Evaluation of New Ground-Penetrating Radar Technology To Quantify Pavement Structures

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Pavement engineers routinely utilize mechanistic-based models for pavement rehabilitation design and for assessing the remaining service life of existing pavement structures. Dynamic and rolling load equipment is used to measure pavement response to those applied loads. The analytical models that utilize such data are dependent on the availability of accurate pavement layer thickness values at the load application points. Ground-penetrating radar (GPR) technology has been used to quantify pavement structures, but the technique has not provided sufficient accuracy or reliability to gain general acceptance. GPR accuracies have generally improved when core data are made available for system calibration; however, the number of cores required to maintain acceptable accuracies effectively defeats the purpose of nondestructive measurements. A new GPR technology, known as Road Radar, takes a different approach to the thickness measurements of multiple pavement layers in pavement structures. This technology uses multiple antennas that provide accurate non-intrusive thickness measurements of multiple layers from 50 mm to greater than 2 000 mm without benefit of any destructive calibration procedure, such as drilled cores. The Road Radar technology, designed into the Road Radar System and proven through extensive field trials and data-acquisition programs, is described in this report. Comparative analysis is presented of pavement structure thickness measurements, using both Road Radar measurements without core calibrations and drilled core measurements. The results of these comparisons are reported for a number of individual projects, as well as statistical analysis performed on approximately 150 pieces of paired data "pooled" from a number of field test sites.

Pavement engineers are becoming increasingly dependent on alternative, versus historically used, technologies to manage their paved road inventories. Superior and more effective systems have been developed to evaluate structural characteristics of existing pavements and to assess remaining service life in existing structures through back-calculation procedures designed for that purpose. These systems typically measure pavement response to dynamically imposed loads. This type of technology is relatively mobile, cost-effective, and provides superior operator safety. Various computer models exist to provide system managers with information that is fundamental to project planning.

Computer models, such as those identified above, depend on reliable input data, including pavement structure thickness and elastic properties of constituent layers, to yield meaningful output information. Construction or "as-built" records, if they exist, are at best approximations and are frequently based on the original design instead of on layer thicknesses actually placed. Furthermore, pavement engineers recognize the limitations and expense of historically collected data from drilled core specimens.

Ground-penetrating radar (GPR) has long been known as a technology amenable to the determination of pavement layer thicknesses (*1–7*). However, past applications of this technology to pavement structure investigations have generally provided neither sufficient accuracy, requiring extensive layer thickness calibrations through drilled cores, nor reliability to achieve wide acceptance by pavement engineers and technologists. These limitations of existing GPR systems are discussed in detail elsewhere (*8,9*). Dawley and Mesher (*10*) have described the GPR enhancements that are embodied in the Road Radar System technology.

Existing GPR technology has been enhanced in the Road Radar System for the purpose of providing a non-intrusive technique for obtaining subsurface information on existing roadway pavement structures. The primary enhancements have been twofold. The first enhancement has been to render the radar unit essentially self-calibrating. This has been accomplished by innovations that enable both the signal travel time and velocity of the signal to be determined at every measurement point, thereby accounting for varying material properties within the structure. The second enhancement has been to develop computer software that permits rapid processing of vast quantities of collected data.

Within this paper a description is provided of some of the innovations that have been incorporated into Road Radar technology to produce the aforementioned enhancements. Furthermore, some of the field testing, which has been undertaken to verify the new technology, is described and some statistical data are provided to validate the system.

ROAD RADAR INNOVATIONS

Initial investigations that utilized general purpose GPR systems for quantifying multilayer pavement structures identified serious shortcomings of these systems as a quantitative engineering tool. Through these critical investigations, a detailed specification was generated to address the requirements of a comprehensive system that would provide accurate quantitative multilayer structure information. This process identified the need for a nondestructive radar system with the capability to resolve multiple pavement structure layers as thin as 50 mm to a total depth of greater than 2 m with quantifiable accuracy. Additionally, the design specification recognized the need for a comprehensive signal-processing environment to allow the automated interpretation of the vast volumes of data typically produced by radar surveys.

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To this end, the Road Radar System discussed herein combines a novel hybrid multiple radar configuration with an extensive signal-processing software environment to provide an accurate, user-friendly environment for automated multilayer data interpretation. The following sections describe the unique aspects of both the system hardware and interpretation software.

Hardware

All GPR systems operate on the principle of the accurate measurement of the propagation times of electromagnetic energy radiated through and reflected from dielectric materials. As this energy propagates through a layered structure, a portion of the energy is reflected at each boundary of electrically dissimilar materials, and the remaining energy propagates into any subsequent layers.

A simplistic block diagram of a bistatic (separate transmitter and receiver antennas) GPR system is depicted in Figure 1. Given this physical configuration for the transmitter (*T*) and receiver (*R*), a pulse radiating from the transmitter at time t_0 and reflecting from a planar reflector at a distance *d* would produce a scaled replica pulse at the receiver (*R*) at some later time t_1. The relationship between the propagation time and propagated distance is given as:

$$p = \frac{1}{2}\, v(t_1 - t_0) = \frac{1}{2}\, vt \qquad (1)$$

where

p = one way propagation distance;
t = propagation time $(t_1 - t_0)$; and
v = radar pulse propagation velocity in the material.

