Pavement Condition Diagnosis Based on Multisensor Data

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High-speed sensors have developed rapidly in recent years, and numerous such sensors can be operated from highway speed vehicles. This sensing technology can now provide pavement condition and performance information far beyond what is currently exploited in pavement management. Data from these sensors, coupled with established knowledge of pavement behavior, can be used to infer causes of pavement conditions and to predict performance. Knowledge of cause can also be used to select appropriate maintenance strategies. This paper demonstrates how the mechanisms of flexible pavement deterioration can be inferred from the data obtained from a "suite" of pavement sensors. Included are data on subsurface moduli, asphalt thickness, and subgrade moisture, none of which are currently measured with high-speed sensors. The paper goes on to show how the subsurface moduli can be computed from continuous data describing rut depth and fatigue cracks, both of which are measurable with current technology. Finally, the computation of asphalt thickness and subgrade moisture content from continuous radar profiles is described. Thus, a complete data set for explaining pavement condition and predicting future performance can now be provided by high-speed sensors. What remains is to integrate these sensor data into current pavement management systems.

During the past fifteen to twenty years, several pavement management systems have been developed and implemented in the United States, Canada, Europe, and Australia. These systems are quite diverse in the concepts and analytic approaches which they use to address equally diverse sets of pavement management decisions. In all of these systems, however, maintenance and rehabilitation management decisions are based on measures of the condition and performance of the pavement.

Pavement conditions are routinely surveyed for four distinct aspects: surface distress, longitudinal profile, structural response, and skid resistance. A variety of instruments is utilized to obtain measures of these four features, and the readings from these instruments are converted into various performance indices. These aggregate indices, such as the pavement condition index (PCI) are then used as a basis for maintenance management decisions. These condition and performance indices, although simple and widely used, aggregate away much of the information available from condition sensors and, more importantly, fail to explain the basic behavior of the pavement.

Concurrent with the emergence of pavement management systems has been an explosion in technologies of high-speed sensing. While these technologies have originated in areas such as geophysics, remote sensing, nondestructive testing, and factory automation, they are now expanding into the domains of civil engineering. Many such technologies have been and are being developed for high-speed surveying of pavement condition. Examples of such developments are acoustic, laser, and optical strobe techniques for continuous measurement of transverse profile (*1*); automated detection and quantification of cracking and surface distress using optical techniques and image processing (*2*); and sensing of pavement layer thickness, subsurface moisture, and voids using ground penetrating radar (*3*). All of these technologies can be implemented from highway speed vehicles, thus permitting frequent and comprehensive surveys of pavement condition.

With this rapid development of high-speed sensors, it is now clear that the current generation of pavement management systems is based on outdated measurement technology. Thus, these systems are incapable of fully utilizing the information that is available from these new and emerging sensor systems. Now that the full potential of these sensors is beginning to emerge, it is time to reconsider their impact on pavement management. The current reliance on indices noted above is an example of a practice which limits the full potential of the management system. Since these indices (for example, PSI and PCI) do not explain patterns and causes, they cannot serve to project future performance, nor can they suggest the appropriate maintenance.

The approach developed in this paper is to pursue a more diagnostic description of the pavement, which goes beyond the simple index. As discussed in the next section, such a description is now possible with the great deal of information provided by high-speed sensors.

BACKGROUND

The pavement conditions measured by sensors are all manifestations of some behavior of the pavement. For example, rutting comes from accumulated plastic deformation; roughness from spatial variations in rutting, frost heaves, and surface distress; cracking from accumulated strain producing fatigue; and so on. Pavement behavior has been studied for many years, and many of these cause-effect relationships are well established. Therefore, if enough manifestations can be picked up by sensors, it should be possible to infer the basic mechanisms which are consistent with the manifestations that are sensed.

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Knowledge of pavement behavior is extensive. For example, it is known that excessive deformation of the pavement surface is a common manifestation of distress in flexible (asphalt) pavement systems. Permanent deformation, in the form of wheel path ruts, results either from shear failure, usually in the asphalt layer, or from consolidation in one or more of the granular pavement layers. The presence of water in either the granular layers or the subgrade acts to reduce internal friction and, hence, to lower resistance to consolidation, particularly during periods of spring thaw. Cracking is another major manifestation of distress in flexible pavements. Extensive cracking contributes to loss of subgrade support and swelling by permitting moisture to directly infiltrate the pavement structure. Fatigue cracking involves fracture of the asphalt material under repetitive loads at stress levels considerably below the ultimate tensile strength of the mix. Asphalt modulus is strongly temperature-dependent, leading to a material which exhibits high levels of strain and plastic behavior in the summer, and which behaves in a more elastic and brittle manner in the winter. As such, susceptibility to fatigue cracking is greatest during the spring and fall, when the material is less brittle but the strains are considerably greater than in the winter months.

Much of the qualitative knowledge described above has been formalized in a quantitative manner. For example, empirical models have been developed to predict the performance of pavement over time based on certain pavement parameters (*4*). More complex models have been developed to represent the changes in pavement structural properties by season or as a function of pavement age or condition. These models can include the preventive and restorative impacts of a hierarchy of potential maintenance and rehabilitation activities (*5*). Mechanistic models employing either continuum mechanics or finite element methods have been developed to incorporate elaborate materials/traffic/environment interactions on the stresses, strains, and deformations within the pavement structure. These are utilized in conjunction with empirical relations to predict the damage manifestations resulting from these stress/strain/deformation histories (*6*).

