GROUND PENETRATING RADAR (GPR) ANALYSIS: *PHASE I*

FHWA/MT-09-005/8201

Final Report

prepared for
THE STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION

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

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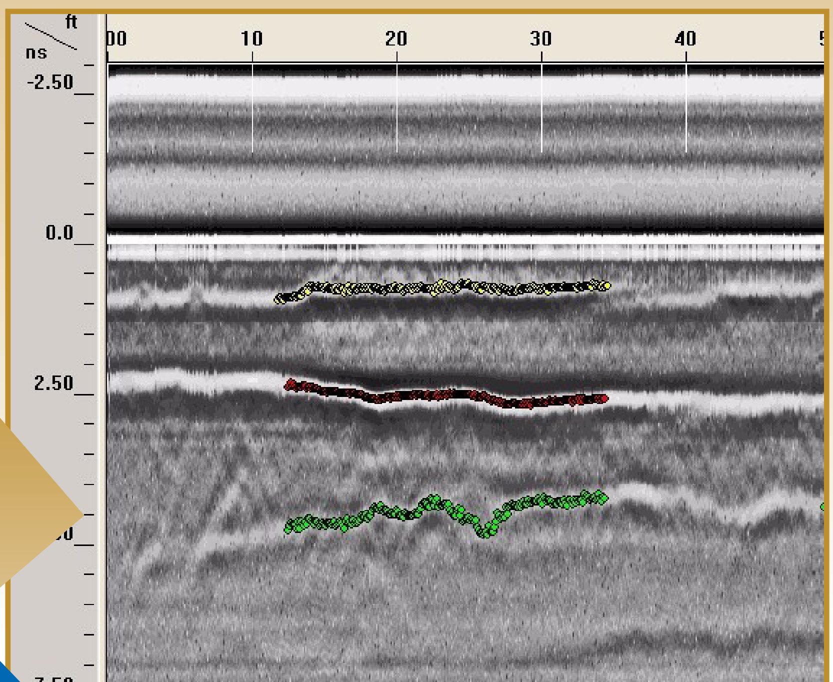
prepared by
Kenneth R. Maser
Jason Puccinelli

Infrasense, Inc.
Arlington, Massachusetts



RESEARCH PROGRAMS

MDT

Ground Penetrating Radar (GPR) Analysis
HWY-308813-RP

Phase I Report

Submitted by
Infrasense, Inc.
14 Kensington Road
Arlington, MA 02476-8016

Prepared for
Montana Department of Transportation
2701 Prospect Avenue
P.O. Box 201001
Helena, MT 59601

in cooperation with the
U.S. DEPARTMENT OF TRANSPORTATION
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16. Abstract

The objective of this work is to evaluate the feasibility of expanding the MDT's Ground Penetrating Radar (GPR) program to a broader range of pavement evaluation activities. Currently, MDT uses GPR in conjunction with its Falling Weight Deflectometer (FWD) data collection program to provide layer thickness data for backcalculation. This program has included a review of literature and software dealing with pavement applications of GPR, a survey of state highway agency (SHA) use of GPR for pavement applications, a review of MDT's GPR program, and a review of MDT's pavement structures, environment, and pavement management, and rehabilitation practices. A detailed review of 47 documented studies shows that GPR pavement thickness measurements typically fall within 2-10% of core values for the bound layers. Most of these studies have used a 1.0 GHz horn antenna (vs. the 2.0 GHz antenna currently used by MDT). Accuracy of the unbound material is less precisely documented. The survey of SHA GPR practice supports the application of GPR for pavement thickness measurements—some agencies use GPR on a regular basis, while other use GPR on a project-specific basis. The application of GPR for measuring density of new AC pavement is currently being developed by Texas and Florida DOT's. Montana's pavement network is 97% AC, with mostly aggregate base but some areas with cement-treated base, and maintenance is typically carried out using chip seals. Based on an evaluation of MDT's rehabilitation and reconstruction practices, it appears that the GPR program can be expanded to provide useful information for the following applications: (a) calculation of structural number for pavement reconstruction and rehabilitation design; (b) insuring proper depth control for mill and fill rehabilitation, and cold in-place recycling; (c) improved structural capacity calculation for network level evaluation; and (d) quality assurance of new pavement thickness and density. In order to investigate the feasibility and value of these program expansions, it is recommended that a field evaluation project be designed and implemented to evaluate the accuracy of GPR pavement thickness (and density) data on Montana pavements, and to correlate these findings with the accuracy requirements of the individual applications.

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1. INTRODUCTION

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

(a) The types of layer structure information that GPR is capable of obtaining.

(b) The level of accuracy associated with this information under different pavement conditions and expected levels of confidence.

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

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

To address these issues, this project has sought to integrate a detailed knowledge of the capabilities and limitations of GPR with the information needs of the MDT. This initial project was proposed in two phases.

The Phase I project seeks to provide a comprehensive assessment of GPR technologies with regard to current and potential applications for application to pavement reconstruction, rehabilitation for different pavement structures, and environmental conditions. Phase II involves the design and conduct of a field validation project to characterize the accuracy and confidence levels of the GPR data for different application conditions. The decision to proceed with Phase II will be made after completion of Phase I.

The Phase I evaluation of the capabilities and limitations of GPR has been carried out through a review of published literature, contacts with equipment manufacturers, and a survey of state highway agency use of GPR. The potential applications of GPR with MDT have been evaluated by characterizing the types of pavement construction and environmental conditions present within the state, and types of reconstruction and rehabilitation treatments employed by the MDT. This information has been gathered through direct discussion with MDT personnel and review of agency documentation.

The Phase I project has been carried out according to the following tasks:

Task 1 – Review of Literature and Survey of State Highway Agency GPR Practices.

Task 2 – Review of Montana's GPR Program.

Task 3 – Documentation of Montana Pavement Structures, Environment, and Rehabilitation Policies.

Task 4 – Interim Report and Feasibility Assessment.

The following report describes the results of these tasks.

2. LITERATURE REVIEW

Originally developed for geotechnical evaluations and mine detection, GPR was introduced for highway applications in the early 1980's. Some initial highway applications, such as detection of voids under joints in concrete pavements, were over-promoted and not particularly successful. In the late ‘80s and early ‘90s, application of GPR for assessment of highway pavement was researched in further depth, and the capabilities and limitations of the technology became better understood. Work by the New England Transportation Consortium (NETC) (Maser 1990) and the Ontario Ministry of Transport (Chung and Carter 1991) demonstrated the capability of GPR for measuring the thickness of asphalt overlays on concrete decks. Subsequent work carried out jointly by Infrasense and Texas Transportation Institute (TTI) established the ability and accuracy of GPR for measuring the thickness of bound AC and unbound aggregate base layers (Maser and Scullion 1992a), and for distinguishing the thickness of individual AC layers within the pavement structure (Maser and Scullion 1992b). GPR application to measurement of pavement thickness has since become a subject of ongoing study by universities and research institutes, and GPR evaluation studies have been carried out by over 15 highway agencies.

In addition to the measurement of pavement layer thickness, this literature review covers a number of other GPR applications including; identification of pavement deterioration (e.g., stripping), estimation of asphalt density and detection of voids. The goals of these studies have been to support: rehabilitation design, FWD backcalculation, pavement management systems, and quality control and assurance of new pavement construction.

Appendix A to this report summarizes the results obtained from 47 published studies. These results have been organized into three application areas—pavement thickness, pavement condition evaluation, and quality assurance. The discussion below summarizes the results of representative studies and presents the key findings in these three application areas.

2.1 Pavement Thickness

Currently the most common application of GPR is the determination of pavement layer thickness. GPR enables a timely and cost effective means of collecting continuous thickness data, contrary to more prevalent point measurements (i.e. coring and test pits). The following provides a synopsis of the, accuracy, equipment, procedures, conclusions, and limitations for both project and network level studies as well as QA/QC projects over the years. The studies have generally compared the GPR results to cores, and have shown differences that range from 2-10%. The lower differences (2-5%) are generally associated with newly constructed pavements, while the bigger differences are generally associated with older pavements.

A variety of antennas have been used in thickness studies. These include the 2.0 GHz, 1 GHz air coupled, 1.5 GHz, 900 MHz, and 500 MHz ground coupled antennas. A study conducted by the Virginia Department of Transportation (VDOT) in 2005 (Al-Qadi et al. 2005) found no difference between the results obtained from an air coupled (1 GHz) and ground coupled (1.5GHz) antenna. A majority of the studies employ the 1 GHz air coupled horn antenna due to both its ability to collect at highway speeds as well as its low susceptibility to radio frequency noise, while still providing adequate penetration and resolution for nearly all pavement structures.

2.1.1 Use of Cores for Calibration and Verification

A large factor in the reported studies is coring information used to both correlate and calibrate the GPR results. A common procedure in these studies is for an analysis to be done in two stages. Stage 1 is a "blind" analysis where the GPR data is analyzed without the benefit of core data, and then the accuracy is evaluated using the core data as "ground truth" information. Stage 2 uses a subset of core data to calibrate the GPR data, producing a new set of results. As reported in a study conducted by the University of Illinois in 2006 (Al-Qadi et al. 2006), the absolute error between the estimated and measured thickness decreased from 5.6% to 4% with a core correction factor. Some of the studies reported in Appendix A took no cores making it impossible to gauge the accuracy and value of the results.

2.1.2 Network vs. Project Level Evaluations

Ground Penetrating Radar data has been used for both network-level pavement management and project-level purposes. Information regarding pavement structure and layer properties is useful at the network level for setting priorities and allocating resources (Maser and Vandre 2006; Williams et al. 2004). Also, layer thickness information is useful at the project level to identify pavement thickness variability for rehabilitation design. For calibration and verification, it is important to note that cores are typically taken on project sections for purposes other than layer thickness. For network-level studies, the number of cores available for this purpose is much more limited.

A number of the studies have shown that the availability of GPR bound layer thickness data leads to more accurate estimation of layer moduli and better prediction of remaining life (Balasundaram et al. 2006). Based on GPR and FWD data collected on LTPP sites in Texas, Briggs et al. (1991) showed that back-calculated layer moduli using assumed layer thicknesses could be up to 100% in error. The study demonstrated that this error would be substantially reduced using local GPR thickness data. In the South Dakota study (Maser 2006) a section on SD 44 was evaluated using the 1993 AASHTO procedure to estimate remaining pavement life. Using the assumed layer thickness from plans (without GPR data), the procedure overestimated the remaining life by approximately 17 percent. The availability of GPR data substantially reduced this error.

2.1.3 Unbound Layers

Some projects found GPR to be inaccurate at predicting base and sub base layers (Ahmed et al. 2004). This mostly happens with thick concrete pavements due to concrete's high conductivity, which attenuates the GPR signal limiting the penetration depth (Maser 1994). With all pavements, thickness can be a limiting factor. Selecting the appropriate frequency antenna can be critical in having the ability to determine base thickness. In general as thickness increases, measuring accuracy decreases (Roddis et al. 1992). Also, in comparing the GPR results to a ground truth data, use of boring data to characterize unbound layer thickness has inherent inaccuracies of its own, and cannot reliably be used to assess the accuracy of GPR-based thickness evaluation. (Infrasense 1997).

2.1.4 Concrete Layer Thickness

In a few of the studies examined, measuring concrete thickness was less accurate then that of asphalt thickness measurements (Willet et al. 2006). This is often due to a weaker contrast between the concrete pavement and base layer (Infrasense 1994a). However, other studies have found concrete thickness measurements to be more accurate due to concrete's less variant dielectric constant (Al-Qadi et al. 2005, Wenzlick et al. 1999). One can conclude that when the interface at the bottom of the concrete can be detected, the GPR results are accurate; however, the interface may not be reliably detected.

2.1.5 Quality Assurance of New Pavement Thickness

Layer thickness estimates are also useful for quality assurance/quality control (QA/QC) for construction of new pavements and overlays. GPR can provide a faster, nondestructive and more complete means of obtaining QA/QC data than coring. The California Department of Transportation (Caltrans) conducted a study, completed in 2003, in which GPR was shown to provide sufficient accuracy to serve as a basis for calculating pay factors (Maser 2003, Maser et al. 2006). The 1 GHz horn antenna system was used for this study, providing average thickness values per section to within 0.1 inch of the coring data. VDOT also conducted a similar study with similar equipment (Al Qadi, et al. 2006), revealing a mean thickness error of 2.9%. The accuracy decreased in the HMA base layers due to the lack of precision associated with the larger aggregate sizes. The study concluded that GPR can be used successfully for QA/QC of new asphalt pavement construction.

2.2 Pavement Condition Evaluation

GPR is also used forensically as a means to measure the condition of pavement. Subsurface distress adversely impacts both the pavement capacity and surface conditions, therefore reducing the life and performance. This technology transmits electromagnetic energy and receives reflections from the different pavement layers. Dielectrics of each layer are measured and areas where there is a high dielectric constant indicate the presence of moisture due to water's relatively high dielectric constant of 81 versus typical pavement material constants ranging 4 to 10. Other contributors to a pavement's varying dielectric constant are the conductivity of the pavement and air void content. A number of studies explore types of subsurface pavement distress including; voids, moisture, de-bonding, and deterioration/stripping.

A 2004 study conducted by the University of Wisconsin–Eau Claire and University of California–Berkley, found GPR to be a reliable means in estimating the volumetric water content in sub asphalt aggregate layers (Grote et. al. 2004). The study used both 900 and 1200 MHz ground coupled antennas to identify "wet zones" beneath both drained and un-drained asphalt pavements. The results of the study were correlated with coring data and found to have a fairly good correlation between predicted and measured moisture content.

Another study conducted by the Kentucky Transportation Cabinet (KTC) in 2008 found GPR data to be inconclusive in detecting subsurface voids but reasonably successful at identifying moisture between pavement layers. For this study, a 900 MHz antenna was implemented on a PCC over DGA pavement section and the results were used to facilitate rehabilitation decisions.

The KTC design committee determined that the GPR data gave the appropriate information to select the optimum design alternate. (Rister et al. 2008).

TTI looked at the use of GPR (1 GHz air coupled antenna) to detect stripping in a section of asphalt over concrete. A number of cores were taken (one every mile) to draw a comparison. GPR proved to be successful in accurately identifying areas where stripping occurred. However, in looking at the cores where stripping was present, the damage was moderate to severe. This indicates that GPR might be capable of detecting the later stages of stripping, but not the earlier stages. (Rmeili and Scullion 1997).

Georgia Department of Transportation (GDOT) and Applied Research Associates (ARA) carried out a stripping detection study in using a 1 GHz air coupled antenna along with infrared thermography (IR), falling weight deflectometer (FWD), and seismic methods. GPR and IR were used to scan the entire pavement and identify local areas to focus the FWD, seismic, and coring tests. The study found GPR to be useful, not as a stand-alone solution, but as an aid in focusing the efforts of the more accurate point tests (Hammons et al. 2006).

Delamation/debonding in a pavement structure is currently the subject of SHRP2 and Federal Aviation Administration (FAA) research. Delamination detection in concrete bridge decks is a well developed capability, but a similar capability for asphalt pavement does not currently exist. One study conducted by the University of Alaska and Texas A&M in 2008 addressed delamination of concrete pavement. This study used a 1.5 GHz ground coupled antenna system on three CRC pavement sections. An analysis protocol was established for delamination detection of concrete pavements. This protocol relies heavily on validation cores. For this particular study, the 40 cores taken confirmed there were no shallow delaminations. The need for additional testing on sections in a less homogeneous condition is suggested in order to gain the appropriate level of confidence in the prescribed protocol. (Liu et al. 2008).

2.3 QA/QC of Pavement Density

Ground Penetrating Radar is also able to measure variations in the density of pavements. The premise is the more a pavement is compacted during construction the higher the density as well as dielectric values. Air has a dielectric constant of 1.0 and thus even a fractional increase in the volume of air produces a decrease in composite dielectric values. Therefore, areas with relatively lower dielectric values can accurately be assumed to have a lower density and to have been compacted less.

Research in Finland has verified the ability to measure asphalt air void content with GPR (Saarenketo and Roimela 1998). Based on this work, the Finnish Road Administration has adopted a specification for using GPR for density quality assurance. The Texas Department of Transportation conducted a study in 2002 that used GPR and infrared for the quality assurance and control respectively of new asphalt overlays. GPR measured the uniformity of the pavement via calculating the density through the obtained dielectric constants of the HMA overlay. Through this study, it is recommended to calibrate the results using at least 3 cores per test section. (Sebesta and Scullion 2003).

A more recent project being conducted by Florida DOT (FDOT) is seeking to develop software that uses the dielectric values obtained in a GPR survey of a newly constructed roadway and provides data that highlights the low and high densities areas. The software used in conjunction with this study enables a technician to process the GPR data onsite, providing plan area maps of the newly constructed section that highlight potentially low density areas. These maps are then used to locate a small number of cores that can then serve to both verify the findings and calibrate the dielectric constant to obtain pavement density. This work is still ongoing, and a final report is expected in the summer/fall of 2009.

2.4 Review of Commercial GPR Analysis Software

Part of the literature review covered a review of commercially available GPR data analysis software. The Montana DOT currently uses GSSI's RADAN© for calculating pavement thickness from the GPR data. However, there are other commercial software packages that are available now or in the near future which may also provide some benefits to MDT's program. Table 1 shows a list of some currently available software programs for GPR data analysis.

Table 1. Summary of Commercial GPR Software

SUPPLIER	SOFTWARE ITEM	CAPABILITIES
GSSI	Radan	General purpose GPR processing. Can use data from other supplier's equipment.
	Radan with Pavement Structure Module	Adds picking and analysis of pavement layers to Radan software.
Sensors and Software	Conquest 3D	3D imaging of concrete.
	Ekko_View	General purpose display and analysis of GPR data.
RoadScanners	Haescan	Pavement layer thickness.
	Road Doctor	Adds video logging and geo-referencing to above.
Penetradar	PavePro	Pavement layer analysis.
GPR-Survey	GPR-SLICE	General purpose GPR processing and presenting. Can use data from a number of supplier's equipment. Data presented in 2D or 3D and integrated with GPS.
IDS	GRED Layer	Pavement and bridge deck layer analysis software. Data presented in 2D/3D. GIS topographic output views.
GEOSCANNERS	GRPSoft	Displaying, post-processing and interpreting GPR data. Can use data from other suppliers.
JILS	WaveTrac	Automated layer thickness analysis for FWD applications.
Sandameier Software	REFLEXW	General processing and interpretation of reflection and transmission data (GPR, seismic and ultrasound). 2D and 3D analysis format.

3. SURVEY OF STATE HIGHWAY AGENCY USE OF GPR

A general survey of State Highway Agencies (SHAs) was conducted to determine their experience with GPR and to evaluate the relevance of this experience to MDT's GPR goals. The purpose of the survey was to ensure that MDT's objectives for their GPR system was consistent with findings and experience of other agencies. During this survey, ninety-two state personnel, representing the forty-eight states were contacted. The only state omitted other than Montana was South Dakota, which was recently surveyed as part of another research effort. Of those contacted, responses were obtained from seventy-one individuals, representing forty-three states.

The survey consisted of sixteen questions, each of which was posed over the phone or through email, depending on the respondent's preference. The questions were tailored to gain as much information as possible on the SHAs current use and experience with GPR related to pavement applications.

A list of the survey questions and a general summary of the responses is presented below. The full detail of the survey response is included as Appendix B and the list individuals contacted as part of this survey is included in Appendix C.

1. What groups within your State have experience with Ground Penetrating Radar (GPR)?

Most of the SHAs have used GPR for one or more applications and some states are presently conducting research projects to explore additional uses of GPR and/or to improve current GPR software. The groups using GPR within the SHAs varied, but could be generally categorized in the following: Pavement Management, Materials Testing, Construction Technologies, Bridge/Structural, Geotechnical/Geophysical, Research, Environmental, and Archaeology.

2. How extensively has GPR been used by your agency?

The use of GPR within the SHAs varied widely. The responses are based both on the number of years of use and the frequency of use. The results were categorized as follows:

Extensive or regular use on an ongoing basis**:**
Alaska, Florida, Indiana, Michigan, Minnesota, New Hampshire, Texas, and Wisconsin.

Limited use of GPR on a case-by-case basis:
Alabama, Colorado, Illinois, Kansas, Kentucky, Louisiana, Mississippi, Missouri, New Jersey, New Mexico, New York, North Dakota, Ohio, Oklahoma, Rhode Island, Utah, Virginia, and West Virginia.

Initiating Use of GPR:
Arizona, Hawaii, and Iowa.

Does not regularly use GPR:

Arkansas, Delaware, Georgia, Idaho, Maine, Nebraska, Nevada, North Carolina, Oregon, Pennsylvania, South Carolina, Tennessee, Washington, and Wyoming.

North Carolina had used GPR extensively, but has ceased using it in Pavement Management due to heavy time demands to analyze the data and concern regarding accuracy of the equipment.

3. Do you perform GPR work using State forces or through contractors and/or consultants?

Table 2 provides a breakdown of the labor forces used by the responding States for GPR data collection.

Table 2. Use of State Forces vs. Contractors and Consultants

<table>
<tr><th></th><th>CURRENTLY USE GPR</th><th>HAVE USED GPR, BUT DO NOT CURRENTLY USE IT</th><th>DON'T REGULARLY USE GPR</th></tr>
<tr><td>State Forces</td><td>10</td><td>2</td><td rowspan="2">14</td></tr>
<tr><td>Contractors/Consultants</td><td>16</td><td>1</td></tr>
</table>

4. For what applications has GPR been used by your agency? Has GPR been effective in the application(s) for which it has been used by your agency?

