Using Time Series to Incorporate Seasonal Variations in Pavement Design

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Analysis of the seasonal monitoring program data of the long term pavement performance program indicated that some pavement structural properties often follow predictable seasonal patterns. Time series is a statistical technique that may be used to develop periodic functions to predict the values of such properties as a function of time. The application of time series technique in characterizing the seasonal variations of pavement structural properties as simulated functions is presented. In addition, the incorporation of such variations in both empirical and mechanistic-empirical methods of flexible pavement design is demonstrated. To this end, a computer program, seasonal variation in pavement design, was written to carry out the required calculations and to facilitate the comparison between empirical and mechanistic-empirical design methods.

It has long been recognized that temperature, moisture conditions, and freeze-thaw cycles have a significant impact on pavement structural properties. Weather conditions are continuously changing during a year and within the same day. As these changes occur, pavement stiffness, strength, and performance vary accordingly. Today more than ever before, highway agencies are faced with the challenge of providing economical designs (or rehabilitation) at specified levels of service. A key element of meeting this challenge is disaggregating and accurately accounting for pavment damage caused by both loading and environmental conditions.

Whereas pavement damage (or serviceability loss) caused by loading is given great emphasis in pavement design, the other important cause of pavement damage, environmental conditions, is often overlooked primarily because the involved mechanisms are not well understood, making it difficult to quantify their effect on pavement deterioration.

In recognition of the necessity of furthering study of the impact of climatic conditions on pavement response, the seasonal monitoring program (SMP) was devised as part of the long term pavement performance (LTPP) program. The primary objective of the program is to provide data needed to attain fundamental understanding of the magnitude and impact of temporal variations in both pavement response and material properties that are caused by the separate and combined effects of temperature, moisture, and freeze-thaw cycles (*1*).

In the SMP, collection of deflection, profile, and distress data is accomplished using LTPP equipment and testing protocols, including falling weight deflectometers (FWDs), profilers, and photographic and manual distress surveys. Instruments permanently installed at the test sections gather environmental data. Time domain reflectometry sensors and thermistors monitor changes in subsurface moisture and temperature, respectively. Electrical resistivity probes measure freeze-thaw depth, and observation piesometers are used to determine the depth of the ground water table. In addition, air temperature probes and tipping-bucket rain gauges monitor ambient temperature and precipitation, respectively. Figure 1 is a schematic showing a typical seasonal site and the locations of testing points and the instrumentation area.

In the analysis of SMP data, the results of time series analysis, autocorrelations, spectral analysis, and nonlinear modeling indicate that some pavement structural properties are time dependent. However, time by itself is not a causal factor in changes to those properties; other explanatory variables change with time, and some changes occur in a systematic manner thus causing the changes to properties. For example, pavement aging (hardening due to age) is not caused by the passage of time. It is actually caused by load compaction and by pavement oxidization. However, because the effects of these two independent variables accumulate with the passage of time and because measuring time is easier than measuring pavement oxidization or load repetitions, it may be easier to develop a regression equation to predict pavement aging as a function of time (age), especially if the exact mechanisms of cause and effect are not fully understood.

For the analysis described, pavement structural properties are characterized using periodic functions. Those functions are then substituted in selected flexible pavement design equations to evaluate the impact of property variations on pavement performance.

CHARACTERIZATION OF SEASONAL VARIATION

Seasonal variations in weather (temperature, moisture, and frost) impose seasonal variations in pavement layers' stiffnesses (elastic moduli). Demographic, social, and economic factors affect travel demand, varying load magnitude and frequency. It is imperative to accommodate variations from both sets of factors in pavement design and analysis. Such variations and the use of periodic functions to characterize such variations are discussed.

Seasonal Variations in Asphalt Concrete Layer Elastic Modulus

The elastic modulus of the asphalt concrete (AC) layer was shown to be exponentially influenced by pavement temperature (*2*). In this case, the exact mechanism is explained by Newton's law.

$$\tau = \mu * \frac{\delta\epsilon}{\delta t} \tag{1}$$

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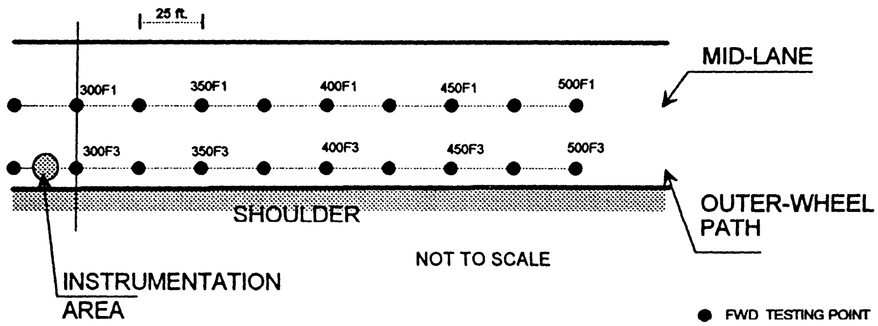

FIGURE 1 Plan of typical seasonal site.

where

τ = shearing resistance between the microscopic layers;
μ = viscosity (a function of pavement temperature); and
$\frac{\delta\epsilon}{\delta t}$ = rate of shear strain corresponding to the relative speed at which one microscopic layer slides by the other.

