$ per lane mile; Cost for 10 lane miles:
6.3 Cost of office data processing and analysis	$ per lane mile; Cost for 10 lane miles:
6.4 Total field operating and office processing cost at 50 % annual use (from items 6.2 and 6.3)	$ for _______ lane miles per year
7. Cost-Effectiveness Estimate	
7.1 Total owning & operating cost / Total number of lane miles surveyed and analyzed (from items 6.1, 6.2 and 6.3)	$ per 10 lane miles; Cost/Lane mile:
7.2 B/C Ratio: (Savings from enhanced FWD deflection data analysis due to accurate GPR-derived thickness data / Total cost of GPR data collection and interpretation)	Benefit/Cost Ratio:

Please return to: Waheed Uddin by e-mail. cvuddin@olemiss.edu or fax at 662-915-5523 Subject: Expert Survey for GPR Evaluation

GPR Evaluation Criteria	Response
8. User Preference	(Rating scale 1-10, 10 being the most favorable)
Rating based on applications of data for asphalt pavement layer thickness, use with FWD data, and cost-effectiveness	
9. Overall Ranking	(Rating scale 1-10, 10 being the highest rank)
Rating (for 1 to 10 mile or longer 2-lane highway)	
10. Comments	Comment by referring to comment number
1. Potential for determination of asphalt and other layers **2.** Potential for thickness of asphalt layer(s) **3.** Potential for thicknesses of asphalt and base layers **4.** Potential for thicknesses of asphalt, base, and subbase **5.** Potential for asphalt degradation (identify - stripping, asphalt content…etc.) **6.** Potential for asphalt layer debonding **7.** Potential for stabilized base/subbase layer degradation **8.** **9.**	
11. References (selected only, not more than 4 most relevant)	
Ref 1. Ref 2. Ref 3. Ref 4.	

12. Additional Comments:

Please return to: Waheed Uddin by e-mail. cvuddin@olemiss.edu or fax at 662-915-5523 Subject: Expert Survey for GPR Evaluation

APPENDIX C

List of GPR Technology Survey Responders

Contact info of GPR technology evaluation survey responders who used CAIT's survey form

Eval. Number	GPR Expert [Reference]	Affiliation	Address and Contact Info
1	Tom Scullion [84]	Texas Transportation Institute (TTI)	Tom Scullion 1218 N Ridgefield College Station, TX 77840 Phone: 979 845 9910 T-Scullion@tamu.edu
2	Carl Bertrand [83]	Spectral Measurements, Inc	Carl Bertrand Spectral Measurements, LLC (512)288-2446 (office) (512)921-9383 (cell) bertrand@spectralmeasurements.com
3	Robert Parrillo [67]	GSSI http://www.geophysical.com/	Robert Parrillo Geophysical Survey Systems 12 Industrial Way, Salem, NH 03079 Phone: 603-681-2059 parrillor@geophysical.com
4	Gary Sanati [71]	Foundations Mechanics, Inc JILS http://www.jilsfwd.com/	Gary Sanati President, JILS 421 E. El Segundo Blvd El Segundo, CA 90245-3922 Phone: +1 310 322 1920 Fax: +1 310 322 5146 GSanati@jilsfwd.com
5	Charles Holzschuher [72]	Florida DOT	Charles Holzschuher, P.E. Friction and Nondestructive Testing State Materials Office, Florida DOT 5007 NE 39th Ave, Gainesville, FL 32609 Telephone: 352-955-6341 Fax: 352-955-6345 Charles.Holzschuher@dot.state.fl.us
6	Ken Maser [75]	Infrasense, Inc www.infrasense.com	Kenneth R. Maser, Ph.D., P.E. President Infrasense, Inc. 14 Kensington Road, Arlington, MA 02476 Phone: 781-648-0440, Xax: 781-648-1778 kmaser@infrasense.com
7	Jerry Daleiden [74]	Fugro Consultants, LP	Jerry Daleiden Fugro Consultants, LP 512 977 1800 JDaleiden@fugro.com
8	Francisco Romero [76]	GEOVision	Francisco Romero Geovision 603-235-9108 romero60@comcast.net
9	Carl D. Rascoe [78]	WaveTech	Carl D Rascoe, P.E. WaveTech Consulting, Inc. 28092 S Satsuma Rd Livingston, LA 70754 Office 225-698-6733 Mobile 225-802-5441 crascoe@earthlink.net

10	Robert Emfinger [77]	EPIC	Robert Emfinger EPIC - Southeast 230 Scottland Drive Alabaster, Alabama 35007 (205) 862-5264 / FAX (630) 839-0761 Cells (205) 862-5264 / (404) 310-2508 E-mail: remfinger@epicpavements.com
11	Victor Torres-Verdin [79]	Evaluación Integral de Obras Civiles	Victor Torres-Verdin, PhD General Director Evaluación Integral de Obras Civiles Mexico City, Mexico +52 55 5634-0049 vtorres@torrestci.com
12	Timo Saarenketo [70]	RoadScanners http://www.roadscanners.com/	Timo Saarenketo RoadScanners Valtakatu 16 Rovaniemi, FIN-96200, Finland Phone: 358 (0)16 420 0500 timo.saarenketo@roadscanners.com
13	James E. Cook [85]	MALA Geoscience MALA USA, Inc http://www.malags.com/	James E. Cook MALA USA, Inc 843 852 5021 James.Cook@malags.se
14	Massimo Losa [80] Laurent D'Onofrio	University of Pisa	University of Pisa Department of Civil Engineering +39 050 553573 losa@ing.unipi.it

Notes:

Louisiana DOTD's Kevin J Gaspard and Leslie Mix provided lots of info on their projects by telephone/e-mails; no formal survey form.
Kevin J Gaspard, Pavement Research Manager, Louisiana Transportation Research Center
4101 Gourrier Ave, Baton Rouge, LA 70808, 225-767-9104 Phone, 225-767-9108 fax;
kgaspard@dotd.louisiana.gov

Bob Briggs of Dynatest (Florida office) provided feedback by telephone/e-mail; no formal survey form.

Bruce Vandre of Utah Department of Transportation did not respond.

Brad Rister of Kentucky Department of Transportation did not respond.