GPR has been used by various SHAs for one or more of the following applications:

- Determine pavement layer thicknesses on network and project levels.
- Detect voids under concrete slabs, locate tunnels and mines under pavement surfaces.
- Assess the homogeneity of pavement surfaces.
- Evaluate bridge decks and detect delamination.
- Locate steel reinforcement and verify cover depth.
- Locate underground utilities.
- Determine presence/location of artifacts including, but not limited to graves.
- Interpolate soil/embankment profiles between bore holes/test pits.
- Support investigation for law enforcement in homicide cases.
- Determine the dielectric constant of a material.
- Develop coring maps/plans.
- Sinkhole mapping.
- Locate depth to bedrock.
- Locate stripping in asphalt.
- Determine thickness of various structural members in bridges.
- Indicate the moisture level of bases and subgrades.
- Look at water table issues.

The survey revealed that most SHAs currently using GPR have found it to be generally effective for their applications and, in some instances, have stated that GPR is currently the only available technology to practically acquire certain data.

There were five SHAs that have utilized or experimented with GPR and have found that it was either not effective or not practical, stating that the interpretation of the data was too tedious or that results were not always successful.

5. ***What are the advantages and disadvantages of the GPR equipment that your agency has used versus other methods for obtaining the same data? What other methods have you used?***

When discussing the advantages of using GPR, SHAs often noted the ability to collect continuous data and that it was a nondestructive test. Its ability to collect large amounts of data and cover a significant area in a short amount of time was also recognized. For air-coupled GPR units, the advantage was being able to collect data at highway speeds with little or no need for traffic control, which was greatly valued in areas with higher traffic volumes. GPR was also noted for being a safer method for collecting data as it lessened the exposure of field personnel to traffic. Cost was also considered advantageous, as GPR could be used to acquire data that would not otherwise be economically feasible. Ease of acquiring the data was also mentioned. An additional advantage is the ability to obtain thickness data at every FWD location and having continuous layer information to identify pavement changes.

The major disadvantage that agencies stated was with regard to interpreting the data. A number of agencies felt that the results were heavily subject to the data interpreter and that the ability to effectively interpret the data was a highly developed skill that is obtained through experience and training. Cost, in some instances, was considered a disadvantage for the quality of results achieved. Other disadvantages included the need to obtain ground-truth data through some other method (coring, boring, etc.) and, FCC regulations that limit the frequency of the antennas that are permitted to use for GPR as well as the filters required to eliminate interference. Also, when using a ground-coupled unit, data collection is slow.

6. ***What are the cost related characteristics of the GPR equipment that your agency uses?***

The States reported a wide range of prices for GPR equipment. Arizona reported the startup cost to be around $112,000 for the equipment, installation, multiple antennas, and software. Florida reported the startup cost to be around $170,000 for the van, equipment, air-coupled & ground-coupled GPR units, and software plus an additional $40,000 for two operators. Hawaii uses consultants/contractors to do GPR and they reported a cost of about $300/hr in the field. Indiana stated that a ground-coupled GPR unit roughly costs between $40,000 to $50,000, and an air-coupled antenna to be similar at about $30,000 to $40,000 plus the additional costs for two operators. Iowa reported the cost of an air-coupled unit and software to be about $80,000. Michigan reported the initial cost to be about $65,000 for the equipment, but a total cost of about $111,000 to cover the equipment, software, and additional antennas of varying frequencies. The remaining SHAs that responded reported costs within the ranges described above.

7. ***Can you describe the complexity of the equipment and data acquisition system? How important is training and support?***

   Many of the States felt that training and support were very important to effectively utilize GPR equipment for data acquisition purposes. They mentioned that it was imperative the operators are familiar with the GPR equipment and know its limitations in regard to special site conditions. They stated that the equipment was technical, but with training could be used with relative ease. The data interpretation is much more complicated and requires additional training and experience in certain applications. Some States noted that the interpretation was more of an "art" than a "science."

8. ***What calibration requirements do you have?***

   The majority of the States reported that they use the manufacturer guidelines in calibrating the equipment. States also mentioned a variety of other methods they use in addition to the manufacturer guidelines:
   - Routine calibration before use per the ASTM standard (ASTM 1998) for air-coupled systems.
   - Static and bounce metal plate tests.
   - Calibrated or in-field cores/concrete blocks of known depths to verify results.
   - Testing the frequency signal for consistency.
   - Running time-stability calibrations to identify signal drops.
   - Using guidelines from the manufacturer or another qualified entity.
   - Arizona developed their own calibration for static tests.

   The States varied in their response to the frequency of these calibrations. Some of the calibration techniques are done daily before use, while others are performed on an annual basis. (*Author's note: The more frequent tests are the routine calibrations used in processing the data. The less frequent tests are those used to evaluate the overall performance of the system.)*

9. ***What procedures/protocols do you follow in using GPR equipment?***

   Many of the States reported using the manufacturer's guidelines for equipment use. The States reported that field conditions, project objectives, and applications of use are determining factors for how the GPR equipment is used, and at what speed it is used. Air-launched units typically run at speeds ranging from 40 to 65 mph.

10. ***What procedures/protocols do you follow in interpreting GPR data?***

    The majority of the States reported that the interpretation of the data is done manually and is complex in nature. States reported that though software is available to assist in data interpretation, it is not yet an automated process and is performed by a trained and experienced individual. Thus detailed procedures and protocols were not reported, but the States did report using various software packages to assist in data interpretation. The software used for interpretation varied from commercial/manufacturer software to software that was developed by the agency using it or another qualified entity.

11. ***What test(s) has your agency performed concerning the repeatability and/or accuracy of GPR equipment? What were the results?***

Most of the agencies mentioned using cores and/or historical data to validate the GPR results. Some agencies have performed research projects on the level of accuracy GPR yields and have felt comfortable with it. Five States reported an error margin of 4%-10% when compared to pavement cores, which they felt was very reasonable. However, a small minority of States mentioned that they do not currently use GPR because it was not accurate enough to be used in their applications. Pennsylvania also reported that weather affected the results. Most of the States verify GPR results with cores or compare results to borings.

12. ***Have you used GPR for construction project quality control? How?***

Four of the forty-three responding SHAs reported using GPR in project construction quality control, but that it was not used routinely in this application. The main properties that were measured using GPR included: pavement layer thickness, air void monitoring, and the depth/location of rebar. Four other States reported that they were looking into using it for project quality control, but are currently not using it for that application.

13. ***Do you utilize GPR for pavement design, rehabilitation selection, or pavement management? If so, how? Has this been beneficial?***

Most States that use GPR in these applications have used it on a project level largely to establish pavement thicknesses to verify existing conditions and identify variations in the pavement. Indiana has used it on a network level and found it to be effective. Louisiana and North Carolina used it on a network level and felt that it was not beneficial due to project time constraints and data analysis issues. Five States have used it for rehabilitation selection and design purposes, and have found it to be effective. Four States have used it in conjunction with their FWD and found it to be effective. Kansas has used it to verify dowel tie placement. Michigan has used it to provide contractors with depth information for mill and fill applications.

14. ***What software does your agency use for interpreting GPR data?***

The States reported a variety of software that they use for interpreting the data and they can be seen in the list below:

- GSSI Radan.
- Custom software developed by the agency (Indiana).
- Penetradar proprietary software.
- ColorMaps & PaveCheck, which were developed by TTI.
- Gradix.

15. Do you have plans to expand or contract your utilization of GPR?

Eleven States are currently looking into expanding their utilization of GPR. Sixteen more States are planning on expanding their use of GPR in the future. Ideas for expansion included:

- upgrading/purchasing equipment
- training staff in data collection/interpretation
- use in conjunction with FWD/RWD
- evaluation bridge decks
- network and project level for evaluation of pavement thickness and homogeneous sections
- identification of slab stability issues
- determination density in asphalt layers.

The remaining sixteen States plan to continue their current level of GPR utilization.

4. REVIEW OF MONTANA'S GPR PROGRAM

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

Figure 1. MDT GPR Vehicle

FWD data collection is carried out on both network, and project levels. On the network level, the production rate is approximately 300 tests per day, and the FWD data collection is typically carried out at 820-ft intervals. The project-level data collection is done at intervals that range from 50 feet to 500 feet, depending on the project The GPR data collection is initiated about 50 feet before the vehicle stops for the FWD test, providing GPR data coverage over the FWD test point prior to stopping for the FWD test. Since the FWD load is located 25 feet behind the GPR antenna, the location of the FWD test point in the GPR data is 25 feet from the end of the file. Data collection rate is typically set to 10 to 15 scans per foot. The only calibration procedure used by MDT is the “bumper jump” plate reflection test, and this is conducted periodically (not daily).

MDT uses GPR layer thickness for determining layer information for use in interpreting FWD data. At the network level, the data collection process described above produces approximately 300 GPR data files per day of FWD data collection, and MDT typically processes a subset of these (about 50 per day). The analysis involves use of RADAN software to “pick” the bottom of the bound and unbound pavement layers, and to process these picked layers to compute the layer thickness. Distinguishing which layers are bound and which are unbound must be made by the operator. Typically the layer picking is carried out for the entire file, even though the GPR data at the FWD test point represents a small portion of each file. This is carried out using the “EZ Tracker” routine, which automatically picks all of the points between a start and end user pick.

A sample of GPR data collected and processed by MDT personnel was reviewed as part of this Phase I work. The quality of the data appears to be good, and the processing of the layer thickness results appears to accurately represent the pavement layer structure. No core data was provided with this GPR data, so it was not possible to assess the accuracy of the GPR analysis.

5. DOCUMENTATION OF MONTANA PAVEMENT STRUCTURES AND ENVIRONMENT

5.1 Introduction

To document the pavement structure and environment in Montana, the research team interviewed Montana Department of Transportation (MDT) personnel in the Pavement Analysis Section of the Materials Bureau who are involved with pavement design and management. The interviews were conducted on February 2, 2009 at MDT Headquarters in conjunction with the project kick-off meeting. Those interviewed included:

- Mr. John Amestoy.
- Mr. Milo Borglum.
- Mr. Dan Hill.
- Ms. Mary Gayle Padmos.
- Mr. Jon Watson.
- Mr. Greg Zeihen.

During the interviews, various manuals, memorandums, and guidelines related to pavement data collection, design, and management were obtained. Key elements of the interviews and the information within these documents are referenced in this chapter. Information provided in this section documents pavement data collection, design, and management as it relates to GPR and MDT procedures.

5.2 Pavement Condition Evaluation

Falling Weight Deflectometer data collection is conducted at both the network-level and the project-level. At the network-level, FWD data is collected at 820-foot intervals and covers the entire network on a 3-year cycle. The project-level data collection is done at intervals that range from 50 feet to 500 feet, depending on the project. This is performed during the initial phases of pavement design and is usually conducted during two different seasons to account for changes in material properties: spring and late summer/early fall. GPR data is collected at each FWD test location.

The load and deflection data collected from FWD equipment is utilized to estimate structural parameters of the pavement layers through a backcalculation procedure. MDT currently utilizes the “Automated Deflection Analysis Procedure” (ADAP) software for backcalculation. The program uses the MODULUS routine to backcaclulate layer properties.

An important input into any backcalculation procedure is the thickness of each layer throughout the pavement structure. MDT uses the following hierarchy for determining layer information for use in interpreting FWD data:

- GPR layer thickness—Priority 1.
- As-built files—Priority 2.
- State Historical Database (Road Log)—Priority 3.

ADAP outputs a number of parameters regarding the existing pavement structure including temperature adjusted resilient moduli, structural number, remaining life, and required overlay thickness.

Other project-level and network-level pavement condition information is collected by MDT including roughness and surface distress; however, these are independent of the GPR data collection, interpretation, and use.

5.3 Pavement Design

Each pavement reconstruction and rehabilitation project in Montana is designed using project-specific data accounting for the existing structure, traffic, climate, and subgrade conditions. Standard pavement sections or catalogs are not utilized by the State.

MDT has investigated the Mechanistic-Empirical Pavement Design Guide (M-E PDG) for designing pavements in Montana, but has not implemented the M-E PDG due to issues with some of the models within the software. The current pavement design manual for MDT is based on the 1993 AASHTO Pavement Design Guide. Only the temperature adjusted resilient moduli information from the project-level FWD backcalculation is utilized in the pavement design process currently. These moduli data are used to supplement the R-value laboratory test results in the design process. The backcalculation results are reviewed to delineate pavement changes and identify soft spots that require subgrade excavation during construction. GPR data is currently being used as an input into the backcalculation process as described above.

The existing structural capacity of pavements receiving mill and fill or overlay rehabilitation is characterized by a structural number that is reduced based on the surface condition. The structural number assigned to the existing pavement is calculated by multiplying each layer thickness by an appropriate structural coefficient. The structural coefficient is based on the surface condition data, which is collected manually by personnel onsite. GPR layer information can be used as an input into the calculation for structural number.

GPR layer information can also be used to ensure the milling depth does not remove too much of the existing pavement layer. If the existing layer is too thin, the equipment can punch through, creating construction problems.

MDT is also utilizing cold in-place recycle rehabilitation techniques. The design process for this type of treatment requires an understanding of the bound material thickness to ensure the proper proportioning of bound and unbound material. MDT is looking to use GPR to evaluate the layer thickness and variability throughout a project during the design phase (Mallick et al. 2007)

The Department follows a policy of crack and seating PCC pavements, and overlaying with a 0.4-foot thick asphalt concrete layer. During construction, the crack and seated pavement is visually inspected to ensure proper cracking. There is no application for GPR in this situation.

5.4 Pavement Management System

MDT has evaluated procedures for developing Structural Capacity Index (SCI) values using network-level FWD data. From this research, a modified YONAPAVE approach was selected for use in Montana to compute SCI, which uses DARwin-developed tables for the effective structural number based on subgrade conditions. One of the determining factors for the selection of this method was that it did not require pavement thickness information as part of the computation. MDT is planning to develop SCI for all pavement sections and include the values as part of their pavement management system (PMS). Network-level layer thicknesses derived from GPR could be incorporated into the SCI calculation by modifying the YONAPAVE approach, or perhaps knowing the thicknesses would lead to selecting an alternate SCI computation approach.

MDT's pavement management system incorporates four measures into the decision tree for selecting renewal alternatives. The four measures are as follows:

- Alligator Cracking Index (ACI):
  An index accounting for the quantity and severity of load related distresses.
- Miscellaneous Cracking Index (MCI):
  An index incorporating the quantity and severity of non-load related distresses (i.e., environmental/materials-related deterioration).
- RUT:
  An index indicating the depth/severity of rutting in the wheelpaths.
- RIDE:
  An index that indicates the roughness felt by end-users traveling down the roadway.

These condition indices are combined with the pavement inventory information to select the most appropriate type of treatment. The inventory data input into the decision tree includes pavement age and traffic (measured in equivalent single axle loads-ESALs). Pavement thickness/structure information is not currently utilized in the decision tree. Figures 2 through 5 provide a representative sampling of the decision trees utilized by MDT.

Depending on the inputs, the decision tree outputs the following renewal alternatives:

- Do Nothing.
- Crack Seal.
- Crack Seal and Cover.
- Minor Rehabilitation.
  - AC Thin Overlay.
  - AC Thin Overlay Engineered.
  - Mill, Fill, and Overlay.
- Major Rehabilitation.
  - Cold-in-place Recycling.
  - Foamed Asphalt.
- Reconstruction.