As temperature changes, the viscosity of the binder material changes (the higher the temperature, the lower is the viscosity), thus changing the shear resistance of the material. The elastic modulus of a material (E) is related to the shear modulus (G) and Poisson's ratio (ν) by the following equation:

$$E = 2(1 + \nu)G \quad (2)$$

This mechanism explains why the elastic modulus of AC decreases as temperature increases. However, because pavement temperature is related to ambient air temperature, which often follows a sinusoidal pattern throughout the year, it is expected that the elastic modulus of the AC layer follows the temperature cycle. This theory is supported by observations made on the seasonal sites included in the analysis (e.g., Sites 48SA and 48SF located at a no-freeze zone in Texas). The sinusoidal function is expressed as follows:

$$E_{AC} = A + B \sin(2\pi f T + C) \quad (3)$$

where

E_{AC} (or $E1$) = AC elastic modulus
A = average value;
B = amplitude of the wave (if the dependent variable is constant then B equals 0);
T = time of observation (e.g., month of the year 1 to 12);
f = frequency (number of increments per cycle equals 1/12 if months are used and there is 1 cycle per year); and
C = phase angle that controls the starting point on the curve and the peak month or months.

Equation 3 indicates that the values of E average A, have a minimum value of A minus B, and a maximum value of A plus B. Figure 2(a) indicates a sinusoidal curve fitted to average monthly values of backcalculated AC-layer elastic modulus in MPa, taken at seasonal site 48SA [additional information on backcalculation and seasonal sites is presented in Ali (*2,3*)]. Figure 2(a) shows the values of constants A, B and f for the given site. The model fits the data points very well (R^2 = 94 percent).

In general, depending on site location (i.e., southern or northern hemisphere and latitude), AC material characteristics, and meteorological variables, the values of A, B, C, and f will change to reflect the average value of $E1$, the magnitude of change, phase angle, and cycle frequency, respectively. In applicable cases, sinusoidal functions may be replaced by other periodic functions to reflect sudden changes of the AC modulus values caused by freezing.

Seasonal Variation in Elastic Moduli of Base and Subbase Layers

According to unsaturated soil mechanics theory (*4*), the elastic moduli of the base and subbase layers are influenced by matrix suction, which is a function of moisture content and material type. However, if a drainage system holds the moisture levels constant within the base and subbase layers, then a constant modulus value corresponding to the optimum moisture content may be assumed for each layer (*5*, pp. 235–254). In cases in which drainage systems are not provided (i.e., modulus values vary), periodic functions similar to Equation 3 may be used to quantify seasonal variation in the elastic moduli of base and subbase layers.

Seasonal Variation in Subgrade Resilient Modulus

The resilient modulus of the subgrade (M_R) is one of pavement properties believed to undergo seasonal variations. Although the exact mechanisms that cause the subgrade resilient modulus to change are not as simple as that of the AC elastic modulus [more details about such mechanisms are presented in Ali (*2,3*) and Fredlund and Rahardjo (*4*)], subgrade resilient modulus often follows a seasonal cycle. The seasonal cycles of subgrade resilient modulus are influenced by moisture content, matrix suction, precipitation, water table, drainability of soil mass, temperature, and freeze-thaw cycles. Freezing and thawing could introduce acute changes in the subgrade modulus. However, because the seasonal sites analyzed are located in a no-freeze zone, sinusoidal functions such as the subsequently described Equation 4 may be fitted with reasonable accuracy to correlate the resilient modulus of subgrade to the month of the year. This is illustrated in Figure 2(b), which indicates a sinusoidal curve fitted to average monthly values of backcalculated M_R in MPa, taken