It becomes apparent that Equation 1 is under-determined; for nondestructive scenarios using conventional GPR equipment, both the distance term and velocity are unknown. The traditional solutions to this dilemma required varying degrees of approximation. In purely nondestructive situations the velocity term was presumed consistent and was approximated based on empirical experience, producing typically inaccurate results. In order to increase the accuracy of such under-determined systems, cores are extracted at noted locations, velocities are determined at these locations, and a piecewise linear velocity assumption is applied to sections between cores. Depending on the number of cores extracted, such an approach may or may not produce acceptable results.

A second purely nondestructive technique for velocity approximation may be derived from the amplitude ratio of the incident and reflected energy at a dielectric interface. This reflection coefficient allows the determination of the layer velocity from the following relationships:

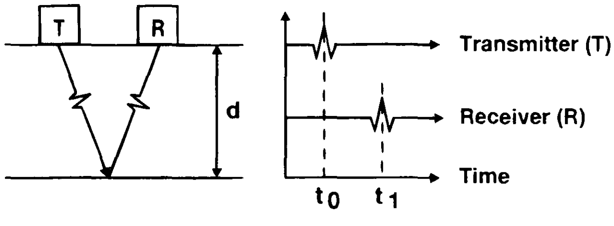

FIGURE 1 Simple bistatic radar antenna configuration and propagation path for a layer of thickness *d*. Time relationship between the transmitter and receiver for a radiated pulse.

$$v = \frac{c}{\left[\dfrac{1+|\rho|}{1-|\rho|}\right]} \quad \text{and} \quad \rho = \frac{A_r}{A_i} \qquad (2)$$

where

ρ = reflection coefficient;
A_r = reflected signal amplitude;
A_i = incident signal amplitude;
c = speed of light (constant); and
v = velocity of the material at the surface of the interface.

Although this technique is commonly used, the calculated velocity values are extremely sensitive to the following elements.

- Accurate signal amplitude measurements. GPR system amplitude measurements are susceptible to fluctuations arising from antenna displacement (spherical losses) and planar surface-interface roughness properties (scattering losses). It becomes evident from Equation 2 that slight amplitude perturbations manifest themselves as severe calculated velocity variations.
- Propagating errors for multiple layer velocity estimation. Subsequent layers in a multilayer structure rely on previous layer velocity determination. These cumulative errors render this technique for multiple layer velocity estimation inappropriate.

In the Road Radar System this velocity determination problem is addressed by employing a novel multiple antenna array configuration (Surface-Coupled Subsystem). This multipath solution provides a technique to accurately calculate the velocity at each radar measurement point. By using the radar antenna configuration depicted in Figure 2, multiple reflection path propagation times for each receiver are recorded simultaneously. As the antenna array configuration geometry is accurately known, the following deterministic system may be developed.

$$p_n = 2\sqrt{d^2 + \left[\frac{s_n}{2}\right]^2} \quad \text{and} \quad p_n = v\, t_n \qquad (3)$$

where

p_n = propagation path length from transmitter to receiver$_n$;
t_n = propagation time (path n);
d = layer thickness;
s_n = transmitter-receiver$_n$ separation; and
v = layer velocity.

This allows the determination of the bulk material velocity and therefore the parameter of interest *d*, the layer thickness when (the number of antennas) $n \geq 2$.

The Surface-Coupled Subsystem is capable of resolving layers from 0.1 m to greater than 2 m. For the thin layer resolution, identified during the system design phase as being of paramount importance to pavement engineers, a second high resolution radar is added. The multilayer structure evaluation system combines a com-

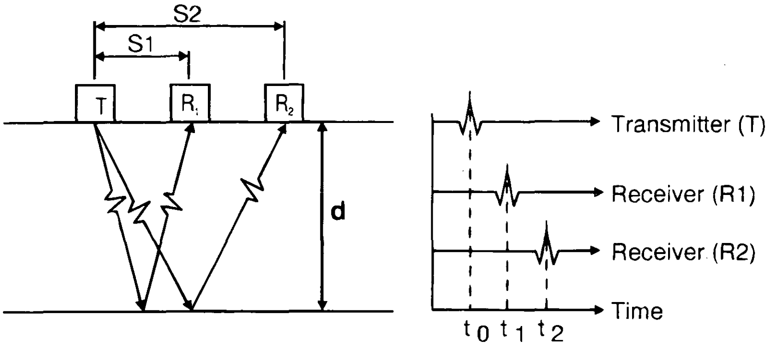

FIGURE 2 Bistatic radar antenna array configuration and multiple propagation paths for a layer of thickness *d*. Time relationship between the transmitter and multiple receivers for a radiated pulse.

plementary high resolution air launch horn-type antenna (Air-Launched Subsystem) with the velocity determining Surface-Coupled Subsystem. The Air-Launched Subsystem allows the resolution of structure layers thinner than 50 mm.