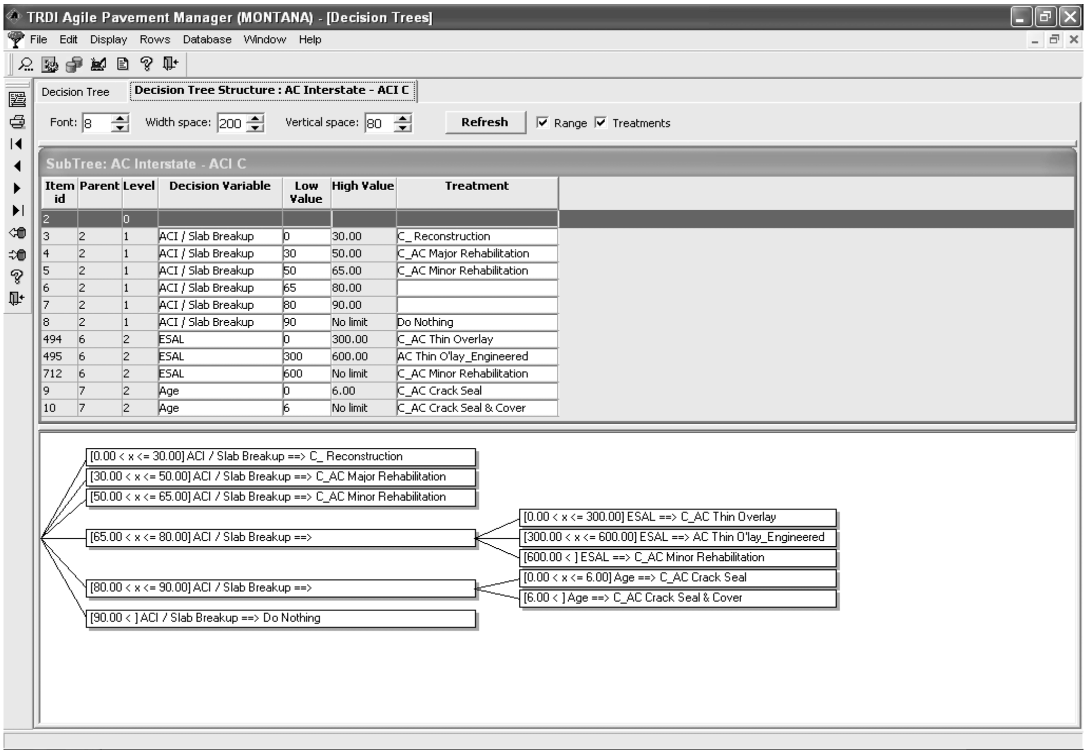

Figure 2. MDT Decision Tree Based on ACI

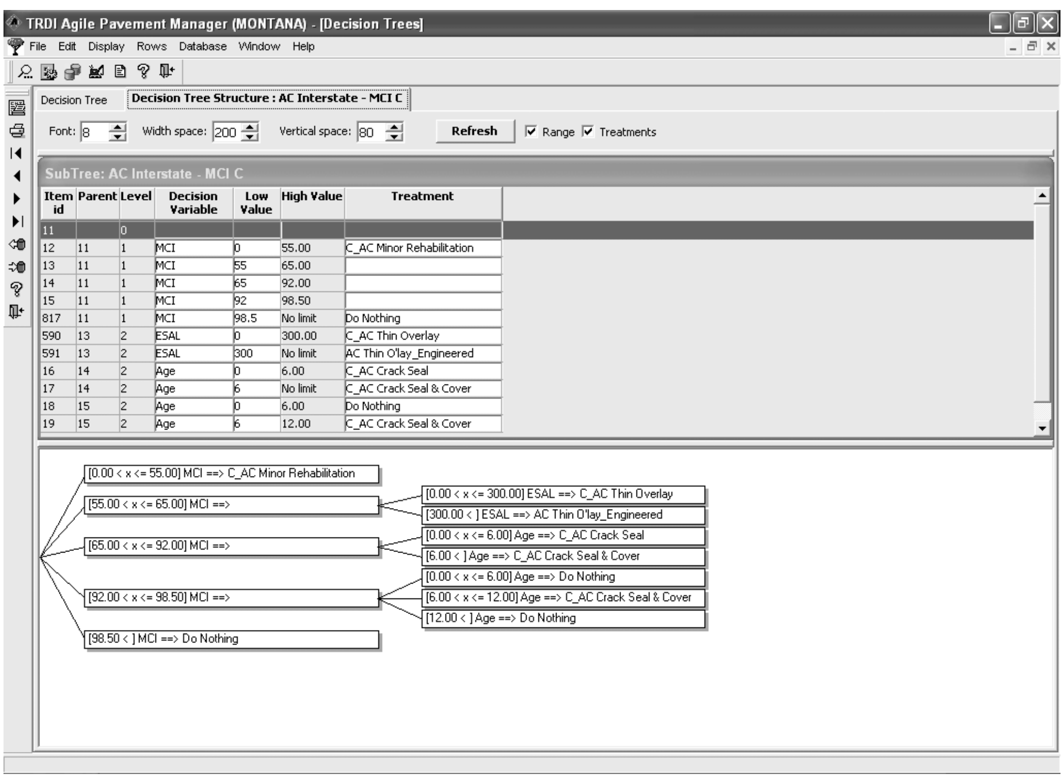

Figure 3. MDT Decision Tree Based on MCI

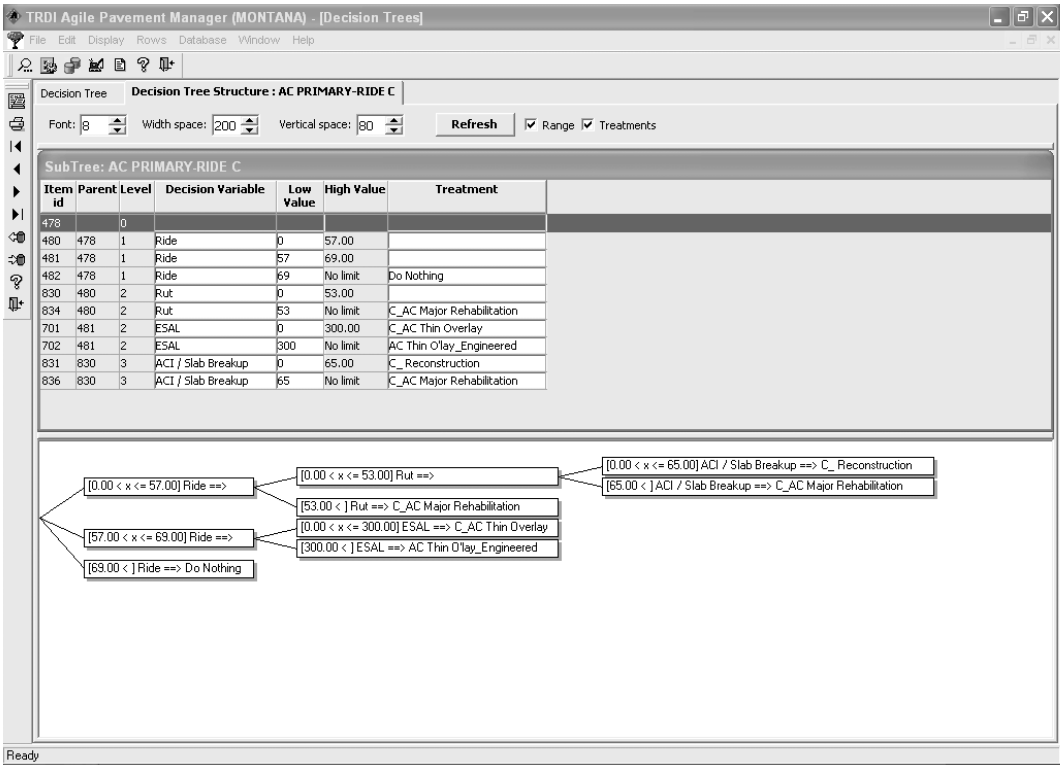

Figure 4. MDT Decision Tree Based on RUT

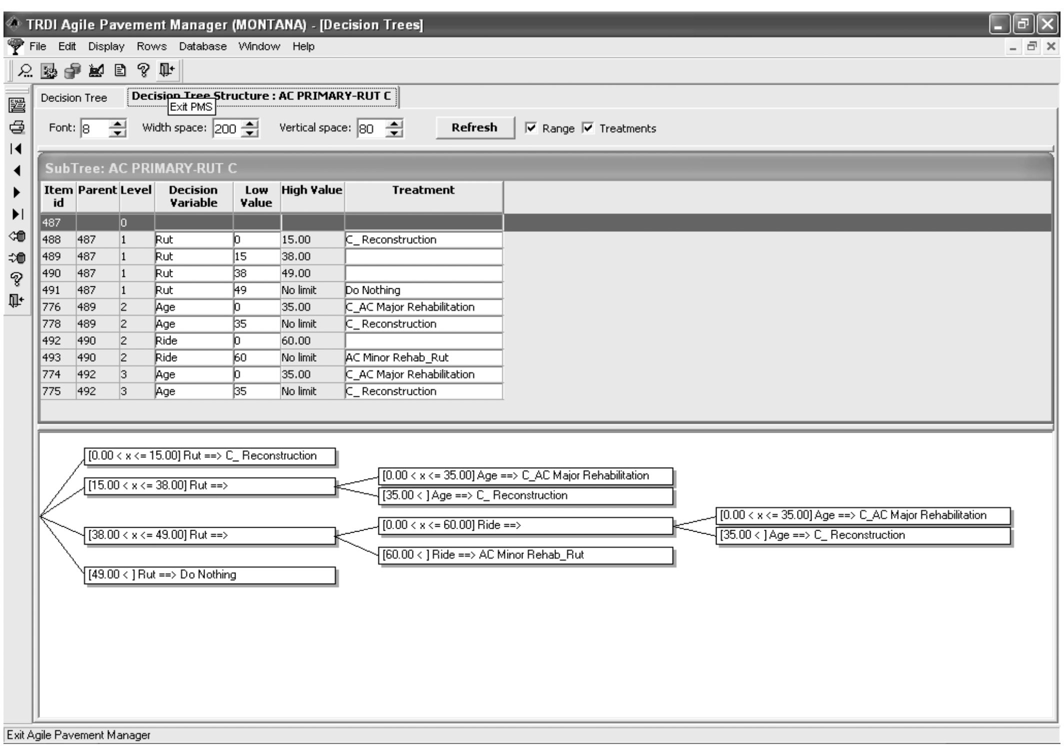

Figure 5. MDT Decision Tree Based on RIDE

5.5 Current Network

The project team consulted with MDT staff to gain an understanding of the most prevalent pavements within the State's network. Over 97 percent of the network has an asphalt concrete pavement surface, with less than 3 percent rigid pavement. The Department has been crack and seating their existing rigid pavement, and overlaying with asphalt concrete. Asphalt treated bases are not typically utilized in the State; however, cement treated bases have been used and are in the network. The state applies a chip seal surface to all of their asphalt concrete pavements. The CIPR pavements on low volume roads are surfaced with only a chip seal, while the higher volume roads receive an asphalt concrete overlay and chip seal. The team will work with MDT staff and information available in the PMS database to select representative pavements for inclusion in the test matrices during Phase 2.

5.6 Environment

The climate in Montana can be divided into two regions: east and west of the Continental Divide. On the west of the divide, winters are milder, precipitation is more evenly distributed throughout the year, summers are cooler in general, and winds are lighter than on the eastern side. There is more cloudiness in the west in all seasons, humidity runs a bit higher, and the growing season is shorter than in the eastern plains areas. The western portion of the State is the wettest and the North Central the driest. Annual snowfall varies from quite heavy, 300 inches, in some parts of the mountains in the western half of the State, to around 20 inches at some stations in the northern portion of the State east of the Continental Divide. On average, the western part of the state receives about 18 inches of precipitation annually, whereas the eastern part receives 13 inches. Statewide daily temperatures average 46° F with annual lows of -24° F and annual highs of 98° F. Some of the higher elevations in the west only have 50 to 100 days of frost-free weather a year as opposed to 120 to 150 days in the lower elevation areas of the east. This information will need to be taken into account when establishing test matrices during Phase 2 of this project. Figure 6 provides a map of average annual precipitation for Montana.

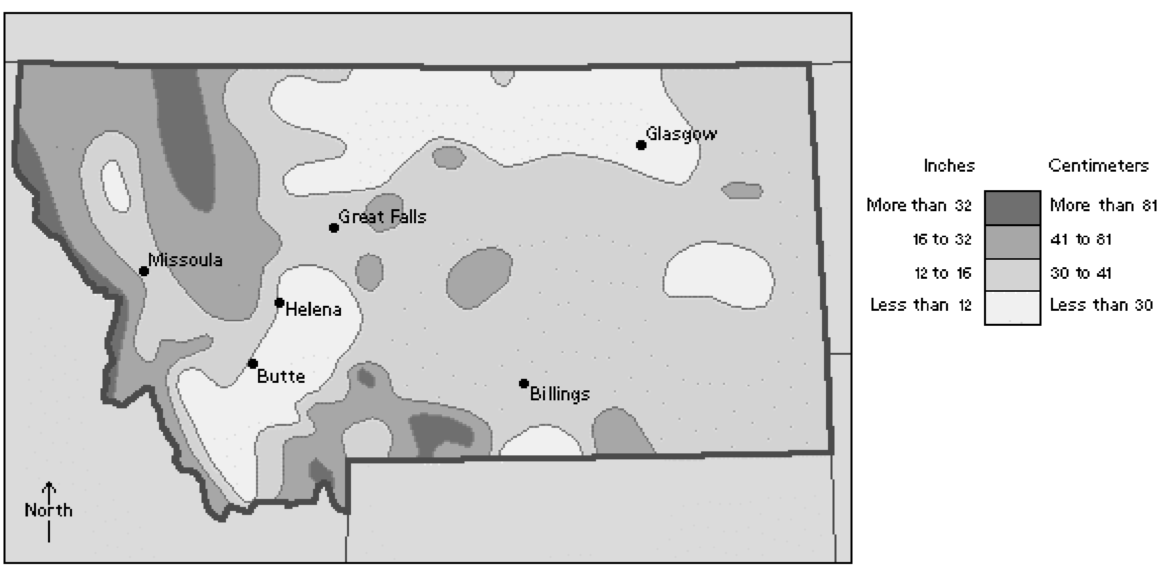

Figure 6. Montana Precipitation Map (World Book 2009)

Figures 7 and 8 provide average temperatures for January and July, respectively. Note that it is difficult to measure AC thickness with GPR when the base is frozen, since the dielectric properties of frozen base are very similar to those of asphalt.

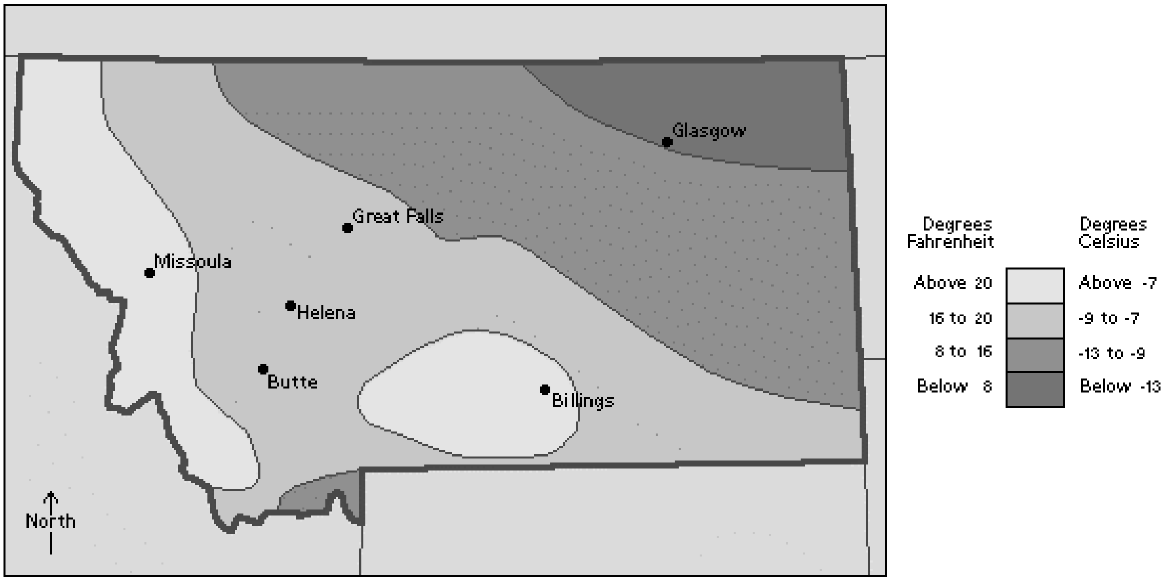

Figure 7. Montana January Temperature Map (World Book 2009)

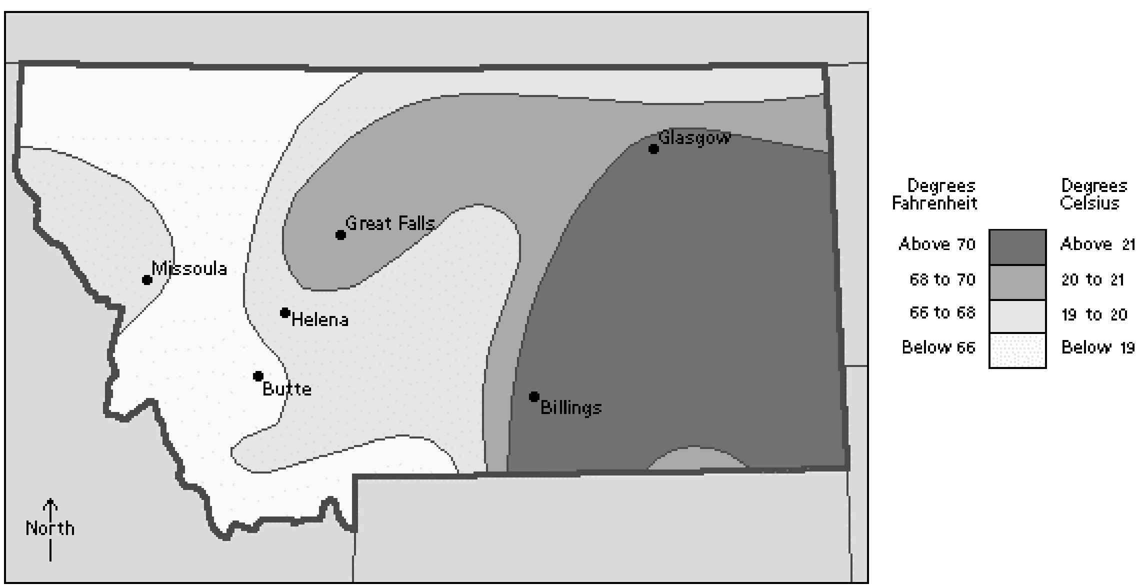

Figure 8. Montana July Temperature Map (World Book 2009)

6. FEASIBILITY ASSESSMENT

6.1 Possible Expansions of the MDT GPR Program

At present, MDT uses GPR primarily for a tool to complement their FWD program. GPR is generally able to determine the bound HMA thickness for this purpose. Based on the information gathered in the literature review, the survey of state highway agency GPR use, and the assessment of MDT pavement structures and rehabilitation program, there are a number of areas where it is feasible and desirable to expand MDT GPR program. These are listed and discussed below.

1. Pavement Design and Rehabilitation
   GPR layer information can be used as an input into the calculation for structural number for pavement reconstruction and rehabilitation design. For pavements receiving mill and fill or overlay rehabilitation, GPR layer information can also be used to ensure that the milling depth does not remove too much of the existing pavement layer. For cold in-place recycle rehabilitation GPR can be used evaluate the layer thickness and variability throughout a project during the design phase to ensure proper proportioning of bound and unbound material .

2. Network Level Evaluation
   GPR could be incorporated into the network level SCI calculation by modifying the YONAPAVE approach. Alternatively, the availability of the layer thickness data could lead to selecting an alternate SCI computation approach.

3. Quality Assurance of New Pavement Thickness and Density
   GPR has already been evaluated for QA of new pavement thickness and density by other agencies, and could be adapted by MDT for this use. Previous studies have shown that this application, in conjunction with the use of pay factors, can result in significant cost savings.

   In order to consider expanding MDT's program in these three areas, it is necessary to determine (a) the level of accuracy required to achieve significant benefit; (b) the ability of MDT's GPR system to achieve this level of accuracy; and (c) the requirements to achieve this accuracy (e.g., calibration coring, level of analysis). With the exception of the QA density application, most of the previous accuracy studies supporting these potential expansions of the MDT GPR project have been carried out with a 1 GHz horn antenna. There are no “off-the-shelf” studies directly supporting these applications using the Montana's 2.0 GHz horn antenna.

4. Determination of Base and Sub-Base Layers
   The 2.0 GHz horn antenna GPR system currently being used by the MDT is limited in depth of penetration to the bound HMA layers, and possibly to shallow aggregate base layers. It is not clear if this system can detect the bottom of CTB layers, since penetration through CTB is more difficult. It is possible to extend the depth range of this system by adding a second, 400 MHz antenna. The MDT's SIR-20 is a 2-channel system, and can support a second antenna, and recent tests by the equipment manufacturer (GSSI) have shown that this combination is workable. Positioning of this antenna would have to be worked out so that it did not interfere with the horn antenna and the FWD equipment.

5. Modifications to Current FWD Program
   As far as MDT's current program in connection with FWD work, it might be simpler to implement continuous GPR data collection rather than collecting data as individual files associated with each FWD test. This can be achieved by lowering the data collection rate to something on the order of 3 to 4 scans per foot (vs. the 10 to 15 scans per foot currently used). This lower data rate is generally adequate to provide the type of pavement layer thickness data needed by MDT.

   It would also be desirable for MDT to establish "calibration" sections within convenient access to MDT's offices in Helena. These would be sections where core data has been collected and documented (layer types, thickness, precise location), and which can be scanned periodically with the GPR system. The thickness calculations resulting from these periodic scans would be independently checked against the documented thickness data to confirm equipment operation, calibration procedures, and data analysis procedures.

6.2 Recommendations

It is recommended that in order to investigate and implement the GPR program expansions discussed above, the MDT should implement the following steps:

1. Evaluate the accuracy requirements of the GPR applications for pavement design and rehabilitation, and for network-level evaluation, as suggested in Section 6.1.
2. Design a field evaluation project to determine, on a statistical basis, the accuracy that can be achieved using the MDT GPR system on typical Montana pavement types for the types of applications being considered.
3. Conduct the field project and evaluate the data.
4. Evaluate the application of GPR for new construction QA/QC based on results from applications being developed by the Texas DOT and the Florida DOT.
5. Develop conclusions and recommendations for the appropriate future use of the MDT GPR system.

The key item in these recommendations, the field test program, would be designed in conjunction with MDT personnel using a test matrix that would include the following elements:

1. Pavement structure (eg. thick AC, thin AC, original full depth AC;
   overlay over original construction, unbound base, cement treated base).
2. AC mix types.
3. Environmental conditions (eg. temperature and precipitation).
4. Pavement condition (good, fair, poor).

Test sites satisfying the requirements of the test matrix would be identified in conjunction with MDT staff. Within each test site, a pavement section—typically 500 feet long—would be selected for data collection and evaluation. Where possible, LTPP sites will be utilized as part of this study, since these sites are well documented and adjacent areas have already been cored.

For each test site, the test plan will specify protocols for GPR data collection, FWD data collection (where appropriate) and the type and location of core samples required for validation of the GPR data. GPR data collection parameters include scans/foot, time range, and vehicle speed would be established for this testing.

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APPENDIX A:

Review of Published GPR Pavement Studies

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
Kansas DOT (Roddis et al. 1992)	layer thickness	AC and PCC	14	GPR thickness within 5-10% of cores	1 GHz horn antenna system	Analyzed automatically. Correlated with direct in-situ measurements and core and material samples.	GPR provides an effective alternative to coring for pavement thickness measurements. Accuracy can improve with calibration cores.	Questionable data due to, poorly defined asphalt/soil base and core damage during drilling. As thickness increases, accuracy decreases.
Texas DOT (Maser and Scullion 1992b)	layer thickness and moisture detection	AC	13	GPR thickness within 5% of cores	1 GHz horn antenna system	GPR data compared to "ground truth" data. Sixty-eight cores; focus on affects of thin overlays.	Identified effects of thin overlays on overall thickness, reconfirmed previously documented GPR thickness calculation, confirmed GPR's ability to detect moisture between asphalt layers, compared two different horn antenna systems.	Poor pavement condition at one site and the chip seal overlay at another (creates distortion of surface reflection) created lower accuracy thus affecting average.
Florida DOT (Fernando and Maser 1997) (Fernando, et al. 1994)	layer thickness and base material type	AC	26	GPR can be used for thickness and for distinguishing different types of base materials	1 GHz horn antenna	Changes made in data analysis to tailor existing procedures for the production/type work expected. QC and data management procedures addressed.	Addressed the feasibility of using GPR to predict layer thicknesses and base material type. Also the feasibility to apply this technology on a network level was considered. Last, FDOT was provided the equipment, software, and training to start their own self sustaining GPR project.	Analysis addressed the need for cores to support data interpretation. Need to be aware of sand-asphalt hot mix layer as it throws off results. Limitations for detection of base material arise if top layers weaken signal and is thus unable to reach a base. Also, presence of concrete in pavement attenuates signal as well.
Air Force (Seucy, et al. 1992)	layer thickness	AC & PCC	2	GPR thickness within 5% of cores	900 MHz ground coupled bow tie antenna and 2.5 GHz and 1 GHz antenna air coupled antennas	Asphalt and PCC pavement tested at a number of test sites with two different types of antennas.	GPR is a potentially powerful tool for airfield pavement evaluation. Both 2.5 and 1 GHz horn antennas appear to provide reasonable performance on asphalt concrete pavements. The 900 MHz ground coupled bow tie antennas have shown greater potential in this application.	The base layer of PCC pavements can be difficult to distinguish because the relatively higher conductivity of concrete can attenuate the signal for thick pavements. Need a method to automate data interpretation for 900 MHz antennas as it works best for PCC pavements.
FHWA (Infrasense 1992)	layer thickness	AC & PCC	4	GPR thickness within 7.5% of cores	1 GHz horn antenna system	Six cores taken and construction history data used to determine accuracy of results and to calibrate.	Results show radar data is a very accurate representation of the pavement layer thickness for both asphalt and concrete pavement. Use of calibration cores may be appropriate for project level work, where high accuracy is important.	None reported.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASUREMENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
SHRP (Maser 1994)	layer thickness	AC, PCC and composite	10	GPR thickness within 8% of cores	1GHz horn antenna system	GPR data correlated with core data from LTPP data base (67 cores). Steps of analysis included blind evaluation, plan data calibrated, core calibrated and then an overall final calibration.	GPR yields accurate thickness data for asphalt, concrete and composite pavements.	Plan data only useful for base layer thickness calibration. Calibrating GPR to old core data proved to be error prone as the pavement was currently significantly different then when the cores were collected. Difference caused by intensive coring pattern. Similarities between base and sub grade made it difficult to detect interface.
FHWA (Hughes et al. 1996)	layer thickness	AC	3	GPR can be used for QA	1 GHz air launched horn type antenna	30 cores taken (1-2 per section) for calibration of results.	GPR remains an accurate tool for determining layer thickness. Interpretation of material is based on strength of reflection between layers, layer boundary pattern and layer thickness.	No previous core data or construction drawings to establish interpretation guidelines of layers. Cores taken on this project acted as QC.
SHRP (Smith and Scullion. 1993)	pavement deterioration	AC	3	Project did not fully achieve objectives	1 GHz and 2.5 GHz air coupled horn antenna system	Measuring GPR's ability to detect stripping, moisture in base layer, voids, and overlay delamination in pavements with 2 different antennas; 2.5 GHz for high resolution of top layers and 1 GHz for relatively deep penetrations.	2.5 GHz system still needs further development. Difficult to use. Interpretation software needs more development, testing, and refinement. The ability to detect layer thickness and moisture content achieved.	GPR not able to reliably detect air-filled voids and stripping.
Wyoming DOT (Infrasense 1994c)	general	AC, concrete and composite	9	GPR thickness within 0.5" of cores	1 GHz horn antenna	Asphalt considered a 1 or 2 layer system; where the base/sub grade interface is detected the dielectric constant of the sub grade was calculated, and where it was not the base was used. 4 correlation cores taken at each site. Split tube samples were taken in the base course at all asphalt pavement sections to determine material composition and obtain samples for moisture analysis.	Correlation between GPR and cores showed an accurate prediction of asphalt thickness. Average deviation of +/- 0.5 inches. Cores and split tubes ranged in thickness from 2-10 inches.	Concrete pavement thickness and sub grade moisture could not reliably be calculated due limited signal penetration and weak electromagnetic contrast between concrete and base materials.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
Minnesota DOT (Infrasense 1994a)	layer thickness	AC & PCC	2	GPR thickness within 2-5% of cores	1 GHz air coupled and 500 MHz ground coupled antennas	A blind calculation of the thickness of asphalt and concrete was first conducted. These results were compared to the coring data to determine the accuracy of the different antennas and applications.	Accurate asphalt thickness data can be obtained using the high-speed horn antennas. Accurate thickness data is obtained for concrete pavements and bases using lower speed ground coupled antennas.	Measuring the thickness of concrete pavements with high-speed horn antennas is not reliable.
SHRP (Maser 1994)	layer thickness	AC	10	GPR thickness within 5-10% of cores	1 GHz horn antenna	Results evaluated in 2 steps (1) blind: without any ground truth data to correlate/calibrate to and (2) calibrated using 1 pre existing core per site.	Radar shown as an accurate ND technique for the evaluation of pavement. The blind results showed an average deviation from the cores of 8% where as the calibrated results showed a lesser average deviation of 5%.	Current cores would provide a better calibration of GPR data.
TRL (UK) (Infrasense 1994b)	layer thickness	AC	4	GPR within 10% of cores	1 GHz horn antenna	Blind calculation of the pavement thickness first calculated. These results compared to core and trial pit data.	GPR results more accurate for cumulative pavement thickness than they are for the individual layers. Repeatability test yielded general agreement in results. Core results helpful to assist in identifying layer material types in radar data.	Layers showing up in cores and test pits but not in GPR data as they do not have a dielectric contrast.
New York (Infrasense 1995)	layer thickness	AC	n/a	No cores	1 GHz horn antenna	GPR data collected. No cores used. GPR thickness data used for FWD backcalculation.	35% of the pavement is likely to have saturated base or sub grade. Radar data was able to explain inconsistencies in FWD data in approx. half the cases.	Lack of contrast between base and subgrade layers limited the ability to calculate base layer thickness to 3% of the data.
Germany (Infrasense 1993)	layer thickness	AC	27	GPR thickness within 10-15% of cores	1 GHz horn antenna	Collect radar thickness data at each core location and correlated that data with the actual core values. Asphalt considered to be a one or two layer system.	GPR provides accurate non-destructive continuous asphalt pavement layer thickness data. Generally good correlation between radar and core data. Discrepancies due to local thickness variations near the cores and a second asphalt layer, which was either not retained in the core or not considered in the GPR data.	In some cases the second layer is a loosely bound material, which is not retained in a normal core. Therefore the cores would only match the first layer. Thickness results done in 1-2 meter intervals due to uncertainty of the actual core location in the radar data.
Kent County UK (Infrasense 1996b)	layer thickness	AC and PCC	7	No cores	1 GHz horn antenna	GPR data collected for rehabilitation project. No cores used. Thickness and layer structures reported.	No ground truth data to correlate or calibrate to results.	Difficult to distinguish between old, deep asphalt vs. base in some cases.

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
Michigan DOT (Infrasense 1996a)	layer thickness and base moisture	AC	4	No cores	1 GHz horn air launched and 500MHz ground coupled antennas	GPR data collected for rehabilitation project. No cores used. Thickness, layer structures and potential moisture content reported.	GPR provides accurate non-destructive continuous asphalt pavement layer thickness and moisture detection data.	Base not seen in parts of data due to lack of contrast between bot-tom layers.
Idaho DOT (Infrasense 1997)	layer thickness	AC & PCC	6	GPR thickness within 7% of cores	1 GHz horn antenna	All pavements analyzed on a network level. One to three 500-foot sections in each of the 8 sections were identified for detailed evaluation and correlation with cores on a project level.	Accuracy achieved using GPR for asphalt and concrete pavement thickness is consistent with past studies. Primary issue raised was identification of material type.	In some cases GPR analysis deemed a base layer to be asphalt when boring data defined it as a granular base. This could be due to a sharp contrast between the base and sub grade. Comparing GPR and boring data thicknesses can be difficult as boring data thicknesses for unbound materials are not very accurate.
Kansas DOT (Infrasense 2000b)	stripping	AC	1	None	1 GHz horn antenna	Reflection between asphalt and base boundaries analyzed. Areas identified where reflection amplitude was 50% lower than the mean value (less contrast between two layers). 7 cores taken to confirm layer boundaries and conditions.	7 cores taken to assess accuracy of GPR data. GPR data highlighted areas where stripping was likely to occur. However, none of the cores confirmed this. Therefore, it is likely that stripping at the bottom is not present in the surveyed section.	None reported.
Illinois STHA (Infrasense 2000a)	pavement layer thickness and condition	AC and PCC	1	Average deviation of -0.18 inches GPR to core data.	1 GHz horn antenna	51 cores taken to correlate to GPR data. Avg. deviation of -0.18". AC to PCC interface condition evaluated by identifying areas where the dielectric constant deviated from the mean by over 30%.	The AC thickness and AC to PCC interface condition data to be used to determine the feasibility of various resurfacing alternatives. Overall, GPR proved to be an accurate tool for determining pavement thickness and condition.	There were a few thickness outliers, which can be attributed to the differences in location between the GPR and core data.
Arkansas HTD (Infrasense 2001)	layer thickness, voids and density of base concrete, moisture in base and sub base	AC & PCC	8	GPR thickness agreed with cores	1 GHz horn antenna	Eight sections totaling 24 miles were surveyed for thickness, voids, and moisture. No cores taken.	GPR surveys conducted showed usefulness of GPR for evaluation of in-service pavement characteristics, particularly for pavement thickness, which can be used in lieu of coring for QC of new AC construction.	Discontinuities in the base layer, mostly due to infiltration of the sub grade in the base material. Voids and moisture detection needs to be verified by direct field observations.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
California DOT (Maser 2003)	layer thickness	AC	11	Average GPR thickness within 0.10" of core	Two different Model 5100 1.5 GHz ground coupled antenna units and a Model 4108 1 GHz horn antenna unit	Various methods tested in laboratory and in field. Asphalt and concrete pavements were tested with both air launched and ground coupled GPR, as well as impact echo and multi receiver mechanical wave methods. Thickness values from each test method were correlated with cores taken at the sites.	Determined two GPR methods for measuring the thickness of new asphalt with accuracy suitable for use with pay factors. Also, impact echo determined to be the best method for measuring concrete thickness but did not obtain initial goal of (0.1 inches).	Common Mid-Point (CMP) GPR method did not work as well as the horn antennas, showing more scatter and exhibiting limitations in the presence of reinforcement. Multi-Receiver Technique was discontinued given the laboratory nature of the equipment and the need to implement and test a new type of impact source.
South Dakota DOT (Maser 2006)	layer thickness	AC & PCC	3	Accurate thickness data; used with FWD provides more accurate structure evaluation	1GHz or 2 GHz horn antennas	GPR distance data correlated with FWD distance data to ensure accuracy. Analysis carried out at 1-foot intervals. Involved tracking layers and identifying layer types. GPR data compared to core data.	In comparing GPR to core data there was an average thickness difference of 0.82 inches. Thickness data used for FWD backcalculations.	Some cores showed GPR overestimated thickness but upon further observation this was likely due to the bottom of the core being missing. For one section a weak contrast between the AC and base produced scattered results.
New Hampshire DOT (Infrasense 2007)	layer thickness	AC	2	Accurate thickness data used in conjunction with Rolling Wheel Deflectometer	1 GHz horn antenna	Marked mile post locations where data was available and also were used to check DMI measured distances. Data analyzed at 1 foot intervals and reported at 0.1 mile intervals.	The core data matches closely with the GPR thickness data. There is a good agreement between the plan data in some areas but not all.	Depth of base difficult to detect in some cases due to weak contrast.
Indiana DOT (Noureldin et al. 2003)	layer thickness and structure	AC and PCC	n/a	GPR provides an accurate estimate of overlay layer both asphalt and concrete, but not for total pavement thickness	500 MHz ground coupled and 1 GHz horn antennas	GPR sections collected every 1000 feet. Enough to accommodate FWD locations. 1 core taken per mile on selected roadways.	Network level testing employing FWD and GPR is a worthwhile. GPR estimated 12" concrete overlay perfectly. However, any pavement layers underneath concrete not seen. Thickness of 13" HMA layer estimated almost perfectly. However 10" rubblized pavement layer underneath picked up inconsistency. Also, 8" aggregate base not picked up by GPR.	Picking layers below overlay were inconsistent. Recommend using more cores to calibrate bottom layers.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
Virginia Tech Transportation Institute (Al-Qadi et al. 2006)	QA/QC new pavements	AC	n/a	Mean thickness error of 2.9% for HMA layers	1GHz air-coupled horn antenna	Survey taken on the base layer and then after the HMA layers were laid down.	GPR can be used successfully for QA/QC of new HMA pavements if used properly.	Highest error in HMA base layer, due to the irregular bottom caused by its roughness and large aggregate size.
Virginia DOT (Al-Qadi et al. 2003b)	layer thickness and moisture content	AC and PCC	n/a	HMA pavement mean thickness error of 6.8 %	1 GHz air coupled horn antenna and 900 MHz ground coupled antenna	Thicknesses correlated/confirmed with coring data and VDOT's knowledge of construction repair history.	Determined pavement layer thicknesses with a minimal error of 6.8%. Located moisture pockets known and unknown to VDOT.	Areas with a great amount of error can be attributed to a discrepancy in the core location. Also, in comparing different sets of GPR data for the same location the results varied by 2.7%.
New Jersey DOT (Ahmed et al. 2004)	layer thickness and structure	AC and PCC	n/a	Pavement layer thickness determined accurately 95% of the time for flexible, rigid and composite type pavements	1 GHZ horn antennas	Network and project level survey. Needed to consider different pavement types, (flexible, rigid, composite) and sections where FWD data had already been collected. After data collected compared to coring/as built data for accuracy measurement.	GPR generally good at predicting pavement types and thicknesses. However not as reliable for predicting base and sub base materials and thicknesses. GPR on a project level in this study did not provide any additional information then at a network level. Suggested to use with supplemental coring and drilling, and not as a stand-alone product. Integration of GPR into the PMS minimizes the gaps and deficiencies in the as built database.	Sub base and base layer identification of material type and thicknesses difficult due to weak contrast.
Virginia DOT (Al-Qadi et al. 2005)	layer thickness	Asphalt and concrete	n/a	Average absolute pavement thickness error 4.6%	1 GHz horn antenna or 1.5 GHz ground coupled antenna	Used air coupled antennas all pavement types, and ground coupled on composite and concrete sections. Correlated results with core locations.	Data analysis results showed no difference between two GPR collection systems. Estimating thickness with GPR decreases in accuracy with an increase in the age of the pavement. Concrete pavement thicknesses estimated more accurately then asphalt when compared to core data in this study.	Dielectric constant based on surface reflection only. Thus for HMA pavements the dielectric constant for the entire layer would be underestimated. Also, presence of thin overlays, smaller than GPR thickness resolution would throw off the assumed dielectric constant for the top layer.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
University of Illinois and Virginia DOT (Al-Qadi et al. 2003a)	layer thickness	Asphalt	9	Using core correction less than 4% average error obtained for layer thicknesses	1GHz air coupled antennas	GPR layer thicknesses correlated and corrected with cores. Correction factor used to eliminate systematic errors due to analysis assumptions. Also effects of GPR vehicle motion on accuracy of thickness results analyzed by doing stationary and moving surveys of same areas.	By applying core correction factor the average absolute error between the estimated and measured thicknesses decreased from 5.6% to 4%. Additionally, an algorithm was developed to estimate the dielectric constant of an entire HMA layer.	Due to error accumulation and energy attenuation, the error increases as the layer depth from the surface increases.
Georgia DOT and ARA (Hammons et al. 2005)	stripping	Asphalt	n/a	none	1GHz air coupled antennas	Several non-destructive survey methods were analyzed to determine their capability to locate areas of stripping, either by themselves or in various combinations. Cores used to calibrate methods. Visual inspections, cores, and laboratory tests used to validate results. Observation of surface distresses, complete GPR survey, Infrared, FWD, and seismic testing used.	As stripping occurs non-uniformly in pavement. Measuring the uniformity of electromagnetic properties may be useful in dividing a test area into sections that can be used to plan seismic and coring tests. Using cores and seismic testing improves reliability of identifying layers with moisture damage and stripping.	GPR is not a stand-alone solution to detecting stripping. The use of seismic and core testing is needed to produce accurate/reliable results.
Ministry of Transportation Ontario (Balasundaram et al. 2006)	layer thickness and condition	AC and PCC	1	none	1GHz and 500MHz ground coupled antennas	Functional and structural condition investigation of the existing pavement consisted of a visual condition survey of the paved surfaces, soils investigation, asphalt coring, a Falling Weight Deflectometer (FWD) survey, and a Ground Penetrating Radar (GPR) survey. GPR data calibrated with the point source data.	GPR can increase the accuracy of a pavement investigation and fill in the gaps between point source investigation tools. GPR identified the precise location changes in the pavement structure. It is necessary to use other means such as boreholes and core information to calibrate the GPR data and interpret the subsurface layering. GPR also provides detailed layer thickness data to provide increased accuracy in FWD results.	None reported
Texas DOT and FHWA (Scullion 2006)	moisture and void detection	AC and JCP	n/a	none	1 GHz air coupled antenna	Used GPR data to determine depth of damage to plan rehabilitation work. Confirmed results with pilot holes.	GPR can be used to locate major defects in either the asphalt covering of JCPs or water filled voids below slab. All GPR interpretations require validation.	Not able to detect minor defects such as thin air filled voids.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
African Eng. International and Aperio Limited (Hartman et al. 2004)	layer thickness	AC	n/a	none	horn and pod antennas	GPR layer thickness data use to calculate layer moduli using FWD data. Existing test pit data was used to calibrate.	On the global scale GPR data matched the in-situ situation well. Layer thicknesses measured compared well with information from as-built records. GPR was able to uncover interface between the old milled asphalt and the new overlay.	None reported.
Kentucky DOT (Willet and Rister 2002)	layer thickn2ess	AC and PCC	8	Using core calibration 2-8 % avg. error for layer thicknesses	1 GHz air launched horn antenna	Tests conducted to identify GPR's repeatability for wet and dry pavements and to determine the optimum number of calibrating cores.	By adding more calibration cores, the predicted GPR results get closer to the actual thicknesses. Four cores for 2 miles of data were deemed to be the optimum number. Use of GPR for asphalt pavement layer thickness is promising though use for concrete pavements must be exercised with caution.	Measuring thickness of concrete pavement layers less accurate. Cores must be used during preprocessing to calibrate GPR results.
Virginia DOT (Diefenderfer et al. 2006)	moisture detection	AC	5	GPR can identify areas of varying dielectric constants attributed to variations in the moisture content	1 GHz air coupled horn antenna controlled by a SIR 20 system	Moisture measured for 5 pavement sections. Used statistically based data normalization procedure to assess qualitatively the moisture condition of the sub grade of flexible pavements.	Study showed GPR can identify areas of varying dielectric constant attributed to variations in moisture constant of the sub grade of various pavement sections. Two advantages of GPR are, it provides continuous readings of moisture conditions, and can be performed at highway speeds with no traffic control. Comparing collection rate of coring to GPR; GPR could cover VDOT's 225 lane mile system in 2% of the time it takes to do coring.	None reported.
Texas DOT (Sebesta and Scullion 2002 and 2003)	QA/QC new pavements	AC	3	GPR and Infrared are viable for implementation in the form of either QC (infrared) or QA (GPR)	1 GHz air launched horn antenna	Infrared imaging and ground penetrating radar used to investigate the uniformity of new overlays.	Infrared imaging and GPR are both effective tools for QC and QA of HMA overlays. If density changes are the primary heterogeneities in new HMA, then GPR is more effective then Infrared. To calibrate results, a min. of 3 cores should be used per test section.	None reported.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
Saskatchewan DHT (Berthelot et al. 2005)	layer thickness and moisture content	AC and PCC	2	The asphalt concrete was 3% thicker measured with GPR then grade hole samples	1 GHz air coupled antenna	GPR thickness values compared to grade hole samples and as built drawings to assess accuracy. Subsurface of pavement measured for moisture content, based on dielectric permittivity.	GPR measures road structure thicknesses accurately to within +/- 3% of ground truth. Also GPR identified significant variability in substructure dielectric permittivity profiles, attributable to variable subsurface moisture. Also, identified drains ability to reduce moisture.	None reported.
University of Alaska and Texas A&M (Liu et al. 2008)	delamination detection	CRC	3	3 step analysis protocol of delamination detection for concrete pavements established	1.5 GHz ground coupled antenna system	Three-step analysis protocol of delamination detection was proposed on the basis of field-collected GPR data and graphic output. These included: preliminary evaluation, development of a site calibration algorithm, and establishment of threshold amplitude difference.	40 cores taken in 3 test sections, all of which confirmed that there were no shallow delaminations. This is likely due to effective corrective measures including optimized material design and curing practices.	Homogeneous condition of test sections produces a low level of confidence in the prescribed protocol.
Missouri DOT (Hickman et al. 2000)	layer thickness	AC and PCC	95	Studies 2 years apart, highly repeatable and give good estimates of layer thicknesses when comparing to design history data	1 GHz air-launched horn antenna system	GPR analysis included choosing sites for drilling and comparing results to design history info.	Through comparing with construction history demonstrated the ability to determine pavement layer profiles. Used to revise and update design history information. Also indicated areas of anomalous radar signals which could be indicative of roadway problems. Data was found to high repeatability in comparing it to results from 2 years prior. Results show GPR can be a good tool for QC in road construction and repair.	None reported.

APPENDIX A: REVIEW OF PUBLISHED GPR PAVEMENT STUDIES, *CONTINUED*

AGENCY (REFERENCE)	MEASURE-MENT OBJECTIVES	TYPE OF PAVEM'T	NO. TEST SITES	KEY FINDINGS	TYPE OF EQUIPMENT	ANALYSIS PROCEDURES	ACCOMPLISHMENTS AND CONCLUSIONS	LIMITATIONS REALIZED
Naval Facilities Engineering Service Center (NFESC) (Malvar and Cline. 2000)	void detection	AC	3	GPR determined to be unreliable means of detecting voids under airfield pavements. Instead, recommended as a complementary measure to determine pavement thickness.	Not specified	A number of non-destructive tests examined as a means for detecting voids in asphalt pavements.	No single technique is capable of providing a complete solution to void detection problems. Found GPR to not be a reliable tool to predict weak areas and should not be used by itself for void detection at this time. The optimum methodology to detect voids was determined to be a combination of visual inspection, Heavy Weight Deflectometer (HWD), and Dynamic Cone Penetometer (DCP) testing.	Though GPR can identify anomalies in the pavement, it cannot quantify their impact on the load capacity.
Texas DOT (Rmeili and Scullion 1997)	stripping	AC	7	GPR effective way to detect stripping in asphalt concrete layers.	1 GHz air launched antenna system	GPR data interpreted before taking the 60 validation cores at 1 mile intervals. Looking to determine; section breaks, average thickness of asphalt layer and extent of severity of any defects.	Section breaks identified by GPR matched breaks found during corning and thickness estimates, and depths to defects were reasonable. Though GPR detected areas of stripping well, cores showed moderate to severe levels deterioration.	Thickness of stripped layer difficult to estimate. This is due to variable lower layer at these locations making data difficult to interpret.
University of Wisconsin, Lawrence Berkeley National Lab, and University of California at Davis (Grote et al. 2004)	moisture detection	AC	2	Ground coupled GPR techniques can be used to estimate the volumetric water content in sub-asphalt aggregate layers with high resolution, in multi-dimensions and in a non-invasive manner.	900 and 1200 MHz ground coupled antennas	Water content estimated from GPR travel time data, identification of wet zones beneath the AC from GPR amplitude data for both drained and un-drained pavement. GPR data for both drained and un-drained sections validated with coring.	The GPR derived estimates of water content with relatively low errors. ((root-mean-square-error of 0.021 cm^3/cm^3). Amplitude analysis of the AC aggregate reflection could also be performed using the more common air launched antenna.	For more accurate results, the thickness of each aggregate layer must be characterized.
Kentucky DOT (Rister et al. 2008)	layer thickness	AC and PCC	5	Radio noise interference corrupted data from the 2.0 GHz antenna making it impossible to obtain thickness measurements for the overlay.	2.0 GHz air launched antenna, 900 MHz and 200 MHz ground coupled antennas	Data too corrupted by noise to analyze.	Data too noisy for thickness analysis. FCC regulations limit antennas use thus disabling the ability to determine thin pavement overlay thicknesses.	Outside radio frequency noise was interfering with collection of useable radar data.