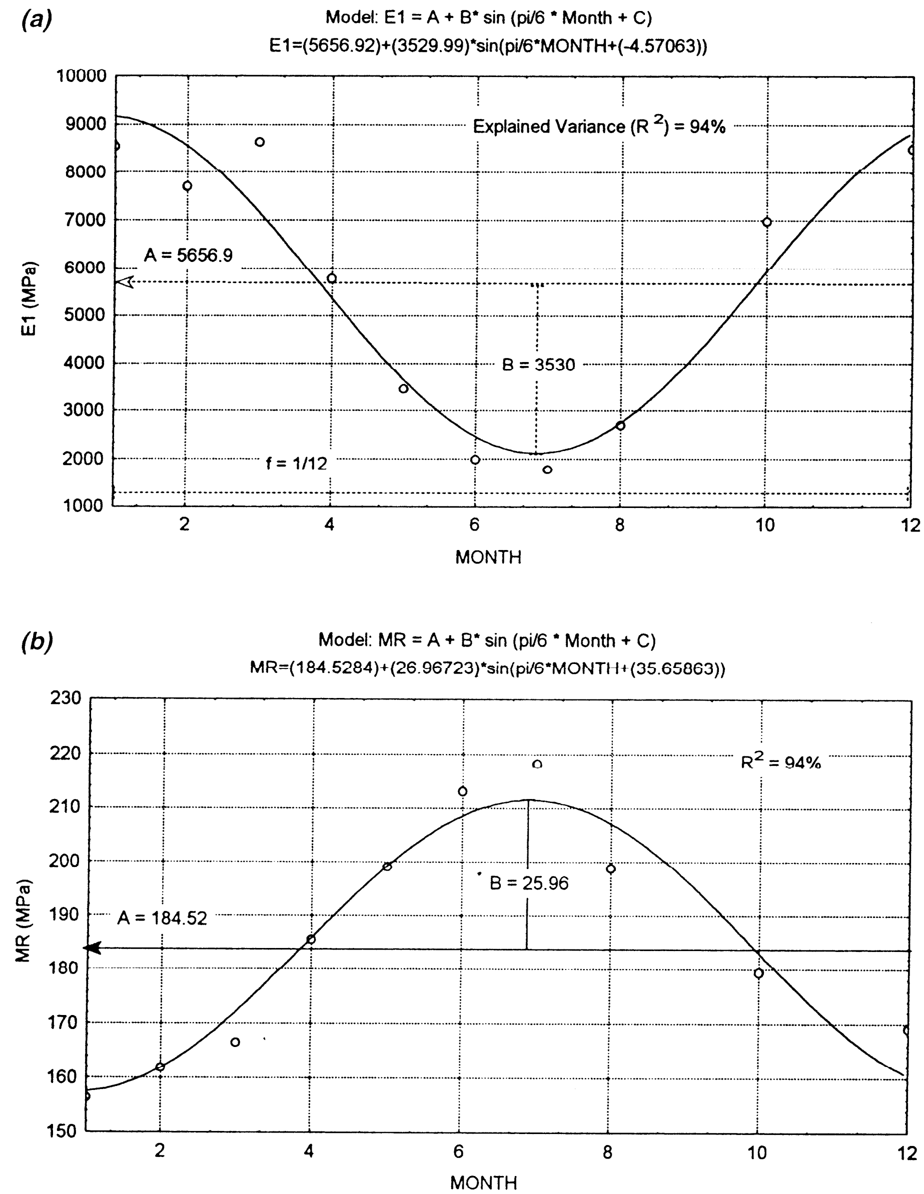

FIGURE 2 Periodic models at site 48SA: (*a*) AC layer; (*b*) resilient modulus.

at seasonal site 48SA. Figure 2(*b*) shows the values of constants *A*, *B*, *C*, and *f* pertinent to the given site. The model fits the data points very well (R^2 = 94 percent). Equation 4 is given as follows:

$$M_R = A + B \sin(2\pi f T + C) \quad (4)$$

Under different environmental conditions the subgrade resilient modulus may be represented by other functions such as polynomial functions, exponential functions (during thaw periods), linear functions, or composite models with more than one function. The combined effect of the changes in the AC modulus of elasticity, the base and subbase layers moduli, and the subgrade resilient modulus results in seasonal variation in pavement strength.

Seasonal Variation in Traffic Volume

There is variation not only from the supply side but also from the demand side. In other words, pavement is a transportation facility provided by a highway agency (the supplier) and used by road users (traffic or demand). The supplied facility undergoes seasonal weakening and strengthening and the demand on the facility undergoes seasonal fluctuations. It is well known that traffic patterns change with seasons, following economic, social, and demographic factors. For example, during the summer as well as at the December holidays, the demand on transportation is higher than at other times of the year. Access roads that serve recreational centers are expected to have more traffic during the summer than the winter.

Functions that represent traffic variation may have a sinusoidal shape similar to that of Equation 3, a sinusoidal shape with dual or multiple peaks, a sawtooth shape, or any other shape.

INCORPORATING SEASONAL VARIATIONS IN PAVEMENT DESIGN

Increasing computing capabilities and significant improvements in data collection techniques and instruments such as weigh in motion and FWDs, have made it possible to accommodate variations from both supply and demand sides in pavement design. Methods for incorporating such variations into existing pavement design algorithms, given that all sources of temporal variations have been quantified, are demonstrated. In this context quantification means that each source of variation is expressed as a function of time. Alternatively, typical values at specified periods of the year may be used. A computer program, seasonal variation in pavement design (SVPD), was written to carry out the required calculations and facilitate the comparison between design algorithms based on serviceability loss and mechanistic-empirical design methods.