Software

A comprehensive radar signal-processing environment provides the means to effectively combine the large volumes of raw radar data from both radar subsystems and to allow automated interpretation to provide continuous multiple pavement layer thickness and velocity profiles. The data processing environment represents a synergism of many programming domains, effectively combining artificial intelligence, time domain digital signal processing, neural networks, and pattern recognition.

This graphical radar interpretation environment exploits a rule-based expert system paradigm to allow a technical individual with limited radar experience to successfully process typical road data. On simplistic planar layer road structures, the system can perform automatic interpretation of the radar data. On more typical variable construction surveys, the system interprets consistent sections and defers to the operator for guidance at the transition points typically representing construction joints or other discrete subsurface anomalies.

The output of the data interpretation operation includes graphical radar data profiles indicating a section of the data acquired during the survey. These profiles present the pavement engineer with the unique opportunity of being able to examine the road cross-section for more qualitative features. Such features include base course or subgrade constituent variations (granular material size variations) and anomalous area investigation. In conjunction with this qualitative data are the quantitative continuous thickness and velocity profiles for each layer in the road structure generated during interpretation. The usefulness of the thickness profiles is self-evident, but initial indications suggest that the velocity profiles are as important, and perhaps more so. It has been suggested that road material properties of interest to pavement engineers may have substantial empirical relationships with the material velocity. These properties include moisture content, compaction (related to density and air voids), and mixture constituent volumetric ratios. All data produced by the system are easily formatted for any pavement management system and can produce statistical analysis as well as tabular and graphical profiles. Typical road section outputs are presented in Figure 3.

SELECTED DATA COLLECTION PROJECTS

Methodology

Data collection programs have been conducted on numerous paved highways, with the cooperation of the highway agencies. Highway locations to be monitored were usually selected by highway agency personnel. Points at which structural data were to be acquired by conventional methodology (coring, auguring) were premarked on the pavement. The outer wheelpath of the travel lane was typically selected for that purpose, and for performing the continuous survey with the Road Radar. After completion of Road Radar data collection, the data were processed, and measured structural layer thickness values were presented to the highway agency personnel. Results from the coring or auguring activity were then used to compare with Road Radar results.

Accuracy and Variability of Measurements

In comparing data acquired by alternative acquisition and measurement techniques, it is essential to recognize the limitations that are applicable to each set of paired data.

With respect to the drilled core procedure for representing pavement layer thickness, reference is made to ASTM Designation D3549, "Standard Test Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens." Test specimens may be laboratory compacted or from compacted bituminous pavements. The ASTM standard states that no measurement precision data are presently available. It is recommended that none be established, since the documented variability in thickness of constructed layers is very large in relation to the expected measurement variability. The following tabulation exists in the ASTM standard, which is a summary of data from studies undertaken by user agencies (S.I. units, in millimeters, are included by the authors).