Most of the knowledge described above has been applied to new design rather than to condition assessment, diagnosis, and maintenance management. The aim of this paper is to show how it can be employed to interpret the data from sensors, and thus to serve as a basis for pavement management. The following section describes how the data from a suite of sensors can be used to infer pavement properties and causes of observed conditions.

DIAGNOSIS FROM SENSORS

Figure 1 shows data obtained from a suite of sensors on a hypothetical stretch of flexible pavement. In this data set, the definitions and sources of data are as follows:

SV represents slope variance and is obtained from a sliding window of profile data (200 feet long, for example), using a commercially available pavement profilometer (*1*).

RD represents rut depth and is derived from transverse profile as obtained by one of the devices mentioned earlier.

CR is density of fatigue (alligator) cracking and is derived from crack sensing devices mentioned earlier as a running average of the percentage of length cracked.

E_a is asphalt modulus, which currently cannot be continuously measured from a high-speed sensing device. Spatial variations in E_a can be inferred from *RD* and *CR*, as described later in this paper.

E_s is the combined base and subgrade modulus, which also cannot be continuously measured, but whose spatial variations can also be inferred from *SV* and *CR*.

h_a is asphalt thickness, which can be continuously measured using ground penetrating radar. h_a is an important variable in explaining *RD* and *CR*, and in predicting E_a.

MC is moisture content in the subgrade, whose variations can be continuously monitored using ground penetrating radar. *MC* is useful in explaining variations in E_s.

Figure 1 thus represents a suite of direct and indirect sensor data which can be used to explain flexible pavement conditions. For example, locations where *SV* correlates with rapid fluctuations in *RD* suggest that the mechanisms causing rutting are dominating the pavement profile (and performance). Where high values of *SV* do not correlate with fluctuations in *RD*, the profile is dominated by other mechanisms, such as differential settlement and frost heaves. This latter conclusion can be reinforced by correlating fluctuations in E_s and *MC*. Where high *RD* is correlated with low h_a, one can infer that the rutting is due to deformation in the asphalt. Where this correlation does not exist, the source of rutting is in the deformation of the base and subgrade. This latter conclusion can be reinforced by correlating reductions in E_s. Where high *CR* is correlated with low E_s and high E_a, one can infer that the cracking of the asphalt is due to excessive asphalt strains due to a weak base and subgrade. Where high *CR* is correlated with high E_s, one can infer that the cracking in the asphalt is due to its brittleness, related to inadequacy of the mix.

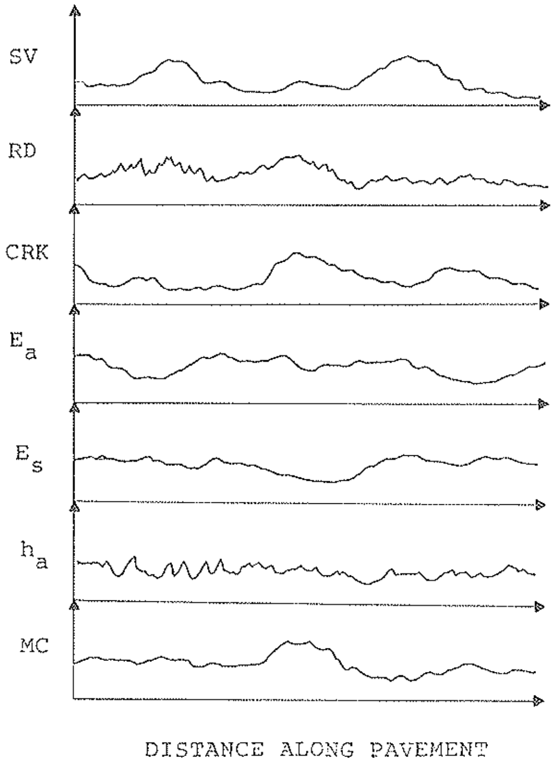

FIGURE 1 Pavement sensor data.

The inferences discussed above provide valuable information for maintenance management. The understanding of the mechanisms producing the observed behavior can lead to the choice of the appropriate model for predicting performance. The explanation of cause can lead to the proper selection of maintenance techniques. For example, if the source of fatigue cracking is known to be weakness in the subgrade, then it would make no sense simply to resurface the road, since the new surface will soon crack as well.

The simultaneous use of multiple sensor data, as discussed above, can be implemented for pavement management in the foreseeable future. Before this can happen, however, certain tasks, like those described below, must be completed.

Completion of the Sensor Picture

Some of the data in figure 1 are not currently available. Based on their current research and development status, automated crack sensing devices should be available within the next two years. Existing radar equipment now exists for continuous monitoring of asphalt thickness, and finalizing this capability for routine field application remains to be accomplished. Monitoring of changes in subsurface moisture content is an inherent radar capability which has already been demonstrated for asphalt-overlaid bridge decks (*21, 22*). Some further demonstration of this capability will be required for asphalt pavements, as discussed later in this paper. Finally, a capability for continuous monitoring of asphalt and subgrade modulus has been explored, but this capability does not appear realizable in the foreseeable future. As noted earlier, these properties can be inferred from rut depth and cracking.