Design Algorithms Based on Serviceability Loss

Effective Roadbed Resilient Modulus (AASHTO)

The AASHTO flexible pavement design method of 1993 (*6*) uses the following equation:

$$\log_{10} W_{18} = z_R S_o + 9.36 \log(SN + 1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \frac{1094}{(SN + 1)^{5.19}}} + 2.32 \log_{10} M_R - 8.07 \tag{5}$$

where

W_{18} = estimated future traffic for the performance period;
Z_R = number of standard deviations (from the standard normal distribution curve) corresponding to reliability level R;
S_o = overall standard deviation;
SN = required structural number to sustain traffic applications in the performance period;
ΔPSI = design serviceability loss; and
M_R = effective resilient modulus of roadbed material.

In this method the subgrade resilient modulus M_R is taken as the weighted average of the seasonal values. The weights are based on the amount of damage that occurs in each season. The effective roadbed resilient modulus is calculated as follows:

$$U_i = 1.18 * 10^8 * M_{Ri}^{-2.32} \tag{6}$$

$$U_{\text{average}} = \frac{1}{n} \sum U_i \tag{7}$$

$$M_r(eff) = \left(\frac{1.18 * 10^8}{U_{\text{average}}}\right)^{\frac{1}{2.32}} \tag{8}$$

where U_i is the damage in season i; there are n seasons in the year; and M_{Ri} is the resilient modulus in season i.

It is assumed that there are no fluctuations in traffic volume, that is, traffic is constant throughout the year.

Integral Method with Constant Structural Number (AASHTO)

Using Equation 5, the effect of seasonal variation in the resilient modulus of subgrade and seasonal variations in traffic volume can be accounted for by giving the total damage (D) to a pavement during its life as follows:

$$D = \frac{\text{Demand (ESALs)}}{\text{Supply (ESALs)}} = \frac{\text{the predicted total traffic (number of load applications)}}{\text{the allowable number of load applications}} \tag{9}$$

ESALs are equivalent single axle loads. Assuming that Miner's linear damage hypothesis (*7*) is valid and applicable, that is, the total damage is the sum of seasonal damages, then:

$$d = N * \int_a^b \left[\frac{f(t)dt}{\left(10^{\left[z_R S_o + 9.36 \log(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \log_{10} M_R - 8.07\right]}\right)}\right] \tag{10}$$

where

N = performance life in years assuming that annual traffic is constant;
a and b = constants that represent the beginning and the end of the year (1 and 12 if seasons are represented by months, or 1 and 365 if seasons are represented by days, and so forth);
$f(t)$ = traffic distribution time function; and
t = time of the year.

The term in the denominator represents the allowable load repetitions at time t for a duration of Δt.

Now let's assume that X equals the term in the denominator that does not include M_R, and Y is the term that includes M_R, that is, Equations 11 and 12:

$$X = 10^{\left[z_R S_o + 9.36 \log(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} - 8.07\right]} \tag{11}$$

$$Y = 10^{[2.32 \log_{10} M_R]} \tag{12}$$

Substituting in Equation 10 and factoring out the constant term X results in the following:

$$\frac{N}{X} \int_a^b \left[\frac{f(t)\,dt}{(Y)_t}\right] = D \tag{13}$$

At the end of pavement performance life, the total damage equals unity. Thus, Equation 14:

$$\frac{N}{X} \int_a^b \left[\frac{f(t)\,dt}{10^{(2.32 \log M_R)}}\right] = 1.0 \tag{14}$$

Substituting Y and X in Equation 10 and replacing M_R by its time function results in the following:

$$N = \frac{X}{\int_a^b \left[\frac{f(t)\,dt}{(\Phi(t))^{2.32}} \right]} \tag{15}$$

where $\Phi(t)$ is a time function of the subgrade resilient modulus.

Solving for *SN* gives the following:

$$SN = -1 + \left[\frac{K}{\left(\frac{PSI^{\left(\frac{1}{B}\right)}}{2.7} \right)} \right]^{\left(\frac{1}{9.36}\right)} \tag{16}$$

where $B = 0.4 + \frac{1094}{(SN + 1)^{5.19}}$ and

$$K = N(1 + r)^{(N-1)} * \int \frac{f(t)}{\Phi(t)^{2.32}} dt / 10^{(ZS-8.27)}$$

Equation 16 is to be used to find the required structural number (*SN*) such that the pavement will survive *N* years, given *f(t)*, $\Phi(t)$ and the traffic annual growth rate (*r*). Alternatively, given an existing pavement structure (*SN*), the number of years *N* that will elapse before the serviceability index declines to a given terminal level may be calculated using Equation 15. It is important to realize that this method will account for seasonal variations in both the subgrade M_R and traffic volume. It assumes that pavement structural number is constant throughout the year. Therefore, the variation in the AC elastic modulus is not accounted for.