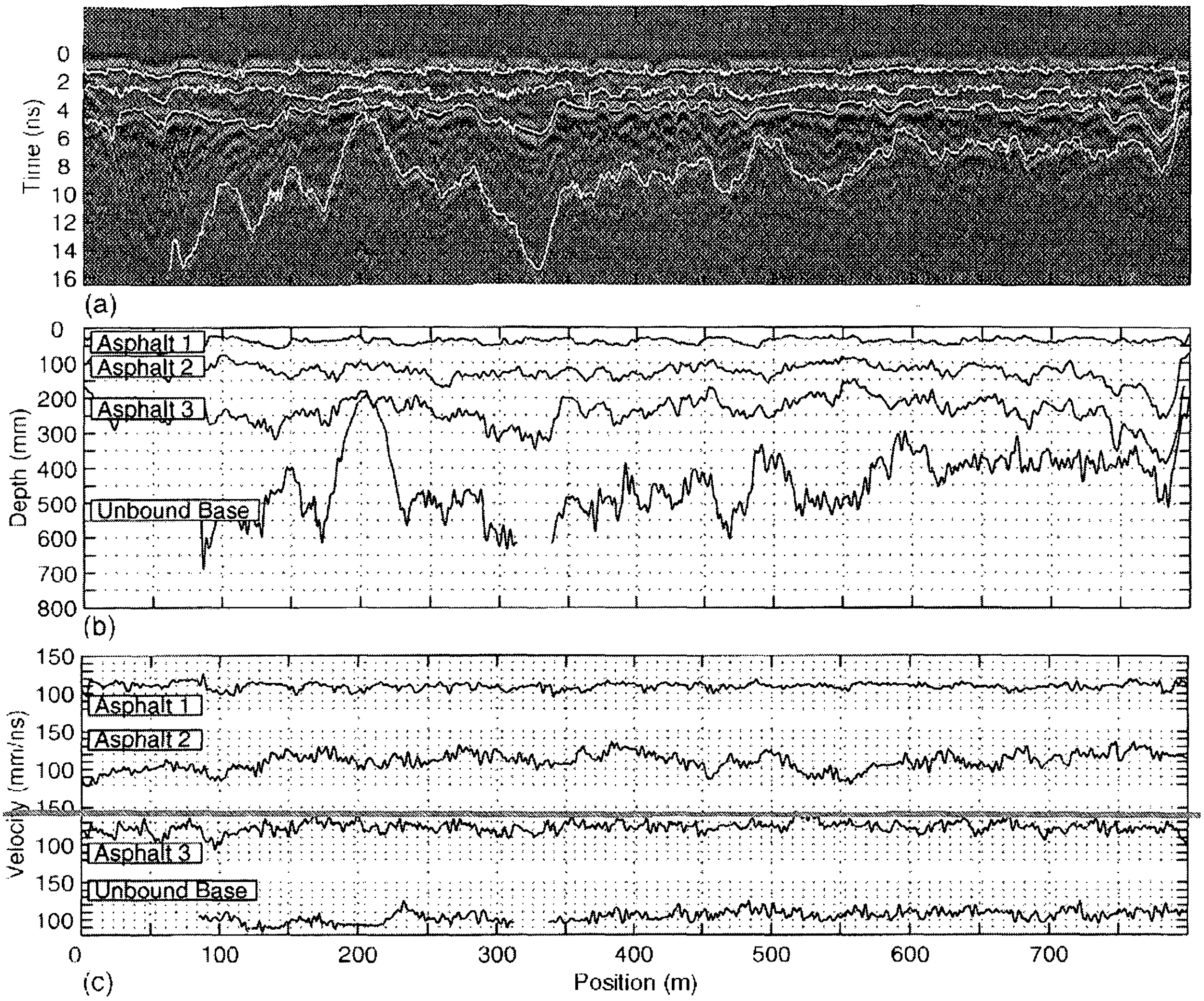

FIGURE 3 (a) Raw radar data with interpreted interface overlays. (b) Interpreted layer thickness profiles. (c) Interpreted layer velocity profiles.

Bituminous Pavement Thickness Variability

Thickness Range in. (mm)	*Standard Deviation in. (mm)*	*Coefficient of Variability (percent)*
1.0 to 1.9 (25.4 to 48.3)	0.21 (5.3)	14.7
2.0 to 2.9 (50.8 to 73.7)	0.29 (7.4)	13.0
3.0 to 3.9 (76.2 to 99.1)	0.37 (9.4)	11.3
4.0 to 4.9 (101.6 to 124.5)	0.53 (13.5)	12.5
6.0 (152.4)	0.75 (19.1)	12.5

In the absence of a precision statement in the ASTM standard, the above values of standard deviation (in millimeters) are used hereafter as a means of assessing how closely the alternative procedures (coring and Road Radar) represent existing pavements at each measurement point.

With respect to measuring thickness of in situ granular base layers using the auguring procedure, no relevant standard exists. However, it is commonly accepted that the field measurement procedure is difficult and imprecise.

The Road Radar operational specification for thickness accuracy is (a) wearing surface (pavement layer)—greater of ± 6 mm, or 5 percent, and (b) base course (second layer)—greater of ± 12 mm, or 10 percent.

For all paired data that were collected at every measurement point at each site, linear regression analysis has been undertaken to ascertain whether or not a statistically significant correlation exists. Commentary is provided hereafter with respect to calculated correlation coefficients (*r*) and their significance.

Site 1: Highway 21, Alberta, Canada

Highway 21 is a four-lane rural divided highway located in east-central Alberta. The pavement structure was known to be a two-layer system composed of deep strength asphalt concrete pavement constructed on a granular base layer. The section of highway pavement structure, which was identified for survey by personnel of

TABLE 1 Asphalt Concrete Pavement Thickness as Determined by Drilled Cores, and by Road Radar Measurements, Site 1—Highway 21, Alberta, Canada

Chainage (km)	Thickness From Cores (mm)		Thickness From ROAD RADAR™ (mm)				
	Recorded	±1σ[a]	Closest[b]	Accuracy Limits[c]	Max[d]	Min[d]	Avg.[e]
20.130	155	136-174	154	149-165	199	147	157
20.221	148	129-167	156	152-168	170	151	160
20.324	150	131-169	155	146-162	160	148	154
20.469	181	162-200	186	185-205	204	186	195
20.566	140	121-159	144	141-155	151	144	148
20.666	181	162-200	185	173-191	187	178	182
20.767	210	191-229	210	198-218	210	205	208
20.867	188	169-207	200	186-206	200	192	196
20.957	164	145-183	165	161-177	174	165	169
$\bar{x}$	168.6		172.8				174.3
σ	21.6		21.8				20.4

[a] See ASTM D3549, Table 1.
[b] At measurement point closest to core location.
[c] ROAD RADAR™ specification of ±5%.
[d] Value limits within 1 m of core location.
[e] Average of all ROAD RADAR™ measurements within 1 m of core location.

Alberta Transportation and Utilities, comprised 1 km in the northbound lanes.

The outer wheelpath of the travel (outer) lane was chosen for an initial survey, and wherein both Road Radar and drilled core data were collected. Pavement thicknesses as determined by drilled cores and by Road Radar measurements are presented in Table 1. In Table 1, the asphalt concrete pavement thickness measured by the Road Radar is reported both as a single measured value at the point closest to the drilled core location, as well as the average of all radar measurements within a 1-m distance on either side of the core location (usually six pieces of data). For this site, nine pieces of paired test data were used for analysis by linear regression. Figure 4 consists of a plot of these paired data as well as linear regression statistics. The calculated value of $r = 0.99$ confirms that there is greater than a 99 percent probability that the paired data are associated (i.e., less than 1 percent level of significance).