Incorporation of Sensor Information into Pavement Management

Once the sensor picture of figure 1 is complete and available, mechanisms for utilizing the information must be incorporated into pavement management systems. These mechanisms will include adaptation of performance predictions to knowledge of current conditions and their causes, as well as specifying maintenance appropriate to the existing and projected conditions.

The work described in the remainder of this paper focuses on the completion of the sensor picture for flexible pavements. The computation of E_a and E_s from rut depth and cracking will first be discussed, and an algorithm along with numerical results will be presented. This will be followed by a discussion of ground penetrating radar, including its capability for sensing asphalt thickness and base and subgrade moisture content.

MODULI DETERMINATION FROM RUTTING AND CRACKING DATA

It was assumed in this study that sensor data would be available describing rut depth and fatigue cracking of asphalt pavements. Rut depth (inches or mm) is reported at regular distance intervals (e.g., every foot or 10 feet). Fatigue cracking, which assumes a characteristic alligator pattern in its advanced stages, is (assumed to be) reported as "Yes" or "No" values at similar distance intervals. No measure of the severity of the cracking is being considered at this time. The cracking sensor reports the percentage of cracked area over a pavement length of interest.

The method for moduli determination utilizing these two sensor inputs can be summarized as follows: (a) formulate quantitative relationships which can predict rutting and cracking based on design, loading, and environmental parameters; and (b) using the measured rutting and cracking values, invert the quantitative relationships formulated above to determine the underlying pavement moduli.

The quantitative relationships for predicting rutting and cracking are described below.

Rutting

Rutting of asphalt pavements can be attributed primarily to plastic deformation, if the rutting occurs in the shear/consolidation mode (*7*). In this formulation, the cumulative permanent deformation Δ of a material specimen subjected to a series of N repeated, identical load pulses is logarithmically proportional to the peak elastic deformation δ produced by any given load pulse, which is assumed to remain constant.

$$\Delta = \mu \delta N^{\alpha} \tag{1}$$

where

Δ = the permanent deformation of the material after N load cycles,
δ = the peak elastic deformation of the material in a load cycle, assumed independent of N,
N = the number of applied load cycles, and
μ, α = materials properties related to compactibility.

The materials parameters μ and α are known to depend on the stress state, load duration, temperature, and moisture content (*8–10*). Subsequent research (*11, 12*) indicates that the permanent deformation properties of asphalt concrete are primarily a function of modulus; those of granular layers are dependent on stress state, while those of subgrade soils depend on moisture content.

The permanent deformation parameters for the pavement structure as a whole have been determined in previous research by regression analysis of the permanent deformations as a function of the number of loads applied to the pavement structure. Analyses of numerous sections from the AASHTO road test results have shown that system μ values range between 0.25 and 0.50 for a spectrum of seasonal conditions and axle loads, while system α values are typically between 0.25 and 0.30 (*13, 14*).

The peak elastic deformation of the pavement structure can be computed mechanistically from the load footprint parameters, layer thicknesses, and layer moduli and Poisson's ratios using elastic layer theory. A simplified relation (*15*) is

$$\delta = \frac{3pa^2}{2KE(a^2 + Z^2)^{1/2}} \tag{2}$$

where

δ = the peak elastic deformation of the pavement surface,
p = the average footprint contact pressure,
a = the radius of the footprint (assumed circular),
K = the fraction of total elastic deformation contributed by the subgrade (typically 0.7 to 0.8 in the AASHTO sections analyzed in the research cited above),
E = the subgrade modulus of elasticity, and
Z = "equivalent" subgrade depth based on Odemark's method (*15*) for equivalencing the deflection of a multilayer elastic half space to that of a homogeneous half space, and is a function of all the layer thicknesses and moduli.

Since the amount of rutting occurring in a given season will depend on the amount of consolidation present at the start of the season, the seasonal traffic, and the seasonal pavement properties, an iterated prediction methodology can be applied to account for the discontinuities across seasonal boundaries. This methodology results in the end-of-season rutting for each season, and, hence, provides the total rutting at any given time by combining the contributions of all previous seasons.

Fatigue Cracking

Fatigue cracking is phenomenologically understood through the empirical validation of Miner's hypothesis. This relation is represented as (*16*)

$$\%C = 20 \text{Log } D \qquad (D > 1) \tag{3}$$

where $\%C$ is the percentage of wheelpath area cracked and D is Miner's fatigue index.

By Miner's criterion, the fatigue index is defined as

$$D_j = \sum_{i=1}^{j} \frac{n_i}{N_i} \tag{4}$$

where

D_j = the fatigue index at the end of season j,
n_i = the number of load applications in season i, and
N_i = the number of loads to failure in season i.

The number of loads to failure at a given strain level and environment is empirically known from laboratory tests (*7*) to be

$$N = K_1 \varepsilon^{-K_2} \tag{5}$$

where

N = the number of loads to failure in the laboratory,
ε = the applied tensile strain, and
K_1, K_2 = brittleness materials properties.