Equation 16 is solved by evaluating the integral part analytically or numerically by dividing the year into small finite segments, evaluating the above damage function in each segment, and adding the values using Simpson's rule, for example. Because the unknown (*SN*) appears on both sides, the equation may be solved iteratively using Newton's method. SVPD calculates the required structural number based on this method and other methods outlined subsequently.

Integral Method with Variable Structural Number (AASHTO)

The structural number, the output of the AASHTO design method, is a function of pavement-layer thicknesses and stiffnesses. It is expressed as follows:

$$SN = \sum a_i m_i d_i \tag{17}$$

where

a_i = structural (strength) coefficient of layer *i*;
m_i = drainage coefficient of layer *i*; and
d_i = thickness of layer (in.)

The structural coefficient is correlated to the modulus of elasticity of each layer; therefore, it is expected that the structural number will be variable depending on the elastic moduli of the layers. However, if a proper drainage system holds the moisture levels constant within the base and subbase layers, then a constant modulus value corresponding to the optimum moisture content may be assumed for the base and subbase layers (*5*). It is then assumed that the major source of variation in the structural number is caused by seasonal changes in the AC elastic modulus. As has been mentioned, the AC elastic modulus follows a sinusoidal form after ambient temperature; consequently, the structural number, in theory, should follow the same pattern (with different amplitude and shift angle.) For example, the structural number could follow the following expression:

$$SN = SN_{av} + \frac{SN_{av}}{3} * \sin\left(2\pi * \frac{M}{12} + C\right) \tag{18}$$

meaning that the structural number is variable, having an average value of SN_{av}, and deviates from the average value by plus or minus one-third of that value. To incorporate these variations in the design algorithm, a gradient search method is used to calculate the required structural number such that the cumulative damage at the end of peformance life equals unity. In this case, the unknown is variable and is inside the integral function. Therefore, numerical optimization techniques have to be used to find the solution.

Using Equation 5 and keeping all time variables inside the integration, the objective function in this case is to minimize the quantity:

$$F = \left(\frac{N * (1 + r)^{(N-1)}}{10^{(Z*S-8.27)}} \int_a^b \frac{f(t)}{\Phi(t)^{2.32} * (SN(t) + 1)^{9.36} * \left(\frac{\Delta PSI}{2.7}\right)^{\frac{1}{B}}} dt - 1 \right)^2 \tag{19}$$

where

f(t) = traffic volume time function in ESALs;
$\Phi(t)$ = subgrade resilient modulus time function;
SN(t) = structural number time function; and

$$B = 0.4 + \frac{1094}{(SN(t) + 1)^{5.19}}$$

F is the objective function to be minimized. The first term in the function represents the cumulative damage to the pavement; the second term is 1.0. Because the cumulative damage should equal unity at the end of performance life, the solution is the structural number that satisfies the condition *F* equals 0.0.

The solution is achieved using two numerical optimization methods. The first method is exhaustive enumeration, in which the practical range of *SN* values is divided into small segments (*SN* from 1 to 10 with increments of 0.1) and the objective function is calculated at each value. The solution is the *SN* value that minimizes the objective function. The second method uses the gradient search technique, in which the objective function is evaluated at a starting point and the gradient (the slope or derivative of the objective function with respect to the unknown) is evaluated at each step to calculate the movement to next value until convergence is reached. SVPD carries out these calculations, plots the objective function, and finds the required structural number.

Example 1

A new expressway is to be constructed. Travel demand forecasting and traffic analysis predicted that the monthly traffic volume per design lane be given by the following time function:

$$ESAL = 27{,}777 + 20{,}000\ \mathrm{SIN}\left(3.14 * \frac{\mathrm{M}}{6} + A\right)$$

FWD testing on existing roads in the area shows that the resilient modulus of the subgrade, in psi (1 psi equals 6.9 kPa), is given by:

$$MR = 5{,}000 + 1{,}000\ \mathrm{SIN}\left(3.14 * \frac{\mathrm{M}}{6} + B\right)$$

where

M = the month of the year,
A = 3,
B = −2,
Serviceability loss = 1.9
Reliability level = 95 percent
Overall standard deviation = 0.35
Traffic growth rate = 0.0

Calculate the required *SN* to sustain $5 * 10^6$ cumulative standard ESAL applications using the following:

1. Effective roadbed resilient modulus (i.e., neglect traffic volume and *SN* variations);
2. Integral method with constant *SN* (i.e., neglect variations in *SN*); and
3. Integral method with variable *SN* assuming that minimum average air temperature is in February and that *SN* follows the temperature sinusoidal pattern. The summer (minimum) value of the AC layer modulus is 333,000 psi (2300 MPa) and the winter (maximum) value is 1,000,000 psi (6900 MPa).