A plot of core thickness variability versus Road Radar accuracy boundaries for the paired data is presented in Figure 5 and is based on limiting values indicated in Table 1. It is reasoned that if the probable pavement thickness represented by the accuracy statement for the Road Radar lies within an envelope representing the pavement thickness variability associated with the drilled core data, then the Road Radar data are at least as representative of the pavement structure as is the drilled core information. This hypothesis is confirmed as indicated in Figure 5.

Site 1 has afforded a unique opportunity to assess the Road Radar accuracy to measure thickness of the second (granular) layer, that is, a multilayer structure. Relevant data are presented in Table 2.

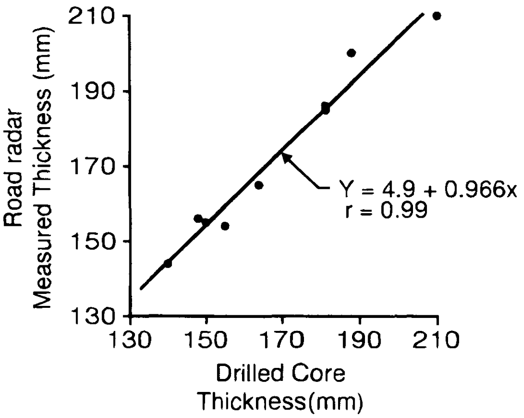

FIGURE 4 Asphalt concrete pavement thickness determined by drilled cores versus Road Radar measurements, Site 1-Highway 21, Alberta, Canada.

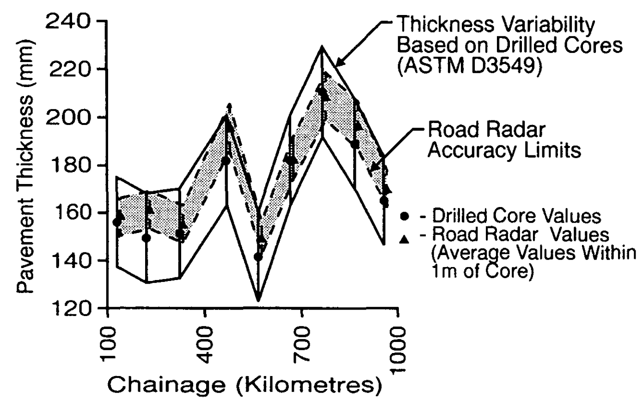

FIGURE 5 Asphalt concrete pavement thickness from drilled cores and Road Radar measurements, Site 1-Highway 21, Alberta, Canada.

TABLE 2 Granular Base Course Thickness as Determined by Augured Holes and by Road Radar Measurements, Site 1—Highway 21, Alberta, Canada

Chainage (km)	Thickness From Augured Holes (mm)	Thickness From ROAD RADAR™ (mm)	
		Closest[a]	Accuracy Limits[b]
20.130	345	335	302-368
20.221	372	299	269-329
20.324	380	354	319-389
20.469	339	318	286-350
20.566	250	236	202-260
20.666	279	303	273-333
20.767	270	272	245-299
20.867	302	253	228-278
20.957	316	263	237-289
$\bar{x}$	317	293	
σ	43	37	

[a] At measurement point closest to core location.
[b] ROAD RADAR™ specification of ±10%

Figure 6 is a plot of paired data as well as linear regression statistics. The r value of 0.76 indicates that there exists at least a 95 percent probability that the paired data are associated. Recognizing the sensitivity of the layer thickness values acquired by the auguring technique, it is considered that the Road Radar precision and accuracy is competent for measurement of multilayer structures.

Site 2: Interstate Highway 15 (I-15), Montana, USA

I-15 is a rural, four-lane freeway. The test site, selected by the Montana Department of Transportation (MDT), comprised a 1.6-km section of the travel (outer) lane in the southbound lanes. Data, which were collected over the most southerly 1.1 km, are presented in Table 3. Relevant data are plotted in Figure 7. In this case, analysis of the paired data has been undertaken in two separate ways. The purpose of this exercise was to identify the most appropriate statistic to use from the data base developed using the Road Radar.

The reasoning for this approach was that, since ASTM recognizes actual pavement construction variability, perhaps it may be valid to average several individual Road Radar statistics. Figure 7, left, is a plot of drilled core values and the single Road Radar value, whereas Figure 7, right, is a similar plot using the averaged Road Radar data. The recorded r values indicate that there exists a 99 percent probability that the paired data are associated, irrespective of the alternative Road Radar statistics used.