Appendix A: Review of Published GPR Pavement Studies, *continued*

Agency (Reference)	Measurement Objectives	Type of Pavem't	No. Test Sites	Key Findings	Type of Equipment	Analysis Procedures	Accomplishments and Conclusions	Limitations Realized
Kentucky DOT (Rister et al. 2008)	void and moisture detection	PCC	1	GPR used to determine voids was inconclusive. However, GPR able to determine areas that were retaining water between the bottom of the PCC and top of the dense graded aggregate layer.	900 MHz ground coupled antenna	One reading taken every 6 inches. GPR data was mapped and moisture ratings were reported every 200 feet based on a calculated threshold from the data. The ratings where then graphed and used to facilitate rehab decisions.	GPR not successful in identifying voids but reasonably successful in determining moisture. KTC design committee determined that the GPR data gave the appropriate information to select optimum design alternate.	GPR not able to detect voids.
Virginia DOT (Maser 2001)	thickness, moisture, and void detection	AC and PCC	3	GPR thickness evaluations all within 5% of core thicknesses and areas where dielectric constant deviated significantly from mean mapped as potentially poor condition	1 GHz horn antenna	GPR data analyzed for thickness and condition at the concrete-asphalt boundary. Thickness compared with coring data. Condition evaluated based on deviations of the calculated dielectric constants from the mean. This likely means a presence of moisture or voids.	GPR is an accurate means for characterizing asphalt layer thickness on composite pavement structures. Also useful to assess the condition of the concrete under the overlay for estimating repair requirements during rehabilitation.	None reported.
Texas DOT (Wimsatt et al. 1998)	thickness, condition, moisture and void detection	AC and PCC	4	GPR was useful in assessing pavement layer condition and rehabilitation assessment. In one project, results from the GPR survey saved approx. 530k compared to the orig. construction plan.	Air launched and ground coupled antennas	GPR used to; assess pavement layer condition, identify the extent of a perched water spring, locate pipe under-drains by calculating local dielectric constants and comparing to the average from the GPR data.	GPR useful for assessing pavement layer condition and rehabilitation assessment for roadways. Data helped to determine rehabilitation strategies, the extent of a perched water spring underneath the pavement, the placement of pipe under-drains, and base repair areas.	None reported.
Alabama DOT (Parker et al., 1999)	Pavement thickness for FWD backcalculation	AC	5	GPR thickness values were of sufficient accuracy to be used for FWD backcalculation	Air-launched antenna	Accuracy of GPR thickness data was determined by comparing the average deviation between core thickness and reported GPR thickness at core locations. Backcalculated moduli calculated using core thickness and GPR thickness were compared.	Differences between backcalculated moduli using core and GPR data were not significant. Study concluded that GPR may be used to estimate bound surface layer thickness for use in FWD analysis.	None reported.

APPENDIX B:

Survey of State Highway Agency Use of GPR

SURVEY OF STATE HIGHWAY AGENCY USE OF GPR

A general survey was conducted with the State Highway Agencies (SHA) to determine their experience with GPR and how it is being used in their agency. Ninety-two state personnel, representing forty-eight states, were contacted. South Dakota was not contacted, since a survey of their GPR experience was recently published. Of those contacted, responses were obtained from seventy-one individuals, representing forty-three states. Responses were received by email or by phone. Complete details on the responses are provided in this appendix.

Some of the responses are listed as "Not Applicable." This was reported for questions that did not apply to the State. For example, a response from a state not using GPR, or one that contracts GPR work out, would be "Not Applicable" for questions regarding calibration.

1. What groups within your State have experience with Ground Penetrating Radar (GPR)?

Alabama: The Maintenance and Construction departments have experience with GPR. We have used GPR to give estimates of void volumes under concrete for concrete rehabilitation projects. Also, a research project was done in the late 1990's in our highway research center. I remember going to a demo and looking at a van with massive antennas about 3-4 years ago.

Alaska: We have used GPR extensively in the past for geophysical work; I do not believe it is been used very much on pavements.

Arizona: We have not really used it since we experimented with it in 2005. We do not currently use it. We have our first GPR unit, and have been trying to use it for the past six months or so, but we have not been able to get any useful information from it. We do not know yet if it is an issue with the software or problems with interpreting the data.

Arkansas: I believe we did a research project in 2001 on GPR, but we do not currently use it.

Colorado: Our bridge unit and materials unit both have experience with GPR.

Delaware: We do not currently use GPR. About ten years ago the Federal Highway Administration (FHWA) had let us use some GPR equipment so that we could try it out. At that time we were checking pavement thicknesses with new construction pavement, but could not get accurate results. I believe there was a one inch variation and that was too much for our pavement focuses.

Florida: I'm out of our materials office and we have our own equipment. When GPR is needed, we do the work ninety percent of the time.

Georgia: We do not have any experience with GPR.

Hawaii: We have used it for project level pavement design investigations. Ken Maser is working with our bridge group to use it for bridge rehabilitation. The other vendors have worked with private industry to find utility locations and I believe the military has used it for United Service Organization (USO).

Idaho: We are currently not using GPR. About 13-14 years ago we did a research project where we put out a request for GPR manufacturers to come to Idaho. We had selected eight different scenarios and asked them to use GPR to run tests on each scenario. We had already tested these sections and knew the results. Not many GPR manufactures showed up. I believe two manufacturers attended. *Road Radar* used a ground-coupled GPR unit and *Infrasense* used an air coupled GPR unit to do the testing. I believe the results were pretty accurate and some did better than others, but a lot has changed in the last 15 years regarding GPR so that study may be considered outdated. Nothing has gone on since then. One of our districts purchased a GPR from *GSSI*, about two years ago. They used it for a while, but found that they did not have the manpower to operate it. They gave the unit to me, but we have not done anything with it in the past year and a half. There was a question on whether to use GPR on a project level with our falling weight deflectometer (FWD) or on a network level with a skid-vehicle. We have recently put in a request to get a more modern Pavement Management System to better manage our pavement thicknesses and the materials used. We're trying to head in that direction, but have not gotten far at this time. When we use FWD, we typically core every half-mile or mile and I think that it would be good to have continuous information.

Illinois: I believe some of the districts have hired consultants or firms to perform work using GPR. I supervise the non-destructive tests and we do not currently own the device.

Indiana: GPR has been used by our Department of Transportation. Environmental applications have included locating underground storage tanks for road widening projects. Our archaeology group has used it for locating drainage tunnels. We have used a ground coupled system for locating voids under pavement, locating underground storage tanks (USTs), and evaluating bridge decks. We have also used an air-launched system to determine thicknesses of pavements and bridge decks.

Iowa: We do not have a GPR unit, but plan to get one. Some districts have had contractors/consultants to do GPR work on a site-by-site basis. They do not have an ongoing survey or any routine use yet. I believe the Iowa State University has a GPR unit that they've used for some projects.

Kansas: Our experience in house with GPR was very limited. We did have our own equipment years ago, but were never very successful with it. We have used GPR to get pavement thicknesses, or to find voids in or under pavements. In both cases we had marginal success at best. We feel that GPR interpretation is more of an "art form" than a "science."

Kentucky: We have a relationship with the University of Kentucky. They have a GPR unit that we use on occasion in our pavement maintenance and design departments. We do not use it ourselves, but hire them to do the work.

Louisiana: GPR has been used in our materials and pavement management groups within our agency. In 1995 we used GPR on a network level to inventory our AC pavement thicknesses. We had problems telling the difference between soil cement and concrete. GPR couldn’t distinguish the difference. GPR was also used on a project in New Orleans after Hurricane Katrina.

Maine: We're in the process now of conducting a pilot study. We are looking at the data to see what we can glean from GPR. I believe the bureau of project development is looking to acquire one.

Michigan: Our construction of technology department has used GPR. It grew out of our research department, but we do not do research anymore. We currently do technical consulting for the whole department. We have our own GPR equipment and have done work for many of the regions.

Minnesota: Our research office and our pavement office have experience with GPR. I believe our research department has the most experience with it, but they gave the device to the production office and they are starting to do work with it for the districts. The central materials lab also has experience with it.

Mississippi: We used GPR once on US 90 after Hurricane Katrina for rehabilitation purposes, but it is not used routinely. I was not involved that much with that project when it was used.

Missouri: We do not have a lot of experience with GPR. There were a few times when we hired contractors to do work using GPR. We experimented with GPR a little bit. Some experiments were better than others. The University of Missouri used to be our academic staff and they assisted us with GPR.

Nebraska: Over the years we have experimented with GPR. We have used it for bridge deck testing. We have found that it isn't refined enough, or easy enough to interpret the results. You have to be pretty experienced in interpreting the data.

Nevada: We are not currently using GPR at this time.

New Hampshire: Our geotechnical group uses GPR for some exploratory aspects and our construction testing group uses it to determine the cover of concrete on bridges.

New Jersey: We do not have a GPR unit. Rutgers University has done some work for us as needed per project.

New Mexico: We have used GPR in a couple of forensic studies to investigate pavement that was failing prematurely.

New York: Our research group would probably be most familiar with it. One of our local researchers did some research on pavement sections on Interstate 87. Departments in our agency have also used it on bridge decks and to locate utilities.

North Carolina: Our pavement department used it for 10 years and then got away from it because it was too time-consuming to analyze the data, and we found the results to be frequently uncertain. Our geotechnical division still uses GPR, but primarily to locate underground storage tanks (USTs) or large voids under pavements, like sinkholes.

North Dakota: Our pavement design and research section, and our materials section hired consultants to do GPR work to look at asphalt depth, and to evaluate bridges.

Ohio: To my knowledge our pavement management section has only looked at using GPR as a possible tool. I do not believe anyone has actually used it on a project level. We do have a research contract that is looking at it currently, but we have not used it. Our geotechnical department has used it to meet special project needs such as locating underground mines or looking for voids near the surface. Another application that it has been used for was with relation to culvert failure, looking at the material above the culvert to see what had happened.

Oklahoma: I believe our pavement management and research sections have experience with GPR, I'm not sure if any of the other groups have experience with it.

Oregon: We do not have any experience with GPR. I do not believe we have ever done any work with it.

Pennsylvania: We do not use GPR at this time. We did a study a few years ago, but I do not believe the GPR results were accurate enough for our applications.

Rhode Island: Our materials and research groups have used it on and off for the past 10 years, and is looking into getting a GPR unit. I'm not sure if our planning section has used GPR at all.

South Carolina: We do not have any experience with GPR. I believe a demonstration was given about 10 years ago. A vendor came and showed us the equipment, but we just felt that the interpretation of the data was very difficult and required a lot of expertise, so we rely on cores when we need pavement thicknesses.

Tennessee: We have had a couple of presentations on GPR, but as far as I know we have never used it on a project. I do not know if our survey unit has used it.

Texas: Our flexible pavement branch and our geotechnical branch are familiar with GPR. Also our pavement analysis team is familiar with it.

Utah: Our pavement management group has used GPR in the past. I'm not sure if our structural division or geotechnical division has worked with it at all.

Virginia: Most of the experience that we have with GPR comes from our transportation department in Charlottesville. They operate the units the Virginia Department of Transportation has. I believe our research council and materials division also has experience with it.

Washington: I do not believe we have ever used ground penetrating radar. We are getting to the point where we are no longer using the falling weight deflectometer (FWD). We have basically used the FWD on all of our highways.

West Virginia: I believe our materials section may have experience with GPR. They had an old ground-coupled model, but they are currently looking into purchasing a new one.

Wisconsin: Our bridge and maintenance group and our geotechnical group have had experience with GPR. Our geotechnical group has their own GPR unit.

Wyoming: We do not have any experience with GPR. We do have a research project with the University of Wyoming to look at bridge deck evaluations for delamination, and one of the methods that they are evaluating is GPR. I believe that research project is scheduled to start in the summer of 2009.

2. How long has GPR been used by your agency?

Alabama: Five years. Less than 3 percent of our pavement system is concrete. Concrete has progressed distress-wise to try to rehabilitate it. Typically we overlay our concrete sections with asphalt concrete. I do not believe we have used GPR over the last year. It was used on other jobs to try to estimate the quantity of a foam under-sealing needed on a project.

Alaska: I'm not sure. I've been here 8 or 9 years, and in that time we have used it for geophysical work pretty extensively.

Arizona: It's been used by our agency for 2 years, but our department only started working with over the last 6 months.

Arkansas: We do not use it at this time.

Colorado: We have used GPR on and off for the past 12 years.

Delaware: We do not currently use GPR.

Florida: We have been using GPR since the mid 1980s.

Georgia: We do not have any experience with GPR at this time.

Hawaii: We have been using GPR for about a year.

Idaho: We are not currently using GPR.

Illinois: I do not know how long it is been used. I have only been in the materials division for a couple of years. The oldest project I know of was around 2003 or 2004 for the IL 29 4-lane study, and those were cross-hole soundings.

Indiana: We have used GPR for about 9 years.

Iowa: We have started using GPR fairly recently. I believe we have used it for the last year or two. Prior to that, we would use FWD to get an idea of voids under pavements. We have looked at using GPR for the past 10 years, but it hadn't made any strides to give us much confidence in it until the last two years. We're currently working on getting a GPR unit that will be attached to our FWD.

Kansas: We have used GPR for about 15 years on and off. More or less it is been used on a case by case basis for specific needs.

Kentucky: I'm not sure, but I know that we have used GPR for at least the last 3 years.

Louisiana: We used it 1995, and also for some work in New Orleans after Hurricane Katrina.

Maine: We are not currently using GPR.

Michigan: We have used GPR for about 10 years.

Minnesota: We have had the GPR equipment since 2002. We acquired the equipment over time. It’s been in our research department for years, but was just recently transferred to our production office about 6 months ago.

Mississippi: I believe we just used it once after Hurricane Katrina for rehabilitation purposes.

Missouri: We have only used GPR for research purposes. The research was contracted through the university and they did some of the primary research. We were trying to use GPR to determine new pavement thickness for quality assurance or to incorporate into our specifications. At that time we got pretty good results. The problem was using aluminum for the dielectric charts. About 6 years ago I did a study of a construction project using a dowel bar inserter and compared the GPR results. We looked at the placement of the dowel bar inserter and compared it with dowel baskets. We felt that we got good results from that. Since then, there have been a couple of times where it is been used to identify dowel placement, and to locate voids under pavement. Lately we have been more receptive to using it as a more main stream forensic tool.

Nebraska: We do not' currently use it. We used it about 10 years ago, and I believe that our bridge deck testing unit has also experimented with it around the same time frame that we have.

Nevada: We do not currently use GPR.

New Hampshire: We have used it for close to 10 years, and our geotechnical department has used it for the last 6-8 years.

New Jersey: A study was done about 8-10 years ago, but we did not use it much because we weren’t happy with results. About 3 years ago, we used it for pavements and are now using it to look at delamination in bridge decks.

New Mexico: We started using GPR a few years ago.

New York: Our maintenance department has used it for the last 2 years, and I believe our research department has used it a little longer to work on studies correlating FWD with GPR.

North Carolina: Our pavement management section is not currently using GPR, but had used it for 10 years. Our geotechnical section is still using it and has used it since the early 1990s.

North Dakota: We performed test projects. Vendors had come in and collected data for us for two years with Infrasense and one year with Penetradar. For three years (2005-2007) we had data collected by GPR.

Ohio: Our geotechnical section has used GPR on and off for 10 years, but it has been used for special cases only.

Oklahoma: We have only done GPR work once and Infrasense was the GPR contractor on that project.

Oregon: We do not currently use GPR.

Pennsylvania: We do not currently use GPR.

Rhode Island: Our materials and research group has used it on and off for the past 10 years.

South Carolina: We do not currently use GPR.

Tennessee: We do not currently use GPR.

Texas: We have been using GPR for more than 10 years.

Utah: We used GPR about 4-5 years ago. We had collected 200 miles of data each year.

Virginia: We have used GPR for about 10 years. A few years ago Virginia Tech lost their capabilities, and VDOT purchased the equipment for evaluations. Right now I believe it is used mostly for research, but they have used it on a project level for forensic applications and on a network-level as well.

Washington: I do not believe we have ever used GPR.

West Virginia: It's been a long time since we have used it. I believe it is been about 10 years.

Wisconsin: We have been using it within our agency for about 9 years.

Wyoming: We do not currently use GPR, but we're looking into it.

3. Do you perform GPR work using States forces or through a contractor(s)?

Alabama: We did not perform the work on that project, and I'm not sure which subcontractor or contractor was involved.

Alaska: We have always used contractors for any geophysical work or GPR work. We do not do it often enough to be good at it.

Arizona: State forces. We were using it for an idea I had in 2004. SMI sells GPR with FWD. I was looking to use GPR with FWD, one right after the other, as an integrated unit. This would have allowed us to use radar for layer thickness and to do FWD on the same area. That was our intent. We were going to use it also as a high-speed unit at 60mph for small projects to give engineers an idea of layer thickness, but we have not been able to get as far along with it as we had hoped.

Arkansas: We do not use it at this time.

Colorado: We have been hiring contractors at this point, but we’re looking into purchasing our own equipment.

Delaware: I do not believe we have ever used it on a project.

Florida: State forces are used 95 percent of the time when GPR work is needed.

Georgia: We do not have any experience with GPR at this time.

Hawaii: So far all of our GPR work has been from hired contractors.

Idaho: It was done by state forces for a while, but we have not been using it.

Illinois: This is specialty work done by pre-qualified consultants.

Indiana: We currently use GPR with State forces.

Iowa: We have hired GPR contractors so far.

Kansas: Both. We own a single frequency unit and have hired consultants with single frequency units. In more recent uses of GPR, we have contracted work and specified the end results (thickness, void locations and severity, moisture locations), and relied on the contractor to appropriately use the equipment and interpret the results. We do typically take cores with GPR to verify results.

Kentucky: University of Kentucky does the work. We have a partnership with them. We develop research topics that they follow up on. They do evaluations of sites. One example was finding the location of an underground tunnel using GPR.

Louisiana: We have hired contractors to do GPR work.

Maine: We are not currently using GPR, but we're looking into acquiring one.

Michigan: We use state forces for about 90 percent of the GPR work. Ten percent is performed by consultants/contractors.

Minnesota: We use state forces mainly, but have hired consultants if we cannot handle the work load. We also do GPR work for the local agencies, if requested.

Mississippi: I believe we hired a contractor when we used it.

Missouri: We have hired GPR contractors mostly. I was not aware of the advancements of GPR until last year. I believe in the past it needed a form of ground-truth to identify one particular type of material. But now, as I understand it, it is to the point where the resolution is really clean.

Nebraska: We do not use it, but we experimented with it using state forces. At the time FHWA was not only pushing it, but had some projects set up where they would bring the equipment out and we could use it.

Nevada: We are not using GPR.

New Hampshire: We use state forces for GPR work. The geotechnical group uses a ground-coupled unit.

New Jersey: We have hired GPR contractors as needed.

New Mexico: We have hired contractors to do GPR work.

New York: Most of the time GPR work is performed by a contractor. Our maintenance unit has their own equipment, but I do not know if Research has their own.

North Carolina: When our pavement management section used GPR, we were using state forces. Our geotechnical section used to use GPR with state forces until about 2002-2003, but since then has hired contractors to do the work because GPR is not performed routinely.

North Dakota: Our GPR has been contracted out.

Ohio: We have hired contractors to do our GPR work.

Oklahoma: We have used contractors for GPR work.

Oregon: We do not use GPR.

Pennsylvania: We do not use GPR.

Rhode Island: So far we have hired contractors to perform GPR work.

South Carolina: Neither, but there was a demonstration over 10 years ago where a vendor came by and showed us the equipment.

Tennessee: Neither. We do not currently use GPR.

Texas: Typically we use state forces, but if we have too much work and not enough manpower to do the work we generally ask the Texas Technical Institute (TTI) to help us. We do not use consultants to do GPR work.

Utah: We hired contractors to do the GPR work for us.

Virginia: We use state-forces for our GPR work. We have a contracting vehicle available through a consultant, but we have used internal forces to do most of the work.

Washington: Neither. We do not use GPR.

West Virginia: I believe we used contractors to do GPR work for us.

Wisconsin: Both. It depends on the particular job. Usually our GPR work for geotechnical applications is done by state forces. Some of the pavement jobs are done by state forces, but there are times when it is contracted out. Bridge jobs have been contracted out due to higher traffic densities. Basically, we perform most of the tasks that can be done using our own ground-coupled GPR. The bridge and pavement jobs that require an air-launched unit are contracted out.