The maximum tensile strain in the pavement structure is assumed to occur at the bottom of the asphalt layer. This strain can be mechanistically computed from the load footprint parameters, layer thicknesses, and layer moduli, using elastic layer theory. A simplified relation, based on the work of Odemark (*15*), is

$$\varepsilon = \frac{3pa^2H}{4E(a^2 + H^2)^{3/2}} \tag{6}$$

where

ε = the maximum tensile strain,
p = the average footprint contact pressure,
a = the radius of the footprint (assumed circular),
E = the subgrade modulus of elasticity, and
H = an "equivalent" depth based on equivalencing the maximum tensile strain in a multilayer, elastic half space to the strain in a homogenous half space, and is a function of all the layer thicknesses and moduli.

The prediction of fatigue cracking also incorporates the seasonal variation in pavement properties. These are particularly significant, since asphalt modulus can increase by an order of magnitude from summer to winter, while subgrade properties are also changing.

From a measurement perspective, observation of fatigue cracking is related to the fact that the pavement at that location has exceeded its fatigue life. The cracking model reported herein computes peak seasonal strain at the bottom of the asphalt layer for each sampled point in the surveyed section. Average seasonal asphalt moduli are determined from an empirical modulus-temperature relation. Local values of subgrade modulus are determined from the average modulus and the statistics of the rutting sensor. The local values of the granular layer moduli (base and subbase) are determined from an empirical relation between granular modulus, and granular thickness and subgrade modulus.

A seasonal value of the "brittleness" coefficient K_1 can be determined as a function of asphalt modulus. The relationship used in this work was regressed from laboratory test data, as shown in figure 2. The coefficient K_2 was found to be related to K_1 as follows:

$$K_2 = 1.859 - 0.241 \text{ Log} K_1 \tag{7}$$

where K_1 and K_2 are as given in equation 5.

The probability of cracking at any location is determined from the following bounded approximation to equation 3, valid for all $D \geq 0$:

$$\text{Prob (Crack)} = \text{Sin}^2\left(\frac{\pi}{2} \cdot \frac{aD^b}{1 + aD^b}\right) \tag{8}$$

where

D = Miner's damage index (see equation 4),
a = 0.217, and
b = 0.266.

Finally, the estimated percent of cracked pavement area is determined by summing the probability of cracking over all locations, and dividing by the total number of sampled points.

Inversion Algorithm

The relationships presented above can be used to predict pavement rutting and cracking, given pavement material properties and loading and environmental parameters. Since the objective here is to predict pavement moduli from measurements of rutting and cracking, an iterative algorithm has been developed to invert these relationships. The function of this algorithm is to compute local average values (at reference

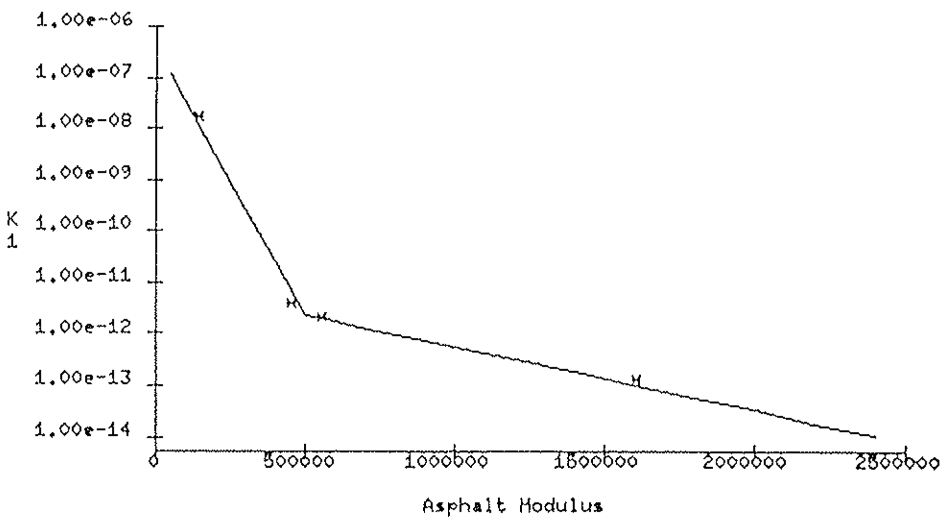

FIGURE 2 Fatigue coefficient K_1 as a function of asphalt modulus.

environmental conditions) of the asphalt and subgrade moduli which reproduce the observed behavior.

A flow chart of the inversion algorithm is shown in Figure 3. The iterative process is initiated by having the user assume values for the reference subgrade modulus, E_s, and the reference asphalt modulus, E_a. The rut depths and percent cracking are then computed and compared with the sensor data. The reference moduli values are then adjusted to force the computed and measured rutting and cracking into greater coincidence. This process continues until the computed and measured values are within some small tolerance (2%, for example), at which point the algorithm is assumed to have converged. The following section describes numerical experiments carried out using this algorithm.

Computational Experiments

The algorithmic approach described above was tested on synthesized pavement data. The algorithm, when applied to synthetic data, should yield the properties which were assumed in the synthesis. If it does not, then there is a problem with the algorithm.