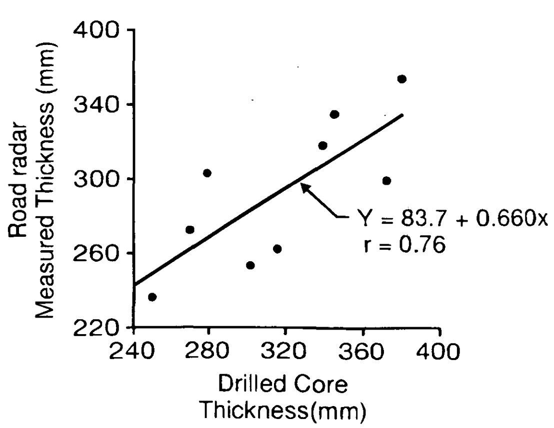

FIGURE 6 Granular base course thickness determined by drilled cores versus Road Radar measurements, Site 1-Highway 21, Alberta, Canada.

Figure 8 is a plot of core thickness variability (ASTM) versus Road Radar accuracy boundaries. As was the case for Site 1, it is demonstrated that Road Radar methodology provides information that is as reliable as the data acquired by coring methodology.

Granular base thickness values were obtained using the Road Radar. However, MDT staff were unable to acquire similar data using conventional auguring methodology.

Site 3: Highway 20, Taivalkoski District, Finland

The Finnish National Road Authority organized an extensive data collection program on paved highways in Finland in the autumn of 1993. The Road Radar was used for data collection purposes.

A number of separate sites were surveyed on Highway 20, one of which is reported in Table 4. Road Radar measurement data include both the single measurement value at the point closest to the drilled core and averaged data from measurements taken within 1 m of the core location. These data are plotted in Figure 9, left and right, respectively. The recorded r values indicate that there exists at least a 95 percent probability that the paired data are associated, irrespective of the alternative Road Radar statistics used. However, in this case, use of the single radar value, measured at the core location, provides 99 percent probability of data association, whereas use of averaged radar data does not.

Data Base of Road Radar Versus Drilled Core Pavement Thicknesses

A total of 147 pieces of paired data (Road Radar versus drilled cores) representing asphalt pavement thicknesses have been utilized in a linear regression analysis. Figure 10 contains a plot of the paired data and a plot of the best fit line where:

TABLE 3 Asphalt Concrete Pavement Thickness as Determined by Drilled Cores and by Road Radar Measurements, Site 2—Interstate Highway 15, Montana, USA

Chainage (Ft)	Thickness From Cores (mm)		Thickness From ROAD RADAR™ (mm)				
	Recorded	±1σ[a]	Closest[b]	Accuracy Limits[c]	Max[d]	Min[d]	Avg.[e]
13 + 24	165	146-184	150	143-159	158	146	151
19 + 83	134	115-153	136	125-139	137	126	132
26 + 43	137	118-156	137	131-145	142	134	138
32 + 34	149	130-168	153	144-160	173	132	152
39 + 62	159	140-178	148	134-148	148	134	141
46 + 23	207	188-226	199	188-208	200	193	198
52 + 80	149	130-168	142	134-148	144	139	141
$\bar{x}$	157.1	N/A	152.1	150.4			150.4
σ	22.8	N/A	21.6	20.5			20.5

[a] See ASTM D3549, Table 1.

[b] At measurement point closest to core location.

[c] ROAD RADAR™ specification of ±5% (of average).

[d] Value Limits recorded within 1 m of core locations.

[e] Average of all ROAD RADAR™ measurements within 1 m of core location.

$$Y = 1.027X - 5.623$$

where Y = GPR (Road Radar) measurement (mm) and X = drilled core measurement (mm).

The calculated correlation coefficient $r = 0.974$ indicates that there is a greater than 99 percent probability that the paired data are associated. The shaded area indicated in Figure 10 represents the uncertainty in the core thickness values in accordance with ASTM Designation D3549. It is noted that a vast majority of the data points lie within the uncertainty limits for the drilled core values.

DISCUSSION OF RESULTS

It has been previously stated that variability may be expected in the velocity of the signal travelling through a nonhomogeneous material. Construction materials cannot be assumed to be homogeneous by their very nature. Manufacturing, placing, and finishing activities all contribute to this reality. Even stringent quality assurance specifications recognize the potential existence of product variability.

The question is, just how important is it to have access to technology that is able to measure the actual signal velocity at each data collection point?

The actual signal velocities measured by the Road Radar unit, at the above three test sites, are presented in Table 5. A number of observations may be made from these tabulations.

- The mean signal velocity at each site is relatively consistent. This might infer that it is valid to assume signal velocity.
- The velocity values recorded at Site 1 are very uniform (V = 1.9 percent). This might support the contention that signal velocity can be responsibly estimated.
- Sites 2 and 3 yielded substantially larger ranges in values than Site 1, even though the mean signal velocity values were similar. At each site individual velocity values exceeded the mean value by at least 13.5 percent. An even greater concern is that 19 percent and 22 percent differences existed between the minimum and maximum measured velocity values at Sites 3 and 2, respectively.
- It is the practice with some other GPR systems, which are used to measure pavement layer thickness, to perform a site-specific cal-