Solution Procedure

Step 1

Using SVPD, the resilient modulus function is used to generate 24 values for different times of the year (e.g., for January, substituting M by 0.5 and 1.0 yields 4,969 psi and 4,974 psi for the first and second halves of January respectively). These values are then used to calculate the effective M_R according to the AASHTO effective roadbed resilient modulus procedure. For reliability level of 95 percent, the corresponding Z value from the standard normal distribution curve is −1.645. Substituting these values in the design equation, the required *SN* equals 5.03.

Step 2

To compare the different methods, the cumulative traffic (ESALs) must be the same in all methods. Therefore, with an annual traffic growth rate of 0.0 and average monthly ESALs of 27,777, the cumulative ESALs will be 5 times 10^6 in 15 years. In the integral method with constant *SN*, SVPD divides the year into 360 segments. In each segment, ESAL and M_R values are calculated and the damage values are summed. To evaluate the sensitivity of the solution to the shift angles A and B, the required *SN* is calculated for all possible combinations of the variables A and B. The *SN* values were between 4.90 and 5.14. Obviously, these values will change if the amplitude (one-half the variation range) of either or both the traffic volume and the resilient modulus functions change.

Step 3

To construct the *SN* time function, it is necessary to assume average values for *SN*- and AC-layer thickness. The *SN* is assumed to follow the following function:

$$SN = SN_{av} + X * SN_{av} * \mathrm{SIN}\left(3.14 * \frac{M}{6} + C\right)$$

where X is a fraction that represents the magnitude of change in *SN* value (amplitude).

C is shift angle to be calculated as follows:

The maximum *SN* will occur in February, therefore:

$$\mathrm{SIN}\left(3.14 * \frac{M}{6} + C\right) = +1$$

$$3.14 * \frac{M}{6} + C = \frac{\pi}{2}; M = 2 \text{ (February)}$$

$$C = \frac{\pi}{6}$$

$$C = 0.524$$

Solution

From correlation charts [after Van Til et al. (8)], at E_{AC} equals 1,000,000 psi (6900 MPa), the structural layer coefficient equals 0.59; for E_{AC} equals 333,000 psi (2300 MPa), the structural layer coefficient equals 0.38. It should be noted that because the variation in the AC layer modulus values is explicitly characterized in this approach, it is not necessary to adhere to the 70°F temperature label on the correlation chart. The correlations between the AC elastic modulus and the layer coefficient are based on the elastic layer theory, in which temperature has no bearing on the results. Therefore, for the purpose of this example these correlations may be used for temperatures other than 70°F, as long as the temperature effect on the modulus values is accounted for explicitly. It may be helpful to refer to Appendix GG of the AASHTO Guide (9).

For a 15.24-cm (6-in.) AC layer the difference in *SN* between the maximum and the minimum values equals 6 times the sum of 0.59 minus 0.38. The amplitude of the SIN function, as expressed in Equation 18, is calculated as follows:

$$\frac{\left(\frac{1.26}{SN_{av}}\right)}{2} = \frac{0.63}{SN_{av}}$$

Therefore, the *SN* time function is calculated as follows:

$$SN = SN_{av} + 0.63 * \mathrm{SIN}\left(3.14 * \frac{M}{6} + 0.524\right)$$

SVPD divides the year into 360 increments, calculates the ESAL, M_R, and *SN* at each increment, and evaluates the objective function. The solution is found when the cumulative damage at the end of 15-year performance life equals unity. Using the exhaustive enumeration method, the required SN_{av} equals 5.2. The gradient search algorithm yields an SN_{av} of 5.2.

To evaluate the degree to which the required *SN* is sensitive to changes in the amplitude and the shift factor of the *SN* time function, the following values were calculated.

SN Time Function	Required *SN*
$SN = SN_{av} + 0.63 * \mathrm{SIN}\left(3.14 * \frac{M}{6} + 0.524\right)$	5.2
$SN = SN_{av} + 1.50 * \mathrm{SIN}\left(3.14 * \frac{M}{6} + 0.524\right)$	5.7
$SN = SN_{av} + 2.0 * \mathrm{SIN}\left(3.14 * \frac{M}{6} + 0.524\right)$	6.1
$SN = SN_{av} + 0.63 * \mathrm{SIN}\left(3.14 * \frac{M}{6} + \pi\right)$	5.0
$SN = SN_{av} + 0.63 * \mathrm{SIN}\left(3.14 * \frac{M}{6} - \frac{\pi}{2}\right)$	5.3

This example illustrates how each variation component affects the outcome of the design algorithm. Further sensitivity analysis is required to evaluate the importance of each variation parameter. Another possible application is to adjust the *SN* calculated by traditional methods by a correction factor. Such a factor could be evaluated and tabulated for all practical combinations of seasonal variation sources. Initial results indicate that the *SN* calculated by SVPD ranged from 0.84 to 1.21 times that calculated by the current method. Subsequent research will address this issue.