The synthesis generates random values of asphalt thickness and modulus, base course thickness, and subgrade modulus, at 1-foot intervals. The values are determined from a second-order, autoregressive process, which requires a mean value, standard deviation σ_x, and two correlation coefficients ρ_1, ρ_2 for each parameter. Figure 4 shows typical results from this synthesis, together with the sensitivity of these results to changes in standard deviation and correlation coefficients. The synthesized pavement data were then utilized to generate rutting and cracking "measurements" using the quantitative models described earlier. The synthesized rutting and cracking values were used as simulated sensor data, to serve as input to the inversion algorithm.

The testing of the inversion algorithm on these data began by using pavement properties known to be incorrect (i.e., different from those used in the synthesis), computing pavement properties using the algorithm, and comparing the resultant properties with those assumed in the pavement synthesis. Figure 5 shows a typical result of such an analysis. The entries in the body of the figure are the subgrade modulus (the upper value in each cell) and asphalt modulus (the lower value) computed by the inversion of the algorithm. These computations were made for various combinations of initial subgrade and asphalt moduli, and cumulative traffic loads (N). The values used in the synthesis were 5,000 psi, 500,000 psi, and 1,000,000 axle loads, respectively. The results show convergence to within ±20% of the correct moduli values for a fairly wide spread of input assumptions.

As can be seen in the figure, the results are considerably improved if the traffic estimate is correct (N = 1 million). However, even in such cases, both moduli tend to be slightly underestimated. This is partly due to the fact that the variance of the observed rutting is not being used in the calculation of the subgrade modulus, which results in an underestimate of the mean modulus in order to account for modulus variation. Inclusion of this effect (a slight modification of equation 1) would raise the computed moduli values.

The moduli also tend to be underestimated because all variation in the rutting observations is assumed to be represented by local variation in the subgrade modulus. Thus, any variation in asphalt modulus or thickness or base thickness will be reflected in a reduced estimation of the subgrade modulus. However, given the current quantitative understanding of pavement damage, information from additional sensors is required in order to resolve the causes of variation in the observed distress patterns.

Discussion of Results

The above results show that local average values of E_a and E_s can be computed from measured rut depth and cracking. This is exactly the information identified in figure 1. It is clear that the accuracy of this prediction is sensitive to a number of assumptions, such as the number of axle loads, climatic changes, and various numerical constants and parameters. Most of these assumed values (e.g., traffic) are constant over a given stretch of pavement. Since our objective is to correlate spatial changes in E_a and E_s with such changes in other sensor