Wyoming: We do not use GPR.

4. ***For what applications has GPR been used by your agency? How effective has it been in these applications?***

Alabama: We used it for looking at voids under the pavement to determine the volume of under-sealing needed under the pavement. I'm not sure how effective it was on that project.

Alaska: There was a project where we used GPR to look at soil profiles for our roads. We have some areas where we have frozen ground and have just used GPR for some specialty areas, but not routinely. We have also used it for embankment profiles and felt that we got good information from it.

Arizona: Right now we're trying to integrate GPR with FWD to give pavement thicknesses on a project level. The GSSI software gives layer depths. In June 2007 we took our FWD over to FMI in California and had a GSSI technical representative meet us and we tried to convince them to write software that gives layer thicknesses rather than depth only. We also talked with Ken Maser to develop software to determine pavement layer thicknesses. I had a rare request to locate a well under a road using a GPR that was 1-2 feet under the pavement. I believe Los Angeles uses their equipment to find pipes and utilities under pavement.

Arkansas: Not Applicable.

Colorado: We have used it in a couple of instances. We have used it to determine the poor concrete on a bridge deck covered with asphalt. We have also used it to look for stripping in asphalt and found it to be fairly effective. We have used it in pavement forensic studies, but not that much. We have also used it to determine layer thicknesses. We use MIT-Scan 2 for steel bar location, as opposed to GPR.

Delaware: Not Applicable.

Florida: We mostly use GPR for forensic pavement studies, using a ground-coupled GPR unit that was from GSSI. We look at depressions and voids as well as sinkhole mapping. We have done some work with the Florida Department of Law Enforcement for homicide cases, but this is done in very special instances. We also perform high-speed tests with our air-launched antennas to determine pavement thicknesses for pre-design. Most systems are GSSI. We can do bridge deck surveys for deterioration and show contours, but this is also not done routinely. We have talked about using it for construction quality control to look for a range of densities to look for the extreme values, but we have not done anything with that. We also use it to identify utility and sinkhole locations. We use other equipment to get the depth and orientation of dowels, and steel reinforcement. We can do it with GPR, but we just have to grid it really tight.

Georgia: Not Applicable.

Hawaii: Right now we have been using GPR for pavement design on a project level to verify existing pavement thickness and find the boundary layer.

Idaho: My recollection of a research project that was conducted about 13 or 14 years ago was that the results were pretty accurate.

Illinois: The one project that I know of was a Phase I study. GPR has also been used on rare occasions to look for underground mines or bedrock depth.

Indiana: We have used GPR in bridge deck evaluations. We have found that the ground-coupled unit has been better for picking out individual rebar and for making corrections. We also use it for determining thicknesses in conjunction with our FWD. We have also used GPR for locating settlement voids under pavements. In one case the settlement was a result of leaking water from a broken pipe and GPR was very useful in detecting the voids under the pavement. We also used GPR for a network level to get an inventory, but now more or less it is been used on a project level. We have found GPR has been effective for HMA thickness, but there is an issue when used for total composite thickness for HMA over PCC and it is not as effective. It works okay for concrete, but it does not work as well as it does with asphalt. GPR is also pretty useful for locating tanks underground; however, one time I looked for 8-10 foot culvert and could not find it. I believe that a clay layer may have been blocking the view. The GPR results for bridge decking agree quite well with the half-cell data. I have not ground-proofed any of the bridges that I have tested, but again the data agrees with half-cell data.

We have used GPR to obtain pavement thicknesses and to determine the dielectric constant of a material. We have used it to identify moisture stripping in asphalt. We have also used it to detect delamination in bridge decks, and to detect voids under pavement. For bridges, it is been used to determine the depth of rebar when looking for delamination. Additionally, it is being used in research projects to experiment with other possibilities and applications of GPR.

Iowa: We have used it to detect voids under pavements. It may have also been used for pavement forensics, but I’m not sure. I believe it is also been used to get a thickness determination in cooperation with the study for void detection.

Kansas: We have used GPR to determine pavement thickness and locate air voids under pavements. It has also been used for bridge deck applications, but I'm not familiar with that. I know that our bridge section currently uses chain drags today rather than GPR.

Kentucky: We have used to GPR to determine the location of air voids and for pavement forensics. I believe that we have looked at pavement thicknesses, but we do not do that regularly, and I'm not sure how satisfied we were with the results. I’m not sure if we have used it for bridge applications.

Louisiana: One district was using it to look at issues underneath the pavement. We used it initially, but not anymore. In 1995 we used it on a network level and took an inventory of the AC pavement thicknesses. We had problems with telling the difference between soil cement and concrete. GPR couldn't distinguish between the two. We have used GPR to locate voids under pavement after Katrina.

Maine: We had a vendor that wanted to introduce us to GPR. We had it attached to our FWD and ran some tests with it. We compared the results to some known data and were exposed to some of the strengths and weaknesses of the technology. I believe they're planning on using it in conjunction with FWD. We possibly may use it on a network-level for a road inventory, but that would probably only be done once. We just recently finished that with our FWD vehicle and have integrated that in our treatment selection. We may also use it to determine which segments are homogenous.

Michigan: We have not used GPR on a network-level. However on a project level, we have used it to determine pavement thicknesses, to locate voids under pavements, and in conjunction with our FWD equipment. We have also used it for bridge deck evaluations and to evaluate pre-cast box beams to verify that the web thickness is appropriate. Other uses have included looking for reinforcing steel, which we have used retrofitting applications to avoid hitting existing reinforcement. We have also used it for utility location under sidewalks.

Minnesota: We use GPR to determining pavement thickness mostly, and I think we have been very effective. In many cases it does not give us the exact thickness, but can show any existing anomalies. It is used to determine the depth and location of reinforcement steel in bridges or pavements. We have also used to locate underground pipes and other subsurface objects. I think we have also tried looking at voids under pavement and possible bridge delamination. In mill and fill applications, we have used GPR to tell the contractor how much he can mill. I believe GPR is used 95 percent of the time for pavement applications and 5 percent of the time for locating subsurface objects including tunnels, sinkholes, mineshafts, etc. We use it a lot to look at bituminous pavements thicknesses to evaluate rehabilitation options.

Missouri: We have used GPR for pavement thickness and also as a tool to look at dowel bar inserters. We may have possibly used it for geotechnical applications about 8-9 years ago in southwest part of our state. It was used as a tool when reconstructing and realigning US-71. On that project, there was an issue with the significant amount of mining that was done in the last 150 years. Mine shafts were all over the place. I believe that they used GPR to try to determine the locations of the mines, and the results may have caused a slight realignment of US-71.

Nebraska: We do not use GPR. It may have been used for bridge deck applications, but I'm not sure. We tried it on pavements to determine thicknesses to reduce the amount of cores needed, but did not use it due to the level of difficulty in interpreting the data.

Nevada: Not Applicable.

New Hampshire: We use GPR for bridge deck evaluation for delamination. Right now GPR is not used for asphalt pavement. Our geotechnical group uses it to fill in the gaps between borings, which they have found to be very effective. About 5-6 years ago we concluded our study that we had done through SPR funding to look at using 3D software to enhance the traditional exploration program. We were hoping to get better data to extrapolate some of the combined data, but I'm not aware of the details on that project.

New Jersey: We have used GPR to determine pavement thicknesses in cases where the as-built drawings were not accurate. We have also used it to evaluate bridge decks for delamination. We have not used GPR on a network-level, but it has been used to detecting voids under pavements and to locate underground utilities.

New Mexico: We have used GPR to do pavement forensic studies. We have used GPR to determine pavement thicknesses and look for air voids under pavements.

New York: We have used GPR on local culvert projects to detect voids and to evaluate bridge decks for delamination. I might be interested in using GPR on a network-level to determine pavement thickness of our road inventory.

North Carolina: Our pavement section used it to determine pavement thicknesses mostly. We stopped using it because it took too much time to analyze the data. Our geotechnical section has used it for locating USTs, sinkholes, and abandoned mines. If you have large void areas under pavements, GPR can be successful; however, if they are located below the water table GPR will not be effective.

North Dakota: We have used GPR for determining asphalt depth and the interface between the asphalt and aggregate bases. It's also been used to look for delamination on bridge decks. We have found GPR to be effective in these applications. It gave us more accurate data than we had.

Ohio: We have used GPR in culvert applications and for void detection under pavements.

Oklahoma: We used GPR on a project to determine layer thicknesses that could be used in conjunction with our FWD results.

Oregon: Not Applicable.

Pennsylvania: Not Applicable.

Rhode Island: We have used GPR for pavement forensics, to detect voids under pavements. We have not used it on a network-level or for detecting delamination in bridge decks.

South Carolina: During the demonstration, we felt that the interpretation of the data was very difficult and required a lot of expertise. We rely on cores when we need pavement thicknesses.

Tennessee: Not Applicable.

Texas: We use GPR for pavement rehabilitation as a tool to help us determine the best course of action. We also use it in forensic analyses to evaluate premature failures in pavement and to locate voids under pavements. It is also used to evaluate possible segregation in HMA mixes by looking for a difference in the dielectric constant. We do not use it for construction quality control, but have used it for dowel bar location. However, we mainly use GPR to determine pavement layer thicknesses and it is used in conjunction with our FWD.

Utah: We used GPR to determine our asphalt thickness. It took a lot of effort to go through the data. There was a lot of data. We had one guy who spent time looking at it, but he retired. I do not feel that we got much out of it.

Virginia: GPR has been used on a project level for evaluations and forensic investigations. We have done a limited amount of projects that used GPR to look at voids under pavements. The use of GPR is not very routine, but rather more sporadic. It has also been used on an as-needed basis for evaluating bridge decks, to perform tests on concrete, and for quality assurance testing for pavement thicknesses in new construction. We have also used GPR for looking at rebar location depth. It’s been used mostly on a project level, but we have talked about doing network-level testing. We have not yet used it for checking delamination or corrosion in bridge decks, nor have we used it to identify high moisture in pavements. We tried using GPR for looking at asphalt stripping once, but it did not get good results, and we’re not sure why.

Washington: We have used GPR to detect voids under pavements and to determine pavement thicknesses.

West Virginia: We have used GPR on a project level to detect voids under pavements and to obtain pavement layer thicknesses. I’m not sure if it is been used for structural work.

Wisconsin: We use GPR for pavement evaluations, which are usually done on a project level. We have used GPR for pavement forensic studies, to locate voids under concrete, and to locate subsurface objects like USTs and large boulders. We have also used GPR to get profiles of rock layers and profiles of marsh bottoms. I believe it has been used in conjunction with FWD, but not routinely. FWD is used more often than GPR. We have had contractors use GPR on bridge deck evaluations for location of rebar and to detect delamination. We have not used it much in pavement quality control, but there have been specific cases where we have done so.

Wyoming: Not Applicable.

5. ***What are the advantages and disadvantages of the GPR equipment that your agency has used versus other methods for obtaining the same data? What other methods have you used?***

Alabama: I'm not sure about the accuracy of GPR. It seems like the only reasonable way to try to get an estimate of voids under pavement. I do not know how else you would do it.

Alaska: GPR is quick. We can cover a large area with it and it can be less expensive, but the information is highly variable depending on the operator. Again, it can be less expensive than drilling or excavating.

Arizona: Advantages include being able to get the layer thickness at the deflection basin at each attempt, rather than having to core every mile or half-mile. Also, it would let the pavement engineer know exactly his layer thickness. Disadvantages have been with the interpretation because it is very difficult and tedious to interpret the data. Ideally we would like one unit that imports layer thicknesses into FWD as one file and have an automated process. If it worked, we would use it to determine pavement thickness and we'd have data at a much denser frequency. Right now we typically core every mile and we do FWD every 2/10 mile.

Arkansas: Not Applicable.

Colorado: Advantages for pavement design include the ability to determine thicknesses on a network level, to determine where steel is or varying materials under pavement layers, and using it on poor areas for forensic studies. There are disadvantages with regard to the level of expertise needed for analyzing the data. Purchasing the equipment can be expensive for various antennas. I'm not sure if we would need new equipment.

Delaware: The disadvantage that we found was that the results were not accurate enough for payment purposes in quality control/quality assurance applications.

Florida: Disadvantages include the FCC regulations that hinder our ability to get what we really need in regards to the antenna frequency. Also the need for interference filters to cut out the noise. The advantage for pre-design is being able to develop an engineered coring plan rather than coring blindly. We still core for verifications, as a ground-truth method. Another advantage with the air-launched system is that you can go 60mph and measure 1ft intervals.

Georgia: Not Applicable.

Hawaii: Advantages of GPR include its ability to get continuous data, and that it is cost effective. Disadvantages include the need to ground truth the results through coring or another method. Also, it is difficult to learn and use the equipment. It requires a lot of skill and experience, making it difficult to just jump in and use it.

Idaho: GPR gives continuous data rather than spot data from coring.

Illinois: GPR is a non-destructive test capable of covering a wide area, but it requires a lot of interpretation. If a boring finds a problem like a suspected sinkhole or mine, I may use the GPR to estimate the extent of the problem. We have also used soil electrical resistivity surveys instead of GPR.

Indiana: The nice thing about GPR is that it is continuous coverage and no traffic control is needed for the air-launched GPR unit. Additionally it is a non-destructive test, which is very useful in bridge deck evaluations. In my experience, it has worked well with UST location. I've considered other methods that could be used in UST location, such as a magnetometer, but GPR has higher resolution and is quick. Disadvantages include limitations due to weather. As an example, if it is raining you may not be able get the accuracy that you need.

Iowa: Advantages are being able to get a pretty good feel for pavement overall thickness and subgrade location without disturbing either. It is also very quick to obtain data compared to coring. A disadvantage to a certain extent is with regard to the initial cost. Also, the complexity of the technology and the data interpretation can be difficult as you get more involved with different applications.

Kansas: The interpretation of the GPR data was pretty messy. It worked great in experiments, but in real world applications it did not provide the extent of information needed.

Kentucky: I think the major advantage of GPR was having technology to identify problems without performing a destructive test. I was not involved in the pavement thickness research, but I heard that one of the disadvantages was that it was difficult at times to identify specific pavement layers. Also, with a ground-coupled unit, the speed at which we can do the testing is slow.

Louisiana: I believe it can help you tell where you lose homogeneity. However, it is my understanding that you still have to core between those sections, so you have to do more than just GPR by itself.

Maine: I'm not sure; we may have worked on a report that addresses this.

Michigan: Advantages of GPR include the nature of the test being nondestructive. In some cases you can avoid destructive testing altogether. It is quick and yields a lot of information. Disadvantages include the complexity of the technology. You need someone who knows what they're doing to analyze the data. If not careful, you can provide people with a false sense of security. Also, if not using an air-launched GPR unit, you need traffic control.

Minnesota: Advantages include being able to collect continuous pavement profile data and the ability to use the results in conjunction with FWD equipment to back-calculate pavement moduli. Our back-calculation procedure is performed every 1/10 of a mile. No traffic control is needed which also makes it a safer tool to use. Additionally, it is able to cover a large area in a short amount of time and yield a very reasonable picture showing the thickness of the pavement. Some of the disadvantages include complexity of the equipment and the need to have highly trained technical people to analyze the data. Also, the results are subject to the interpretation of the operator, and it is subject to wave interference, so you can't use it in proximity to cell phone towers.

Missouri: Some of the disadvantages include the need to have a drastically different dielectric constant material (aluminum) to use that as a breakpoint to measure thickness. Additionally there can be signal confusion for multiple steel arrangements, but I've learned recently that a lot of those issues have been overcome. Advantages include the ability to get a clear picture without as much need for ground-truth. Overall I think it seems to be the fastest, quickest way, to get the picture. I believe some of the magnetic equipment has some calibration issues and has some limitations. GPR seems to be ahead of the curve.

Nebraska: The disadvantage was that it was difficult to interpret the data.

Nevada: Not Applicable.

New Hampshire: The advantages of GPR include its ability to collect data quickly and it has cost benefits in geotechnical applications, especially when used in conjunction with deeper borings. GPR gives enhanced accuracy for an area. Some of the disadvantages are that the picture is not always clear enough to yield results, and water tables adversely affect the results.

New Jersey: Advantages include its ability to cover a much bigger area, as opposed to coring in one location. The nature of the test is non-destructive. The disadvantage is that sometimes the results are inconclusive.

New Mexico: I did not think that GPR accomplished much for us. Every once and a while it would reveal a void, but I did not think there was really a void there. There may have been a place where the pavement had delaminated, but I do not know. The people at our laboratory said that it will be very useful for new pavement design in order to determine the pavement thickness of existing layers.

New York: It is difficult to compare GPR with other data collection methods due to the nature of the data collected, but it probably gives better information than using a hammer on bridge decks to detect voids. Other advantages include its non-destructive nature and its ability to rapidly collect data. Disadvantages are found in the interpretation of the data, which can be tricky, and so it is important to have someone with experience.

North Carolina: For pavement management, the major disadvantages were the time required in interpreting the data, and that the results were often uncertain, and you needed to core to verify the results. Advantages included its ability to collect data at highway speeds. For geotechnical applications, the disadvantages include the need to have highly skilled people to use the equipment and the interpretation of the data was very difficult. GPR did not always yield a clear result, and so you need another method of data collection to ground truth so that you can reduce the level of uncertainty. Also, though the data collection is done quickly, the turnaround on the results many times was longer than desired in the field. An ideal tool would be able to determine the answer quickly. Advantages include its ability to have continuous coverage as opposed to coring at discrete points. GPR can be effective if you are looking at rebar on a bridge deck, but only if there is only one layer of rebar. With multiple layers, it can be more difficult. We tried to use it locate timber piles under the concrete and were not successful.

North Dakota: GPR defined a much better picture than anything else we could have used. However, we still had to take a couple cores to verify the accuracy of the data and to set up the interpretation of the data.

Ohio: Advantages include the ability to achieve 100 percent as compared to coring or looking at test pits. It also allows you to better target where you are going to take borings. Some of the disadvantages include its limitations to yield effective results in various site conditions (clay materials and high groundwater tables). It also has trouble determining the difference between the top of the concrete and the bottom of a stone base. It is highly technical and difficult for the untrained to pick up and run with it. It pretty much requires contractor usage.

Oklahoma: Advantages of GPR include its ability to give 100 percent coverage of the segments that we wanted to test and to do so quickly. The disadvantage is that coring is needed to verify layer thicknesses.

Oregon: Not Applicable.

Pennsylvania: We did a study a few years ago, but the results were not accurate enough for our applications.

Rhode Island: I’m not sure. I was not there at the time.

South Carolina: Difficult to interpret data.

Tennessee: Advantages of GPR is that it is virtually nondestructive, meaning that you only have to take a few cores for verification purposes.

Texas: GPR is a very good tool. You could run tests at highway speeds, get full coverage, and use it as a valuable tool for evaluations and in making rehabilitation decisions. It also can be helpful for obtaining information about layer thicknesses, stripping in asphalt, presence of moisture, and presence of voids in pavements. The disadvantage is that you need skilled and experienced technicians to evaluate and interpret the data. Right now we have several people here who have a lot of experience with GPR and who are good at it.

Utah: The advantage is that you obtain continuous information and it can be effective for seeing if you have consistency between cores. The disadvantage is related to the interpretation of the data, which is very time consuming.

Virginia: Advantages include the ability to test with limited amount of traffic control. This is a huge advantage for us and we are able to get a larger quantity of structure information than through traditional coring. With the vast amount of data, it is easier to see changes in the pavement structure. The biggest disadvantage has been in the analysis and having qualified staff available and experienced to interpret the data. This has been the biggest hurdle that we have not overcome so that GPR can get more routine use around the state.

Washington: Not Applicable.

West Virginia: The advantages of GPR are its ability to perform a non-destructive test quickly and without the need for traffic control, which also increases the level of safety when comparing it to other test methods. The disadvantage is that you need a highly trained person to be able to read and interpret the data. The learning curve is much steeper as compared to other data collection methods.

Wisconsin: Advantages of GPR include being able to collect a large amount of data quickly. You can also use it to fill in areas with other forensic data from cores, boring, etc. GPR is good at getting fast and accurate characterization of bridge decks and delamination, and is safer for bridge decks because there is no need for traffic control. Disadvantages are found in the interpretation of the data, which is very complex. Site conditions can limit the effectiveness of GPR, like in areas with clay and silt, especially with water saturation. In these conditions, GPR is not effective.

Wyoming: Not Applicable.

6. ***Do you have any information related to the initial start-up, operation, and/or maintenance costs? If so, what are they?***

Alabama: No.

Alaska: No.

Arizona: I do not. I believe the startup cost for the entire unit was about $112,000 for installation, software, and antenna. I believe the antennas alone are about $25,000 to $35,000 for a 2 GHz horn antenna.

Arkansas: No.

Colorado: No.

Delaware: No.

Florida: I believe the start-up costs for a van, GPR equipment, air-launched and ground coupled units is about $170,000 with all the equipment. Additional cost for 1-2 operators is about $40,000.

Georgia: No.

Hawaii: We hire GPR contractors, and I believe it roughly costs around $300/hr for field costs.

Idaho: No.

Illinois: No.

Indiana: I believe the ground-coupled unit ranges from $40,000-$50,000 and I think that the air-launched system is similar at about $30,000-$40,000. The operational cost is staffing 1 or 2 technicians to operate the equipment. I have not personally monitored the maintenance costs.