Mechanistic-Empirical Design Methods

In mechanistic-empirical design methods pavement performance life is predicted by the following framework.

1. Assume a layered structure (i.e., layer thicknesses, elastic moduli, Poisson's ratios, and so forth). If the analysis is to be conducted on an existing pavement, this information is already available;
2. For the expected (or existing) loading and environmental conditions, calculate pavement response to a given single axle load using mechanistic models. In this context pavement response refers to stresses, strains, or any specified failure criterion. Two failure criteria widely used in the analysis of flexible pavements are horizontal tensile strain at the bottom of the asphalt layer that ultimately causes fatigue cracking and vertical compressive strain on the surface of the subgrade that causes permanent deformation;
3. The number of load applications the pavement can sustain before failure is calculated on the basis of pavement response (from Step 2) using repetition to failure equations or charts. These equations or charts are based on extensive laboratory (or in situ) pavement testing and are given for each type of failure; and
4. The number of load applications to failure is then known and the rate at which loads are applied to actual pavement is known or predicted, so performance life can be calculated.

How seasonal variations in elastic moduli and traffic volume of pavement layers are incorporated in design methods that are based on fatigue and permanent deformation is illustrated next.

Damage Function Based on Fatigue

Let it be assumed that the pavement structure shown in Figure 3 is the subject of analysis. The hot-mix asphalt (HMA) layer has a thickness of h_1 and elastic modulus that is time dependent (influenced by air temperature). The subgrade resilient modulus is also time dependent (influenced by moisture and other environmental conditions). The base course has a thickness of h_2 in inches and a constant elastic modulus of E_2 (assuming that a proper drainage system is provided). In the analysis, the base course elastic modulus may also assume time-dependent values if testing confirms that behavior. Traffic volume represented by ESALs is time dependent.

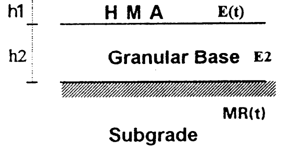

FIGURE 3 Pavement model.

A variety of mechanistic tools exist to calculate the horizontal tensile strain at the bottom of the HMA layer. For instance, Burmister's elastic layered theory may be used to calculate internal forces and displacements in pavement layers. Alternatively, on the basis of finite-element analysis, internal forces and displacements at specified vertical and horizontal locations in the pavement may be calculated. ELSYM5 (*10*), ILLI-PAVE (*11*), MICH-PAVE (*12*), KENLAYER (*13*), and CHEVRON (*14*) are software programs (some based on elastic layer theory and some based on finite element analysis) that may be used to serve this purpose. The theoretical background, the assumptions on which these programs are based, and the differences among such programs are presented elsewhere (*13*). In this analysis the CHEVRON code is used to calculate the horizontal tensile strain at the bottom of the HMA layer and the vertical compressive strain on the top of the subgrade.

Assumptions of the CHEVRON Code The following are the assumptions on which the algorithm is based:

- Each layer is characterized by thickness, Poisson's ratio, and elastic modulus;
- Pavement layers are linear elastic with constant modulus at every point in the layer;
- The load is applied uniformly over a single, flexible circular area of specified radius;
- Layers extend infinitely in all horizontal directions;
- There is 100 percent horizontal strain and vertical stress continuity across layer interfaces; and
- The bottom layer is semi-infinite in depth.

Fatigue Life Equation The Asphalt Institute (AI) equation (*15*) relates horizontal tensile strain at the bottom of the AC layer to number of load repetitions to failure (N_f) as follows:

$$N_f = \frac{0.0796}{\epsilon_t^{3.291} * E^{0.854}} \tag{20}$$

where E is the elastic modulus of HMA in psi and ϵ_t is in strain units.

The damage to the pavement from a single load application is given by:

$$D_i = \frac{1}{N_f} \tag{21}$$

Substituting from Equation 20 in Equation 21 yields the following

$$D_i = 12.563(\epsilon_t)^{3.291} * E^{0.854} \tag{22}$$

If traffic volume in ESALs is given by a time function $f(t)$, then the cumulative damage (D) in N years is given by:

$$D = N(1 + r)^{(N-1)} \int_a^b f(t) \cdot D(t)\, dt = 1.0 \tag{23}$$

where

$D(t)$ = damage time function in Equation 22 when E is replaced by its time functions;
ϵ^t = a calculation in each increment using mechanistic models (e.g., CHEVRON code);
a and b = boundary conditions (the beginning and the end of the year, e.g., 1 and 12 if monthly increments are used); and
r = annual traffic growth rate in percent.