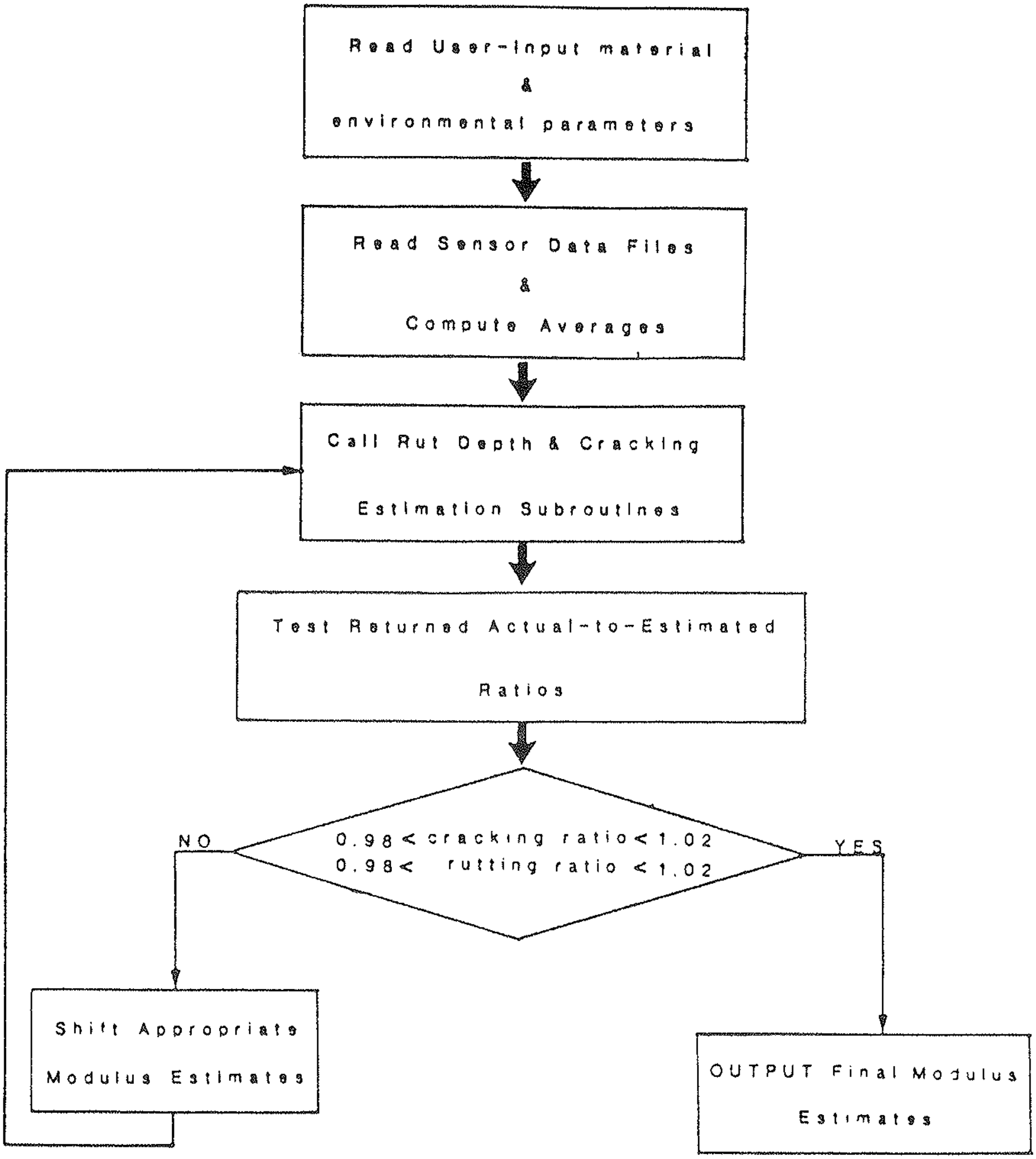

FIGURE 3 Inversion algorithm.

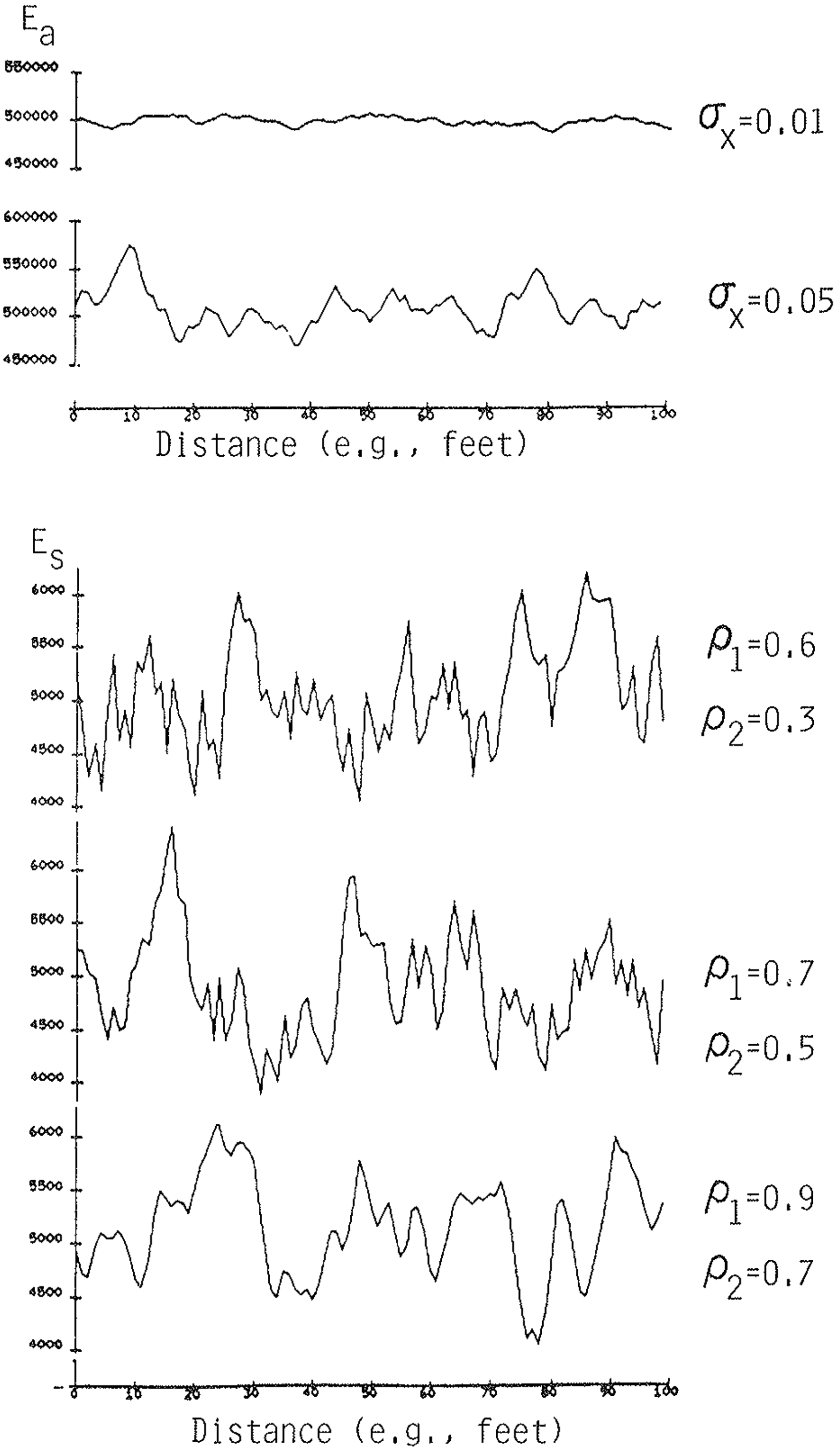

FIGURE 4 Synthesized pavement data.