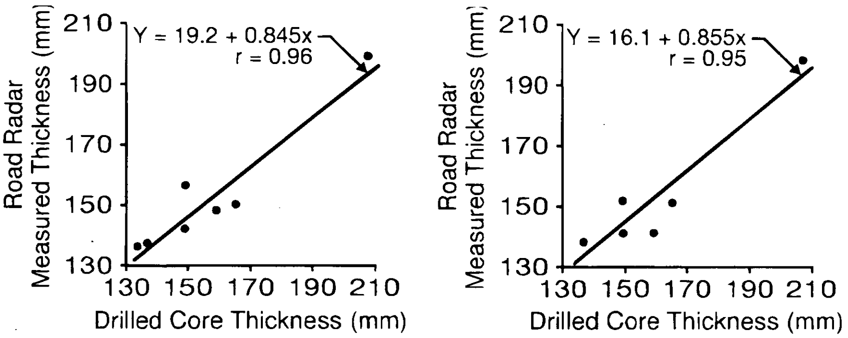

FIGURE 7 Asphalt concrete pavement thickness determined by drilled cores versus Road Radar measurements, Site 2-Highway 15, Montana, USA.

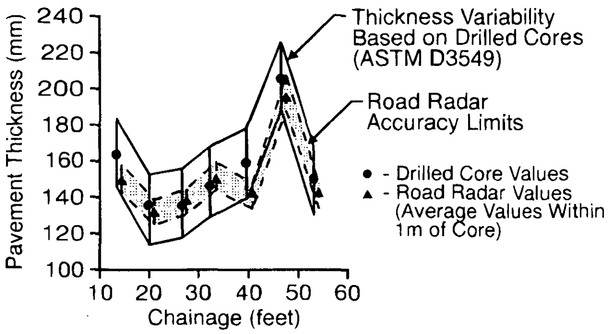

FIGURE 8 Asphalt concrete pavement thickness from drilled cores and Road Radar measurements, Site 2-Interstate 15, Montana, USA.

ibration using a single piece of drilled core data to provide the layer thickness information, and then to back-calculate the signal velocity. Significant errors can exist when this practice is followed.

Following is an illustration of how pavement layer thickness calculations are influenced by signal velocity.

Case: Interstate Highway 15, Montana

Assume the unit calibration is performed at core location chainage 32+24, at which point the signal propagation time was determined to be 2.01 ns (1E-9 sec). The measured core thickness at this point was 149 mm.

$$d = \frac{1}{2} vt \tag{4}$$

where:

d = layer thickness (mm);
v = signal velocity (mm/ns); and
t = propagation time (ns).

Given t = 2.01 ns and d = 149 mm, therefore v = 148 mm/ns.

At Station 46+23, the core thickness was determined to be 207 mm (Road Radar measured thickness was 199 mm), at which point the signal velocity was 121 mm/ns (with t = 3.29 ns).

However, if the velocity value was assumed to be 148 mm/ns, then the calculated pavement layer thickness would be 243.5 mm (an error of 17.6 percent).

GPR systems are recognized to be very precise in measuring signal travel time. The heterogeneous nature of the material, through which the signal is transmitted, has to be recognized with respect to the velocity of the signal during its elapsed propagation time. The fact that changes in signal velocity exist within a survey data set is a signal that a non-uniform condition exists, and that different sections of the pavement structure may perform differently because of this condition. Velocity variations within a pavement layer may result when pavement density is variable, or when moisture is present within the pavement layer (which may be expected when pavement density is substandard).

Similarly, moisture build-up in underlying granular base and subbase layers appears as an anomaly on the data outputs. These "indicators" can serve to alert pavement engineers of a condition that may require attention to mitigate the occurrence of premature structure distress.

TABLE 4 Asphalt Concrete Pavement Thickness as Determined by Drilled Cores and by Road Radar Measurements, Site 3—Highway 20, Taivalkoski District, Finland

Chainage (m)	Thickness From Cores (mm)		Thickness From ROAD RADAR™(mm)				
	Recorded	±1σ[a]	Closest[b]	Accuracy Limits[c]	Max[d]	Min[d]	Avg.[e]
SITE 1							
20	50	45-55	51	45-57	55	48	52
40	50	45-55	49	43-55	51	46	49
60	47	42-52	49	43-55	50	47	49
90	45	40-50	46	40-52	50	45	47
140	42	37-47	39	33-45	43	38	39
180	45	40-50	42	36-48	42	39	40
210	55	50-60	52	46-58	55	48	52
260	50	45-55	48	42-54	49	44	48
280	52	47-57	49	43-55	49	36	47
300	53	48-58	49	43-55	51	39	48
$\bar{x}$	48.9		47.4				47.1
σ	3.9		3.8				4.2

[a] See ASTM D3549, Table 1.
[b] At measurement point closest to core location.
[c] ROAD RADAR™ specification of the greater of ±6 mm or ±5%.
[d] Value limits within 1 m of core location.
[e] Average of all ROAD RADAR™ measurements within 1 m of core location.