Iowa: I believe the equipment, including hardware and software, costs about $80,000 for an air-coupled unit.

Kansas: The equipment and software were created by Kansas University. The cost information is all lost to history along with the requirements, equipment protocol, and software.

Kentucky: No.

Louisiana: No.

Maine: No.

Michigan: I believe that the equipment is about $65,000 for the system intended to do pavement thicknesses. The total cost is about $111,000, and since then we have expanded it to do structural work and geophysical work which accounts for five additional antennas plus some other equipment. That includes training from the manufacturer and necessary software.

Minnesota: I heard that it was probably about $50,000 for the equipment, but I believe that was about 5 years ago.

Missouri: No.

Nebraska: No.

Nevada: No.

New Hampshire: No.

New Jersey: No.

New Mexico: No.

New York: No.

North Carolina: No, we bought it in the early 1990s so our figures would be obsolete.

North Dakota: No.

Ohio: No.

Oklahoma: No.

Oregon: No.

Pennsylvania: No.

Rhode Island: We recently got a quote from a supplier that was someone in the $40,000 range for the equipment.

South Carolina: No.

Tennessee: No.

Texas: I really do not know. We have had our units for more than 10 years. Every once in a while we have done upgrades or maintenance but I do not remember the cost being that significant.

Utah: No.

Virginia: I believe we bought both systems as a package through GSSI for about $60,000. This included the Road Scan and Bridge Scan software. We have not had any other costs, as far as I know. The nice thing is that it included everything we needed.

Washington: No.

West Virginia: No.

Wisconsin: We're not as familiar with the van-mounted equipment that Ken is dealing with, but I believe it can cost between $100,000 and $300,000 to get something like that going. But you can pick up a nice ground-coupled system for $20,000-$30,000. For small type pavement evaluations you could go as low as $10,000-$12,000.

Wyoming: No.

7. Can you describe the complexity of the equipment and data acquisition system? How important is training and support?

Alabama: No, we hired consultants to do this work.

Alaska: No, we hired consultants to do this work.

Arizona: It's pretty simplistic. I designed an antenna mount for the antenna that fits on the vehicle. It goes into a receiver and is made of a composite material. You turn on the software, do a simple calibration that takes 10 minutes, and set up the file and you're ready to test. The antenna has to be a certain distance away from the vehicle. If you're in route you do not want the antenna attached. Sir-20 is a program that acts as the brains of the radar. Data collection goes from Sir-20 to the laptop through an Ethernet cable. There are three different software program that are used. The first is for calibrating the equipment, the second is for data calibration, and the third is for processing the data. It's fairly simple to do data collection. The hard part comes with interpreting the data after it is been collected. I was not pleased with their processing software because it gives depths instead of thickness. It's up to the operator to pick the layers so you'd look at the information and try to decide what is a layer and what isn't a layer, which leaves a lot of variability. The processing software is too overbearing and takes too much work. One of the jobs we did was 80 lane miles with 5 tests per mile. That's 400 tests and we would have had to integrate those into 400 separate FWD files. That is a lot of work and I would like it to be automated.

Arkansas: No. We aren't currently using GPR, but we're looking into it.

Colorado: I've seen GPR used, at least some of the older GPR equipment. It seemed difficult to determine where steel areas were or poor areas. There is a definitely a knack in interpreting the data.

Delaware: No.

Florida: All our equipment is GSSI so we have a search warning. We have two 2 GHz antennas for high-speed surveys. We use booms on the front of the van. We can run ground-coupled on the back. We have a variety of ground antennas (1.5 GHz, 900 MHz, 100 MHz, and 80 MHz).

Georgia: No. We do not have any experience with GPR at this time.

Hawaii: No, we hire consultants to do this work.

Idaho: We have not yet used the GPR equipment that was given to us from another district. We feel that we will need someone to come and train us on GPR.

Illinois: Not Applicable.

Indiana: Training is important before you start, and it is really important with the interpretation of the data. It takes someone with experience to interpret data. UST location is more visible and easier to detect. Locating voids under pavements can be difficult to notice. You need experience if you are looking at a complex pavement, and you need the education and experience for interpreting the data.

Iowa: Training is very important. When doing a layer analysis, the interpretation can become more of an art rather than a science. If you're just looking at pavement thicknesses and verification it seems pretty straightforward.

Kansas: No. In more recent uses of GPR, we have contracted work and specified the end results (thickness, void locations and severity, moisture locations), and relied on the contractor to appropriately use the equipment and interpret the results. We do typically take cores with GPR to verify results.

Kentucky: No.

Louisiana: No, we hired consultants to do this work.

Maine: No. We aren't currently using GPR, but we're looking into it.

Michigan: Training is very important. GPR data analysis is a technical skill. The data acquisition is pretty straightforward. You want someone who knows how to run the equipment and maintain the equipment. Since it is electronic and can be easily damaged if the appropriate person is not taking care of it.

Minnesota: We're using the GSSI commercial GPR equipment. In terms of data acquisition, it is not that complicated to run the test, but the problem comes with analyzing data as it is very technical. The equipment is highly technical and is subject to wave interference, so you can't use it in proximity to cell phone towers. It's very delicate equipment so training and support is very important. It's not something that you can learn on your own.

Missouri: No, we have contracted the work out.

Nebraska: We have experimented with GPR and have found that interpreting the data is very difficult.

Nevada: No, we currently do not use GPR.

New Hampshire: We use a ground-coupled unit from MALA-Geosciences. Training is very important for knowing how to use the equipment, but also when it can be applicable (water table and clay areas can affect data) since it is very site-specific.

New Jersey: No, we have contracted the work out.

New Mexico: No, we have contracted the work out.

New York: No, we have typically contracted the work out. However, I know that the interpretation of the data can be tricky and that you need someone with experience.

North Carolina: No, I was here at the tail-end of our use of GPR, but I know that analyzing the data is very time-consuming and is complex.

North Dakota: No, we contracted GPR work out.

Ohio: No.

Oklahoma: No, we contracted GPR work out.

Oregon: No.

Pennsylvania: No.

Rhode Island: We are looking at getting a ground-coupled unit, possibly from MALA-Geosciences.

South Carolina: No, but we were given a demonstration of GPR about 10 years ago and felt that the interpretation of the data was very difficult and required a lot of experience.

Tennessee: No.

Texas: We have a very user-friendly software (ColorMAP) to analyze the data. Additionally, we also have a new software called Pave Check that uses video cameras associated with GPR. You can see the area that has distress along with the GPR signal.

Utah: No, we had contracted the GPR work out.

Virginia: The equipment is not too terribly complex. It may take some experience to set up the equipment, but it is fairly simple. However, the data analysis is very complex. I think a lot of experience is needed to interpret the data and it is almost more of an art than a science.

Washington: No.

West Virginia: Interpreting the data can be very complex and requires a skilled person with expertise in that area.

Wisconsin: The equipment is fairly complex. You should know how the system works and its limitations before you use it. Acquiring the data is relatively easy, but interpreting can be very complex. You definitely need someone who knows GPR, and what you're looking for. There is a tradeoff between the frequency of the antenna and the depth of resolution: the deeper you go, the less resolution you have. This is not a big deal if you are ranging from 1-3 feet deep. However, if you are trying to scan 5-6 feet below the surface, GPR may not be as effective. Size of the objects that you are looking for becomes very important at greater depths. The GPR may not be able to detect small objects at greater depths.

Wyoming: No.

8. What Calibration requirements do you have?

Alabama: Not Applicable.

Alaska: Not Applicable.

Arizona: The software does the calibration. Initially you have the bounce type of calibration which Radan software does for you. However, it is a little cumbersome to have a few guys stand on the bumper and jump up and down to give the “bounce” needed so the software can account for vertical change while driving. For stationary tests there is no need to do bounce tests. We came up with a different calibration for static tests. The software takes a little practice to get familiar with, but it is doable.

Arkansas: Not Applicable.

Colorado: Not Applicable.

Delaware: Not Applicable.

Florida: We do a monthly performance check where we look for signals to verify consistency. We also look for time-stability and see if the signal drops off. We have a maintenance plan with the developer (GSSI).

Georgia: Not Applicable.

Hawaii: Not Applicable.

Idaho: Not Applicable.

Illinois: Not Applicable.

Indiana: For air-launched units we follow the ASTM standard that involves metal plate calibration to determine velocities. You may also need to do a calibration in place using a calibration core to tighten up the results and to verify required thickness is achieved for a contractor. When looking for voids, no calibration is used. When evaluating bridge decks, no calibration is used, but we do have a processing procedure that we follow.

Iowa: Not Applicable.

Kansas: Not Applicable.

Kentucky: Not Applicable.

Louisiana: Not Applicable.

Maine: Not Applicable.

Michigan: We check our equipment ourselves about every few months. We also check it monthly to verify that the results are reasonable. We do this by running GPR tests on concrete blocks of known depths and compare the known values to the GPR readings.

Minnesota: We follow the calibration requirements from GSSI. When we start a job, we perform a 5-10 minute procedure for calibrating the equipment. This involves using a metal plate on the ground, but I'm not aware of any more calibration that may be needed.

Missouri: Not Applicable.

Nebraska: Not Applicable.

Nevada: Not Applicable.

New Hampshire: We check it with our borings and compare the profile to the bore hole data.

New Jersey: Not Applicable.

New Mexico: Not Applicable.

New York: Not Applicable.

North Carolina: Not Applicable.

North Dakota: Not Applicable.

Ohio: Not Applicable.

Oklahoma: Not Applicable.

Oregon: Not Applicable.

Pennsylvania: Not Applicable.

Rhode Island: We recently got a quote from a supplier that was somewhere in the $40,000 range for the equipment.

South Carolina: Not Applicable.

Tennessee: Not Applicable.

Texas: We do the calibration every time they go out to run tests with the metal plate that determines the signal absorbed in pavement and the signal reflected. We have

TTI help us with a major calibration of the equipment that is performed once a year.

Utah: Not Applicable.

Virginia: We calibrate the equipment every time before we go out. However, we do not have a procedure to calibrate the antennas.

Washington: Not Applicable.

West Virginia: Not Applicable.

Wisconsin: The calibrations procedures for GPR are not as complex as a lot of our other equipment. As long as we keep up with our routine maintenance and follow the manufacturer's requirements, the GPR stays calibrated. There are things that you can do to test the accuracy of the readings by verifying the results with cores or borings of known properties.

Wyoming: Not Applicable.

9. What procedures/protocols do you follow in using GPR equipment?

Alabama: Not Applicable.

Alaska: Not Applicable.

Arizona: I developed our protocols for the static tests that we do using GPR. For static tests and our integrated system, driving speeds are around 4-5 mph and we go 50 to 75 feet before we stop. Now the truck can be over the area we tested. For high-speed tests (60-65 mph) bumper calibration is needed to account for vertical variation, and that was developed by GSSI.

Arkansas: Not Applicable.

Colorado: Not Applicable.

Delaware: Not Applicable.

Florida: Typically high speed surveys are performed at 60 mph or the speed limit. We have a guideline to determine what our limits are in regard to our traveling speed and the resolution needed.

Georgia: Not Applicable.

Hawaii: Not Applicable.

Idaho: I'm not sure, but I believe that we had used it in the past for evaluating bridge decks for delamination in the south-central and southeast Idaho area. The department that may have used it for evaluating bridge decks gave the unit to us and we're going to try to make something out of it, but have not gotten around to it.

Illinois: Not Applicable.

Indiana: The procedures and protocols vary per project. When a client contacts me, the client gives me their objectives. From their objectives, I will determine the needed intervals to achieve the appropriate level of accuracy.

Iowa: Not Applicable.

Kansas: The cost information is all lost to history along with the requirements, equipment protocol, and software.

Kentucky: Not Applicable.

Louisiana: Not Applicable.

Maine: Not Applicable.

Michigan: We do not have a written standard of procedures to follow. The procedures can vary depending on the application and site conditions. We use what has worked well in the past to achieve the same goal. When doing air-launched testing, the system speed affects the results. Part of that depends on how many antennas we're using and our driving speed. Additionally, our software limits us on how much data we can acquire at one time.

Minnesota: I do not believe there are any such standards. We determine the speed based on requirements, which is about 45-50mph. In more detailed applications, we may need to use ground-coupled equipment at a slower speed. We follow the manufacturer's recommendations and see what has worked well in the past.

Missouri: Not Applicable.

Nebraska: Not Applicable.

Nevada: Not Applicable.

New Hampshire: We use a ground-coupled system and we pull it like a sled. It goes pretty slow and the depth we can look at typically ranges from 10-15 feet. We use the equipment in accordance to the manufacturer recommendations.

New Jersey: Not Applicable.

New Mexico: Not Applicable.

New York: Not Applicable.

North Carolina: Not Applicable.

North Dakota: Not Applicable.

Ohio: Not Applicable.

Oklahoma: Not Applicable.

Oregon: Not Applicable.

Pennsylvania: Not Applicable.

Rhode Island: Not Applicable.

South Carolina: Not Applicable.

Tennessee: Not Applicable.

Texas: We normally perform the tests at posted speed limits when using the air-launched system. Our ground-coupled system is performed at a much slower speed and normally requires traffic control. I believe there is an AASHTO standard for using GPR.

Utah: Not Applicable.

Virginia: Generally we use the recommendations from the manufacturer. We try to run the tests at the prevailing speed for the air-launched system. Otherwise, it is based on the needs of the project.

Washington: Not Applicable.

West Virginia: Not Applicable.

Wisconsin: The application or circumstances of use dictate how you use GPR. Pavement and bridge deck applications are much different than geotechnical applications. The equipment used can also be different with regard to using a ground-coupled system or an air-launched system.

Wyoming: Not Applicable.

10. What procedures/protocols do you follow in interpreting GPR data?

Alabama: Not Applicable.

Alaska: Not Applicable.

Arizona: That's the only part I do not like. I tried to work with GSSI they wrote some software called Easy Tracker, which helped us a little bit, but still left interpretation to the operator. It was not automated. It did not get us where we wanted it to. I believe efforts have been made to develop some automated software, but I have not seen it or purchased due to financial constraints.

Arkansas: Not Applicable.

Colorado: Not Applicable.

Delaware: Not Applicable.

Florida: We have handbook that covers all of this. When we do high-speed surveys we'll manually pick all the layers. It gets tedious, but we get better results. We also use the vendor software and use GPR with manufacturer recommendations.

Georgia: Not Applicable.

Hawaii: Not Applicable. Our GPR contractors interpret the data. They deliver the GPR results to us and they put in a line that delineates the bottom of the bonded layer.

Idaho: Not Applicable.

Illinois: Not Applicable.

Indiana: The procedures used are based on experience. If it is an air-launched survey or a bridge deck evaluation, then I use my own software and my own processing. I use what is available commercially for acquiring the data and use some commercial software for processing, but I typically try to adapt it so that I'm not just stuck using what is available. I use a combination of vendor software and my own software developed during my research getting my PhD.

Iowa: Not Applicable.

Kansas: See response above.

Kentucky: Not Applicable.

Louisiana: Not Applicable.

Maine: Not Applicable.

Michigan: We're using the software from GSSI (Radan) to collect the data and to interpret the results. We use the automatic thickness selection and review the thicknesses manually. Again, there is no ASTM protocol for interpreting the data. The procedures would be different if we were using GPR on a network-level, which would require a standardized system.

Minnesota: We use the GSSI software (Radan) to interpret the data. We also take cores at various locations to verify results. We typically scan an area, review the scan, and inform the district where to take cores. We then use those cores to get the constant of the material. The program yields an output that is basically a bunch of squiggly lines. You have to manually pick the points that you're looking for and so you need a pretty good idea of what you're looking for. We have not automated the process yet, but we are following manufacturers recommendations. We also take cores to verify that our results are reasonable. We also use historical records, but typically they are used to get an idea of the pavement thickness. Sometimes our as-built drawings are not as reliable as they should be. We view them as a rough approximation.

Missouri: Not Applicable.

Nebraska: Not Applicable.

Nevada: Not Applicable.

New Hampshire: We visually inspect the GPR and compare it to the boring logs to check for reasonability.

New Jersey: Not Applicable.

New Mexico: I do not know; I did not interpret the data. I think they just looked for voids and the thickness of pavement.

New York: Not Applicable.

North Carolina: Not Applicable.

North Dakota: Not Applicable.

Ohio: Not Applicable.

Oklahoma: Not Applicable.

Oregon Not Applicable.

Pennsylvania: Not Applicable.

Rhode Island: Not Applicable.

South Carolina: Not Applicable.

Tennessee: Not Applicable.

Texas: We use ColorMAP software to assist in data interpretation. This program was developed by TTI.

Utah: The vendor did most of the interpretation.

Virginia: We follow the manufacturer recommended procedures. We always compare the GPR results with historical records. We also verify the results with cores when we are able to do so.

Washington: Not Applicable.

West Virginia: Not Applicable.

Wisconsin: Again, it is a little different for each circumstance. Each type of antenna and frequency can vary the way you should interpret the data. We use proprietary software in our collection and interpretation so it is also dependant on which software you use.

Wyoming: Not Applicable.

11. Have you performed any tests on the repeatability/accuracy of GPR equipment?

Alabama: No.

Alaska: No.

Arizona: Yes. In 2005, I met with the technical representative from GSSI and Gary Sanati from FMI. We sampled tests comparing coring vs. GPR. GSSI did it manually to find layer thicknesses. We did come within 4-5 percent of the cores, which we felt was very acceptable.

Arkansas: No.

Colorado: No.

Delaware: Yes, with FHWA, but again, the results were not accurate enough to use for project quality control/quality assurance purposes.

Florida: There have been some studies that looked at the accuracy of GPR for thickness and the repeatability of GPR equipment that we have looked at. We have also compared the GPR results at different speeds comparing a 25 mph survey with a 60 mph survey.

Georgia: No.

Hawaii: We use coring to ground truth the results.

Idaho: Thirteen or 14 years ago we did a research project testing the accuracy of GPR and I believe the results were pretty accurate; some scenarios did better than others, but a lot has changed in the last 15 years regarding GPR, so that study may be considered outdated. Nothing has gone on since then.

Illinois: Not to my knowledge.

Indiana: I have verified pavement thicknesses with coring.

Iowa: No.

Kansas: In more recent uses of GPR, we have contracted work and specified the end results (thickness, void locations and severity, moisture locations), and relied on the contractor to appropriately use the equipment and interpret the results. We do typically take cores with GPR to verify results.

Kentucky: I’m not sure either way.

Louisiana: No, but when we used it we found that GPR couldn’t distinguish the difference between soils cement and concrete.

Maine: A vendor came once and let us experiment with the equipment. We ran tests on samples of known values and verified the GPR results.

Michigan: Yes, we have done repeatability tests using the radar and have done coring to confirm thicknesses. We have a few concrete blocks with embedded steel that we check regularly also.

Minnesota; We did some research looking at cores and the dielectric constant. It's probably within 5 to 10 percent, depending on the field conditions. Generally we take cores to verify our results.

Missouri: We experimented with GPR a little bit. The University of Missouri assisted us with that and some experiments were better than others.

Nebraska: We experimented with GPR and felt that it was not refined enough.

Nevada: No.

New Hampshire: We use the borings to check against the GPR results. GPR is used to interpolate soil profiles between borings.

New Jersey: We have done coring to verify the results.

New Mexico: No.

New York: No.

North Carolina: Every time we used GPR we would always ground-truth it. We thought it was a tool we could use for many applications, but it gradually evolved into only using it to find large voids/objects under pavements like finding USTs or sinkholes.

North Dakota: We have verified the results with coring.

Ohio: No.

Oklahoma: We performed coring to verify the results.

Oregon: No.

Pennsylvania: Yes. We did a research project a few years ago, but we found that the GPR results were not accurate enough for our applications. There were some issues with calibration and weather conditions that affected the accuracy.

Rhode Island: No.

South Carolina: No.

Tennessee: No.

Texas: When we use the GPR for guidance on coring. Rather than coring at random, we core at areas of concern that the GPR equipment has detected.

Utah: No.

Virginia: Typically we ground-truth our GPR results with cores taken in the field.

Washington: No.

West Virginia: No.

Wisconsin: We always perform some method of ground-truth (coring, boring, etc.) to verify that the GPR results are reasonable.

Wyoming: No.

12. Have you used GPR for construction project quality control? How?

Alabama: No.

Alaska: No.

Arizona: No. We wanted to. One thing that we wanted to use it for was to verify HMA overlays were ½ inch over concrete. We found that we could not do it because it was rubberized asphalt over concrete and the deflection data wouldn't work. We wanted to do quality control and quality assurance. However, we mainly wanted GPR for FWD and also for high speed (60mph), but we have not gotten there yet.

Arkansas: No.

Colorado: No.

Delaware: No.

Florida: We're looking into using GPR for construction quality control. Right now the challenge would be having the right people there at the right time.

Georgia: No.

Hawaii: No.

Idaho: No.

Indiana: No.

Iowa: No.

Kansas: Not that I know of. I believe in one instance it was used to verify the presence of tie steel during construction. That resulted in them putting in tie steel.

Kentucky: I do not believe so, I have not heard of that.

Louisiana: No.

Maine: No.

Michigan: We have used GPR as a tool to assist the inspectors. However, we do not have any specifications that say that we will determine if a pavement is acceptable based on radar alone. If a client is suspicious of a problem in the pavement, we'll use GPR to narrow down where the problem areas could be and where they should be looking.