EXAMPLE DATA

$h_a = 6''$ $h_{base} = 20''$

$E_a = 500$ ksi $E_s = 5$ ksi

$N = 10^6$ $RD_{avg.} = 0.55''$ % cracking = 22%

RESULTS

INPUT E_s \ E_a (ksi)	250	500	1000
2.5	487 4.79	488 4.79	487 4.79
5.0	488 4.78	490 4.76	487 4.80
10.0	487 4.80	488 4.77	487 5.61

FIGURE 5 Results of moduli prediction using inversion algorithm.

data, absolute accuracy is not important. An incorrect assumption will displace the entire curve of figure 1 up or down, but it will not affect the variations.

GROUND-PENETRATING RADAR FOR DETERMINATION OF ASPHALT THICKNESS AND SUBGRADE MOISTURE

Ground-penetrating radar is the electromagnetic analog to ultrasound. In radar, short pulses of electromagnetic energy are emitted from an antenna. These pulses penetrate materials which act as dielectrics (e.g., rock, soil, concrete, and asphalt). Dielectric discontinuities in these materials, such as material interfaces and metal inclusions, produce echoes which are received at the antenna. The pattern of echoes, referred to as the waveform, is produced by successive arrivals of echoes from different interfaces. Thus, the waveform contains information regarding the location of interfaces, the nature of the material contrast at the interface, and the properties of the material layers. Radar has been applied to the determination of thicknesses and subsurface properties in concrete pavements (*3*) and bridge decks (*17, 18*). The basic principle underlying its application to asphalt pavements is illustrated in figure 6. Here it is seen that the principal components of the waveform are the reflection from the top of the asphalt, the reflection from the asphalt/base boundary, and the reflection from the base/subgrade boundary. The intensity of these reflections will be proportional to the strength of the contrast in dielectric properties between layers.

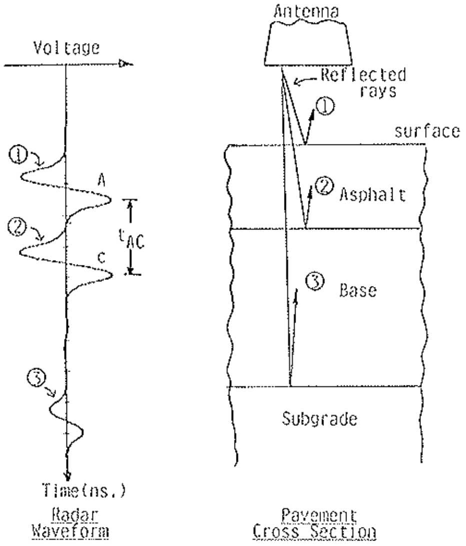

FIGURE 6 Radar model for pavement.

Asphalt Thickness

Asphalt thickness can be computed from the time difference between points *A* and $C(t_{AC})$ shown in Figure 6, and from the velocity of the electromagnetic wave in asphalt, V_a. The velocity, V_a, can be computed as

$$V_a = 11.8/\sqrt{\varepsilon_a} \text{(inches/nanosecond)}$$

where ε_a is the dielectric permittivity of asphalt. The dielectric permittivity can be estimated using the flat plate reflection test (*19*) on the asphalt of interest. Measurements by one of the authors yield values of ε_a ranging from 5.0 to 6.0, with associate V_a ranging from 4.8 to 5.3 in./ns. Since t_{AC} is the round-trip travel time of the pulse in the asphalt layer, the thickness can be computed as

$$h_a = V_a t_{AC}/2$$

Figure 7 shows typical field data collected on a newly constructed 9-inch thick asphalt pavement. In the data set illustrated, fifty waveforms were generated for each second of vehicle travel, which, at 30 mph, yields approximately one waveform per foot of pavement. The waveforms shown in figure 7 represent a subsample of these data at 5-foot intervals. Note the sensitivity of t_{AC} to gradual changes in h_a at this sampling scale.

Subgrade Moisture

The response of radar to a layered medium can be predicted analytically if one knows the thickness, dielectric permittivity (ε) and conductivity (σ) of each layer. Such a model has been developed for bridge decks (*18*) and applied to pavements (*20*). Littlefield has computed the dielectric properties of the subgrade ε_s and σ_s as a function of moisture content, and has studied the radar response versus subgrade moisture content. Figure 8 shows a typical result of this work. The amplitude of the reflection from the top of the subgrade is plotted versus moisture content of the subgrade. Note that the relationship is strong, suggesting that this portion of the radar waveform can be used to infer spatial variations in moisture content.

The relationship described above has been successfully used to detect moisture under the asphalt overlay of reinforced-concrete bridge decks (*21*). Its adaptation to asphalt pavements is straightforward, but will require consideration of the normal variation in subgrade material properties.

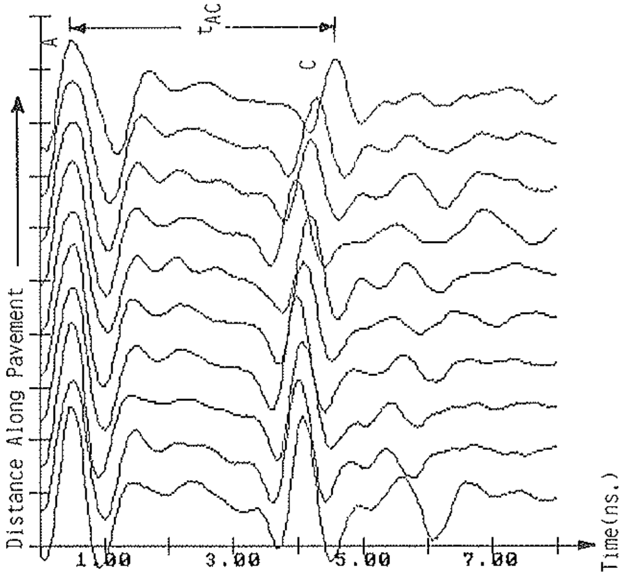

FIGURE 7 Radar field data.