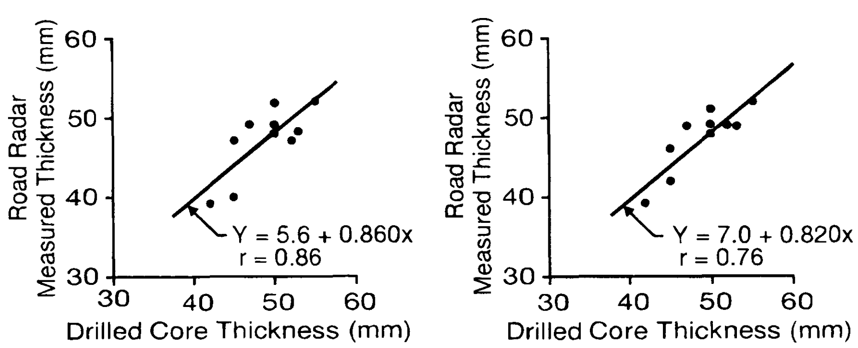

FIGURE 9 Asphalt concrete pavement thickness determined by drilled cores versus Road Radar measurements, Site 3-Highway 20, Taivalkoski, Finland.

CONCLUSIONS

This paper has described adaptations that have been made to conventional GPR technology for the purpose of developing a nonintrusive technique to measure layer thickness in composite pavement structures. In the past, scepticism on the part of potential users of the GPR technology has been primarily related to unsatisfactory reliability and accuracy as a result of the inability of earlier GPR systems to determine signal velocity at each data collection point. This deficiency has been overcome through innovations that are incorporated in the Road Radar.

Core and Road Radar data collected as described in this paper displayed excellent correlations in all cases. It is not realistic to expect such close associations as a routine. The mere task of ensuring that comparative sampling locations are exact requires technologists to be extremely careful—usually in the presence of heavy vehicular traffic volumes. Experienced pavement construction engineers recognize the real limitations that are associated with producing uniform pavement structures, both in profile and in cross-section.

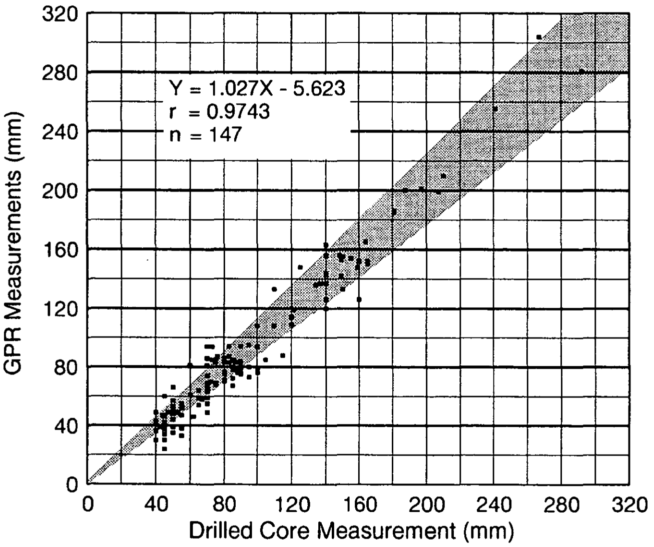

FIGURE 10 Comparison of 147 GPR measurements of asphalt pavement thickness to direct core measurements. The shaded area indicates uncertainty in core results according to ASTM standard D3549.

GPR technology has been developed to provide a reliable, non-intrusive method for obtaining subsurface information on roadway pavement structures. The primary enhancements were threefold:

1. An effective self-calibrating capability that provides multi-layer pavement thickness measurements that are at least as accurate as standard coring and auguring methods, as determined from measurements made in Canada, the United States, and Finland, where construction methods and materials differ substantially.
2. Layers as thin as 50 mm were resolved using a 2.5 GHz centre-frequency radar.
3. A semi-automated interpretation software package can process and interpret pavement layer thicknesses on very large data sets, which allows greater reliability and reduced turn-around time. The system also provides a warning if it cannot interpret a response so that the operator can guide the process. Often this warning also indicates that there is a change in the pavement structure.

With these developments, GPR offers pavement engineers a quantitative, nondestructive method to determine pavement thickness on a continuous basis as accurately as core sampling. In addition, it potentially offers quantifiable information on the pavement properties such as material composition, density, and moisture content. These enhancements are expected to make GPR technology a practical operational measurement instrument for pavement engineers.

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TABLE 5 Road Radar Signal Velocities at Various Test Sites

Site 1 - Highway 21, Alberta, Canada		Site - 2 Interstate Highway 15, Montana, USA	
Chainage (km)	Velocity (mm/ns[a]	Chainage (ft)	Velocity (mm/ns)
20.130	126	13 + 24	128
20.221	133	19 + 83	130
20.324	130	26 + 43	131
20.469	129	32 + 34	148
20.566	131	39 + 62	124
20.666	125	46 + 23	121
20.767	128	52 + 80	128
20.867	129		
20.957	131		
x̄	129.1	x̄	130.0
σ	2.4	σ	8.0
V(%)	1.9	V(%)	6.2
Range	125-133	Range	121-148

Site 3 - Highway 20 Taivalkoski District, Finland	
Chainage (m)	Velocity (mm/ns)
20	120
40	127
60	127
90	134
140	127
180	143
210	120
260	120
280	120
300	120
x̄	125.8
σ	7.3
V(%)	5.8
Range	120-143

[a] Velocity unit is millimetres per nanosecond (mm/ns).

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