Minnesota: Not at this time. I am hoping that Ken Maser’s research project in Florida may help us in regard to quality control.

Missouri: No.

Nebraska: No.

Nevada: No.

New Hampshire: No.

New Jersey: No.

New Mexico: No.

New York: No.

North Carolina: No.

North Dakota: No.

Ohio: No.

Oklahoma: No.

Oregon: No.

Pennsylvania: No.

Rhode Island: No.

South Carolina: No.

Tennessee: No.

Texas: No. We had a research effort looking into correlating the air voids from the cores to the dielectric constant, but this is just a research effort and not something we use right now.

Utah: No. We just used it for forensics to determine the thickness of our existing pavements.

Virginia: No, but this is an area that has been discussed.

Washington: No.

West Virginia: No.

Wisconsin: Yes, but this is not an application that is used routinely. However, if a need arises, we will investigate it.

Wyoming: No.

13. Do you utilize GPR for pavement design, rehabilitation selection, or pavement management. If so, how? Has this been beneficial?

Alabama: We had talked about using it on a network basis, but nothing has been done so far. It seems that you would still need to core to verify the level of accuracy. We have not used it due to high groundwater (saturated base) in our area. It is our understanding that with the water present it would be difficult to differentiate between the layers and, therefore, determine a thickness.

Alaska: No.

Arizona: We were hoping to use it mainly in conjunction with our FWD to back calculate layer moduli, and also for high-speed testing for mill and fill, and use it as a quality control/quality assurance to verify that we got what we paid for. We have a slight problem because the majority of our highways have a 0.5 inch friction course which changes the speed that the GPR goes through it, and thus the radar goes through the AC and has a different speed. However, I think that we may have overcome this.

Arkansas: Not at this time, however, it is been discussed and we're trying to determine if GPR will be effective in pavement management.

Colorado: We have used GPR in the past to look at pavement thicknesses.

Delaware: No.

Florida: We currently evaluate 60 percent of pre-designs for thicknesses. These are at a project level and we supplement coring. At one time, people wanted to promote a network level GPR survey, but we feel that using GPR on a project level has been effective.

Georgia: No.

Hawaii: We use GPR for pavement design to find the bottom of the bounded layer and to see variations within the project layer.

Idaho: No, but we had originally talked about using GPR in conjunction with our FWD equipment.

Illinois: No.

Indiana: Yes, we have used it in these applications occasionally for determining pavement thicknesses. We have also used it on a network level to determine rehabilitation status. We have used GPR to support FWD for back-calculating pavement moduli.

Iowa: No, but we have talked about using GPR in this application on both project and network levels.

Kansas: Yes, but it has not been used in this way routinely. GPR is used more on an as-needed basis to locate air voids, dowel ties, and determine pavement thicknesses.

Kentucky: No.

Louisiana: We had used GPR on a network level to get an inventory of our AC pavement thicknesses, but we had problems telling the difference between soil cement and concrete.

Maine: No, but we have talked about it using it on a network level to get an inventory of our pavement thicknesses, but that would probably only be done once. We're also looking into using it in conjunction with our FWD equipment.

Michigan: Our use in this regard is limited to certain projects. We have used it to back-calculate layer moduli. I'm not sure how much we have used it for rehabilitation. We have used it to confirm the thicknesses of existing pavements and to verify thicknesses of pavements before an overlay. We have also used it in urban areas where there used to be street car rails in the pavement that were overlain with asphalt concrete. This was a mill and fill application and the contractor wanted to know how deep they could mill without hitting the rails.

Minnesota: We have used it for rehabilitation selection, but it depends on district requests. We mainly use GPR for pavement thicknesses. There is a research project that is looking into using FWD with GPR to back-calculate pavement layer moduli.

Missouri: No. We have an FWD, and we use the deflection basin data and run that through elastic layer programs to back-calculate the layer moduli.

Nebraska: No, but right now we are looking at the feasibility of using GPR in our agency.

Nevada: No.

New Hampshire: No.

New Jersey: I'm not sure. I know we have used it for pavement thicknesses when we were uncertain about the accuracy of our as-built drawings.

New Mexico: No, but our laboratory staff had mentioned that it could be useful in determining existing pavement thicknesses for new pavement design.

New York: We might move toward using it for these applications in the future, but as of now, it has not been used for pavements. I might be interested in using it on a network level to determine pavement thicknesses.

North Carolina: We had used GPR with FWD on occasion. Our main use was just trying to collect pavement thickness on a network-level. We tried, but we could not do it. We tried to use it as a tool to rehab roads in applications where we grind asphalt mix with base and mix with cement. We were trying to figure out the existing layer thickness, but we found it to be more cumbersome due to time constraints in the field because we wanted to do targeted sampling.

North Dakota: We have used it for pavement design. Ultimately, we needed to determine the depth of asphalt that we had. It just gave us an indication of the areas that were thicker. It did not change our design, but it was one of the tools that we used to maintain the 50 percent of asphalt in our base for full depth reclamation (FDR) of blending asphalt and base. We found that GPR worked really well for that.

Ohio: No.

Oklahoma: We used it on a project to get layer thicknesses that could be used in conjunction with our FWD.

Oregon: No.

Pennsylvania: No.

Rhode Island: No.

South Carolina: No.

Tennessee: No.

Texas: We currently use GPR for pavement design and to assist with making decisions on pavement rehabilitation. We have found it to be effective.

Utah: Yes, for pavement management and pavement rehabilitation. We just used it for thicknesses.

Virginia: We have used GPR on a few rehabilitation projects. We have used it more for forensics to determine what was placed after construction. In some cases, we have used it to determine what is there before rehabilitation. We have used it in conjunction with our FWD equipment.

Washington: No.

West Virginia: We have used it for determining pavement thicknesses.

Wisconsin: Yes, but it has not been done routinely. Usually we hire consultants to do GPR in these applications.

Wyoming: No.

14. What software does your agency use in interpreting GPR data?

Alabama: Not Applicable.

Alaska: Not Applicable.

Arizona: Radan.

Arkansas: Not Applicable.

Colorado: Not Applicable.

Delaware: Not Applicable.

Florida: We use the most recent software from GSSI.

Georgia: Not Applicable.

Hawaii: We do not use the GPR equipment. I'm not sure, but I think the contractor used GSSI.

Idaho: Not Applicable.

Illinois: Not Applicable.

Indiana: We use the vendor software for data collection. We use our own software that we developed for interpreting the data. For bridge deck evaluations, we use GSSI software. However, I use my own software for correcting amplitude to account for travel time and for contouring.

Iowa: Not Applicable.

Kansas: The equipment and software were created by Kansas University. The cost information is all lost to history along with the requirements, equipment protocol, and software.

Kentucky: Not Applicable.

Louisiana: Not Applicable.

Maine: Not Applicable.

Michigan: Radan.

Minnesota: Radan.

Missouri: Not Applicable.

Nebraska: Not Applicable.

Nevada: Not Applicable.

New Hampshire: We visually inspect the data. We have manufacturer software (GPR Ramac) that we use to filter the results.

New Jersey: Not Applicable.

New Mexico: Not Applicable.

New York: Not Applicable.

North Carolina: When we used GPR with state forces we had a Penetradar system and their software.

North Dakota: Not Applicable.

Ohio: Not Applicable.

Oklahoma: Not Applicable.

Oregon: Not Applicable.

Pennsylvania: Not Applicable.

Rhode Island: Not Applicable.

South Carolina: Not Applicable.

Tennessee: Not Applicable.

Texas: We currently use ColorMAP which was developed by TTI. We also use PaveCheck, which is basically ColorMAP, but it incorporates video because we upgraded our units to include video. This software is able to synchronize the location of the GPR tests with that of our FWD.

Utah: Not Applicable.

Virginia: Radan.

Washington: Not Applicable.

West Virginia: Not Applicable.

Wisconsin: We use Gradix, primarily. Both units are from MALA Geosciences and we have found the operating software is helpful.

Wyoming: Not Applicable.

15. Do you have plans to expand or contract your utilization of GPR applications?

Alabama: Right now we do not have plans to do either.

Alaska: We do not have plans to do either at this time.

Arizona: Yes, if we can get it to work. We have plans to integrate it with FWD and high-speed testing. Once we are comfortable with it, we may branch out in other applications.

Arkansas: Right now we're trying to figure out if GPR could be used by pavement management. We have mentioned using it in conjunction with FWD testing. And we might want to use it for homogenous pavement sections to verify existing pavement conditions in order to determine layer thicknesses.

Colorado: Expand sometime in the future.

Delaware: We do not plan to expand our use of GPR at this time. We have done tests using the MIT scanner to measure dowel bar locations and those results were pretty good, but again, we do not have plans to expand GPR at this time.

Florida: Future ideas would be having a raised set-up and using GPR to map underground utilities. Also, sometime we would like to get a high-speed lower frequency antenna, something less than 1 GHz.

Georgia: We do not plan to expand our use of GPR at this time.

Hawaii: For now and the next few years, we will stick with using GPR for pavement thicknesses and for depth placement of rebar in bridges. Ken Maser is currently talking with our bridge group to see if it may be something they are interested in using in the future for other applications.

Idaho: The previous intent was to mount GPR onto either our FWD vehicle or some other vehicle and run tests in the summer to analyze in the fall. I'm not sure if we're going to have enough people to do two operations on one unit. Plus we need someone to come out and do the training on GPR. We are hoping to start using it eventually. At this point we're not too hopeful that we'll get much out of it.

Illinois: No.

Indiana: Yes. We want to use it more for bridge deck evaluations. I recently spoke with the district engineer about using GPR for determining pavement thicknesses—not to be used quite "in place of" coring, but used to pick up some of the slack. I can see us getting more requests for UST locations and other geotechnical applications.

Iowa: We hope to expand our use of GPR. This expansion depends on our budget, but we plan to get an air-launched unit in the next year or two. We plan to use it on a network-level to verify existing pavement thicknesses and on a project level as needed.

Kansas: Not right now. We will watch other places and see if the multi-gain antennas are getting better results.

Kentucky: Well obviously I have limited information, but I would like to see us use it more to identify potential slab stability issues on projects. I would also be interested in looking into using high-speed data collection GPR equipment on a more widespread basis.

Louisiana: We had talked about it expanding our use of GPR, but if we do, we'll focus on one district at a time. That's what I heard, but with the current budget, that's doubtful right now. We were going to try to use GPR in conjunction with our Rolling Wheel Deflectometer (RWD) to back-calculate the structural number of the pavement.

Maine: We are considering expansion depending on the results of our pilot study on GPR.

Michigan: I would love to expand it, but right now the budget is pretty tight. We have been trying to upgrade our equipment for the last two years. As soon as the money is available, we'll try to upgrade. We're hoping the next FWD we purchase will be equipped with a radar unit, but this is a long-term goal.

Minnesota: We are looking at using GPR for bridge deck evaluations for delamination. Right now we do not have a lot of experience with that, and we do not have an abundant amount of resources at this time. It also depends on the amount of work that the district needs performed.

Mississippi: We'd like to expand our use of GPR, but the expense right now is not feasible. We would like to use it on a network level to inventory all our pavements. It would be nice for verification.

Missouri: Not at this time, but some people in our department our exploring the idea of expanding our use of GPR.

Nebraska: We are doing a research project to determine the feasibility of using GPR within the state, but are currently not using it. The results of the research project that we are doing will determine whether or not we use GPR in the future.

Nevada: Not at this time.

New Hampshire: We have plans to buy a new ground-coupled unit. We will most likely purchase from the same manufacturer.

New Jersey: GPR is currently used on a project by project basis and will probably continue to be used on the same basis.

New Mexico: We do not have plans to expand our utilization of GPR at this time.

New York: Right now we are still evaluating it. The expansion would be to use GPR on a network-level for pavement thicknesses. GPR would need to have an automated way of interpreting the data; otherwise, it would be too time consuming on a network-level. Additionally, it would have to be able to collect the data at highway speeds or the posted speed limit.

North Carolina: Right now we plan to keep it stable.

North Dakota: Well, we did not do any GPR work last year, and we're not doing anything this year. For what we're paying for, we're not seeing a huge return on the investment. It's very costly to have someone come in and do it. However, we have been looking into using it in conjunction with our FWD.

Ohio: We are in the middle of a research project investigating GPR. The results of that research project will dictate how we proceed with GPR. Our geotechnical group uses it based on site conditions and may use seismic or electrical resistivity as other tools to meet the specific needs of the project.

Oklahoma: We hope to do another similar project to back-calculate the layer moduli.

Oregon: We have thought about using GPR, but right now it is not at the top of our priorities.

Pennsylvania: Not at this time.

Rhode Island: We have plans for expanding our utilization of GPR. Right now we’re looking into purchasing a ground-coupled unit.

South Carolina: Not at this time.

Tennessee: As far as I know, we do not have plans to expand our use of GPR at this time.

Texas: I think that the use of GPR in Texas has been growing constantly and is used as a tool to make better decisions in pavement management.

Utah: Not at this time.

Virginia: Yes. We would like to look at using it for delamination, density in asphalt surface layers, and corrosion measurements on deck surfaces. Our expansion depends on having the manpower needed and the experience to effectively analyze the data.

Washington: Not that I’m aware of.

West Virginia: Yes. We are planning on purchasing a GPR unit. It may take some time due to budget constraints, but we’d like to get one.

Wisconsin: We will probably continue to expand the use GPR on the consultant side with a consultant like Ken Maser.

Wyoming: We may use it for bridge deck evaluations, but that would be quite a ways down the road. We do not have plans to do any evaluations on GPR in relation to pavement thickness.

APPENDIX C:

List of State Highway Agency Survey Contacts

LIST OF STATE HIGHWAY AGENCY SURVEY CONTACTS

FULL NAME	AGENCY	DEPARTMENT	RESPONSE
Scott George	Alabama Department of Transportation	Pavements	Yes
Billy Connor	Alaska Dept of Transportation & Public Facilities	Division of Planning and Programming	Yes
Billy Hurguy	Arizona Department of Transportation	Pavement Management	Yes
Dennis Rusher	Arizona Department of Transportation	Pavement Technician	Yes
Paul Burch	Arizona Department of Transportation	Manager-Pavement Design Engineer	No
Mark Evans	Arkansas Department of Transportation	Pavement Management Engineer	Yes
Terrie Bressette	California Department of Transportation	Flexible Pavement Engineer	No
George Cornell	California Department of Transportation	Materials	No
Jay Goldbaum	Colorado Department of Transportation	Pavement Design	Yes
Edgardo Block	Connecticut Department of Transportation	Pavement Management Engineer	No
Wayne Blair	Connecticut Department of Transportation	Materials & Research	No
Ravi Chandran	Connecticut Department of Transportation	Materials & Research	No
Jennifer Pinkerton	Delaware Department of Transportation	Pavement Management Engineer	No
Jim Pappas	Delaware Department of Transportation	Materials & Research	Yes
Steve Guy	Florida Department of Transportation	Pavement Management Engineer	Yes
Charles Holvschuher	Florida Department of Transportation	State Materials Office - Non-destructive Testing.	Yes
Monzy Matthews	Georgia Department of Transportation	Pavement Test Engineer	Yes
James Turner	Georgia Department of Transportation	Pavement Test Engineer	Yes
Abe Casey	Hawaii Department of Transportation	Materials Testing & Research Engineering Program Manager	Yes
Lori Cool	Hawaii Department of Transportation	Pavement Management	Yes
Mike Santi	Idaho Department of Transportation	Division of Highways	Yes
Ladonna Roween	Illinois Department of Transportation	Materials and Research/Pavement Management	Yes
Tommy Nantung	Indiana Department of Transportation	Pavement Research Engineer	Yes
Duane Harris	Indiana Department of Transportation	Pavement Management Engineer	Yes
Chris Brakke	Iowa Department of Transportation	Pavement Design and Management	No
Jason Omundson	Iowa Department of Transportation	Pavement Investigations	Yes
Rick Milller	Kansas Department of Transportation	Pavement Management Engineer	Yes
Jon Wilcoxson	Kentucky Transportation Cabinet	Pavement Management Engineer	Yes
Christophe Filastre	Louisiana Department of Transportation	Pavement Management Engineer	Yes
Robert Skehan	Maine Department of Transportation	Pavement Management Engineer	Yes
Brian Luce	Maine Department of Transportation	Project Development	No
John H. Andrews	Maryland Department of Transportation	Pavement Testing	No
Tim Smith	Maryland Department of Transportation	Materials Technology	No
Jeff Hall	Maryland Department of Transportation	Materials Technology	No
Matthew D. Turo	Massachusetts Highway Department	Pavement	No
Mr. Tom Hynes	Michigan Department of Transportation	Materials & Research	Yes
Tim Croze	Michigan Department of Transportation	Pavement Maintenance Engineer DOT	Yes
Curtis Bleech	Michigan Department of Transportation	State Pavement Engineer	Yes
Dave Webber	Michigan Department of Transportation	Construction Tech (Pavement Investigations)	Yes

LIST OF STATE HIGHWAY AGENCY SURVEY CONTACTS, *CONTINUED*

FULL NAME	AGENCY	DEPARTMENT	RESPONSE
Shongtao Dai	Minnesota Department of Transportation	Materials & Research	Yes
Dave Janisch	Minnesota Department of Transportation	DOT Pavement Management Engineer	Yes
Steve Adamsky	Minnesota Department of Transportation	Pavement	Yes
Cindy Grogan Drake	Mississippi Department of Transportation	Pavement Management Engineer	Yes
John Donahue	Missouri Department of Transportation	Pavement Engineering	Yes
Jay Bledsoe	Missouri Department of Transportation	Pavement Management Engineer	Yes
Dan Nichols	Nebraska Department of Transportation	Pavement Management Engineer	Yes
Michele Maher	Nevada Department of Transportation	Materials Engineer	Yes
Parvis Noori	Nevada Department of Transportation	Geotechnical	Yes
Eric Thibodeau	New Hampshire Department of Transportation	Materials & Research	No
Dick Lane	New Hampshire Department of Transportation	Materials & Research	Yes
Krystle Pelham	New Hampshire Department of Transportation	Materials & Research	Yes
Camile Crichton-Sumners	New Jersey State Department of Transportation	Research	No
Eileen Sheehy	New Jersey State Department of Transportation	Manager of Materials	Yes
Joe Beke	New Jersey State Department of Transportation	Pavement Management	No
Robert Young	New Mexico Department of Transportation	Pavement Management	Yes
Rick Bennett	New York Department of Transportation	Pavement Management	Yes
Dr. Judith B. Corley-Lay	North Carolina Department of Transportation	Pavement	No
Clark Morrison	North Carolina Department of Transportation	Pavement Design and Management	Yes
Jane Berger	North Dakota Department of Transportation	Pavement Management Engineer	Yes
Clayton Schumaker	North Dakota Department of Transportation	Materials and Research Engineer	Yes
Aric Morse	Ohio Department of Transportation	Pavement Engineering	Yes
Gene Geiger	Ohio Department of Transportation	Pavement Engineering	Yes
Ginger McGovern	Oklahoma Department of Transportation	Pavement Management Engineer	Yes
John Coplantz	Oregon Department of Transportation	Pavement Management Engineer	Yes
Lydia Peddicord	Pennsylvania Dept of Transportation	Pavement Design	Yes
Colin A. Franco	Rhode Island Department of Transportation	Central Office	Yes
Mike Byrne	Rhode Island Department of Transportation	Principle Civil Engineer	Yes
Paul Annarummo	Rhode Island Department of Transportation	Pavement Management Engineer	Yes
Thomas Shea	South Carolina Department of Transportation	Pavement Management Engineer	Yes
Andy Johnson	South Carolina Department of Transportation	Research & Materials	Yes
Jim Maxwell	Tennessee Department of Transportation	Materials & Tests	Yes
Jim Waters	Tennessee Department of Transportation	Surveying	Yes
David Horn	Tennessee Department of Transportation	Pavement Design	Yes

LIST OF STATE HIGHWAY AGENCY SURVEY CONTACTS, *CONTINUED*

FULL NAME	AGENCY	DEPARTMENT	RESPONSE
Magdy Mikhail	Texas Transportation Institute	Pavements and Materials Systems Branch Manager	Yes
Gary Kuhl	Utah Department of Transportation	Pavement Analysis	Yes
Bill Ahearn	Vermont Department of Transportation	Materials & Research	No
Michael Polgruto	Vermont Department of Transportation	Pavement Management Engineer	No
Brian Defendorfer	Virginia Department of Transportation	Research	Yes
Trenton Clark	Virginia Department of Transportation	Pavement Engineer	Yes
Ron Owens	Washington Department of Transportation	DOT Pavement Management Engineer	Yes
Jon Livingston	Washington Department of Transportation	Materials	Yes
Mike Bower	Washington Department of Transportation	Structures	Yes
Araon Glisby	West Virginia Department of Transportation	Materials Engineer- DOT	No
Robert Watson	West Virginia Department of Transportation	Pavement Management Engineer	Yes
David Mainer	West Virginia Department of Transportation	Division of Highways	Yes
Mike Mants	West Virginia Department of Transportation	Materials	Yes
Roy Capper	West Virginia Department of Transportation	Materials	Yes
Dan Reid	Wisconsin Department of Transportation	Materials Center	Yes
Bill Duckert	Wisconsin Department of Transportation	Pavement Management Engineer	Yes
Rick Harvey	Wyoming Department of Transportation	Materials/Pavement Engineer	Yes