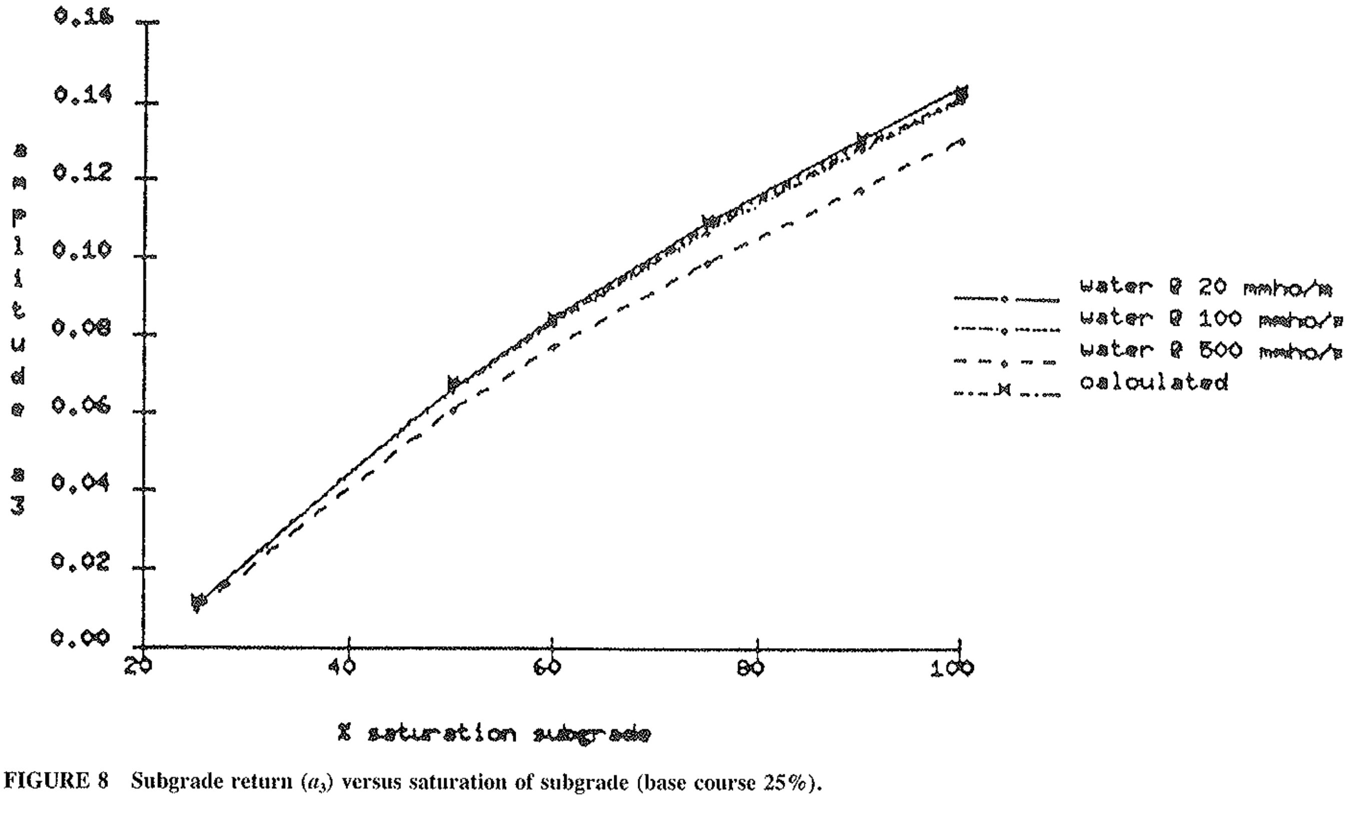

FIGURE 8 Subgrade return (a_3) versus saturation of subgrade (base course 25%).

CONCLUSIONS

This paper has described the level of information that state-of-the-art sensors can provide to pavement management. This level of information is far greater than that being considered by the current generation of pavement management systems. In addition, the nature of the sensor data is different from that which is currently utilized by pavement management systems. A suite of high-speed sensor data representing slope variance, rut depth, cracking, asphalt and subgrade moduli, asphalt thickness, and subgrade moisture content has been described as a basis for explaining the condition and predicting the performance of asphalt pavement. It has been shown that the two moduli, while not continuously measurable directly, can be inferred from rut depth, cracking, and asphalt thickness. Also, it has been shown that spatial variations in asphalt thickness and subgrade moisture content can be determined using ground-penetrating radar. Thus, the sensor suite described above can be completed using highway speed survey vehicles. What remains now is to complete the development of the cracking and moisture sensors and to develop means for incorporating all these data into the pavement management process.

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