Damage Function Based on Permanent Deformation

Theoretically, permanent deformation is primarily caused by vertical compressive strain at the top of subgrade. SVPD uses the CHEVRON code to calculate this strain.

The AI equation relates vertical compressive strain on the subgrade surface to number of load repetitions to failure (N_d) as follows:

$$N_d = \frac{1.365 * 10^{-9}}{(\epsilon_c)^{4.477}} \tag{24}$$

where ϵ_c is vertical compressive strain at the top of subgrade.

The damage to the pavement from a single load application is given by:

$$D_i = \frac{1}{N_d} \tag{25}$$

Substituting from Equation 24 in Equation 25 yields the following:

$$D_i = \frac{10^9}{1.365} * (\epsilon_c)^{4.477} \tag{26}$$

If traffic volume in ESALs is given by a time function $f(t)$, then the cumulative damage in N years is given by:

$$D = N(1 + r)^{(N-1)} \int_b^a f(t) \cdot D(t)\, dt \tag{27}$$

where $D(t)$ is the damage time function in Equation 26 when E is replaced by its time function, and ϵ_c is calculated at time t using the CHEVRON code, for example.

Pavement performance life is defined as the number of years that will elapse before the cumulative damage equals unity, therefore:

$$D = N(1 + r)^{(N-1)} \int_b^a f(t) \cdot D(t)\, dt = 1.0 \tag{28}$$

Given a pavement structure, SVPD subdivides the year into small increments, calculates the expected ESALs, E and M_R values in each increment, and the critical stresses (or strains) using the CHEVRON code, evaluates the integral function, and solves for (N) performance life of the pavement as determined separately by fatigue and permanent deformation.

Example 2

Given a pavement section with the following data:

- HMA:

thickness = 5 in.,
$E = 10^6 + 4 * 10^5 * \text{SIN}(3.14 * \frac{M}{6} - 0.5)$ psi, and
Poisson's ratio = 0.35

- Base layer:

thickness = 12 in.,
E_2 = 100,000 psi (690 MPa), and
Poisson's ratio = 0.35;

- Subgrade:

$M_R = 5{,}000 + 2{,}000 * \text{SIN}\left(3.14 * \frac{M}{6} - 5\right)$ psi, and
Poisson's ratio = 0.4; and

- Traffic data:

monthly ESAL $= 18{,}000 + 10{,}000 * \text{SIN}(3.14 * \frac{M}{6} + 5.6)$,
annual traffic growth rate = 2 percent.

All of the time functions used are monthly values (M is the month of the year, 1 to 12). Proceed as follows:

1. Plot the subgrade resilient modulus, the HMA elastic modulus, and traffic time functions;
2. Plot the damage per ESAL as a function of the time of the year based first on fatigue, then on permanent deformation; and
3. Based first on fatigue, then on permanent deformation, calculate pavement performance life in years.

Solution

Figure 4 shows a plot of E, ESAL, and M_R time functions (only for illustration, not as part of the solution). The horizontal axis represents segments of the year; the year is divided into 24 segments; segments 1 and 2 are the first and the second halves of January respectively, 3 and 4 are first and second halves of February, and so forth. The HMA elastic modulus has an annual cycle that peaks in April and reaches its minimum value in October. ESAL is expressed by an annual cycle that peaks in April and reaches its minimum value in October. M_R also follows an annual pattern with minimum value in July.

Figure 5 shows the fatigue damage function and the permanent deformation damage function associated with one ESAL application; therefore, both damage functions are independent of ESAL function. The fatigue function is expressed by Equation 22, and permanent deformation function is expressed by Equation 26. Measured for fatigue, an ESAL would cause damage of 1.32 times 10^{-7} in August and 1.02 times 10^{-7} in March. That is to say, it would take 7,575,757 standard load applications in August or 9,803,921 in March to cause failure of the pavement.

Measured for permanent deformation, an ESAL would cause a damage of 6 times 10^{-7} in August and 1.8 times 10^{-7} in February. That is to say, it would take 1,666,666 standard load applications in August or 5,555,555 in February to cause failure of the pavement. This indicates that the damage caused in August is about 3.5 times the damage caused in February. The output of SVPD indicates that for 2 percent annual traffic growth, performance life in fatigue is 24.9 years and in permanent deformation is 11.04 years. Obviously, permanent deformation is the governing criterion.

The example given demonstrates how seasonal variations in properties of pavement layers influence pavement performance and life expectancy. On the basis of this example, in which very reasonable values are assumed for seasonal variations (based on actual SMP data), seasonal variations play an important role in damage analysis. It was shown that a single standard load application in one season causes a damage that is equivalent to 3.5 standard load applications in a different season.

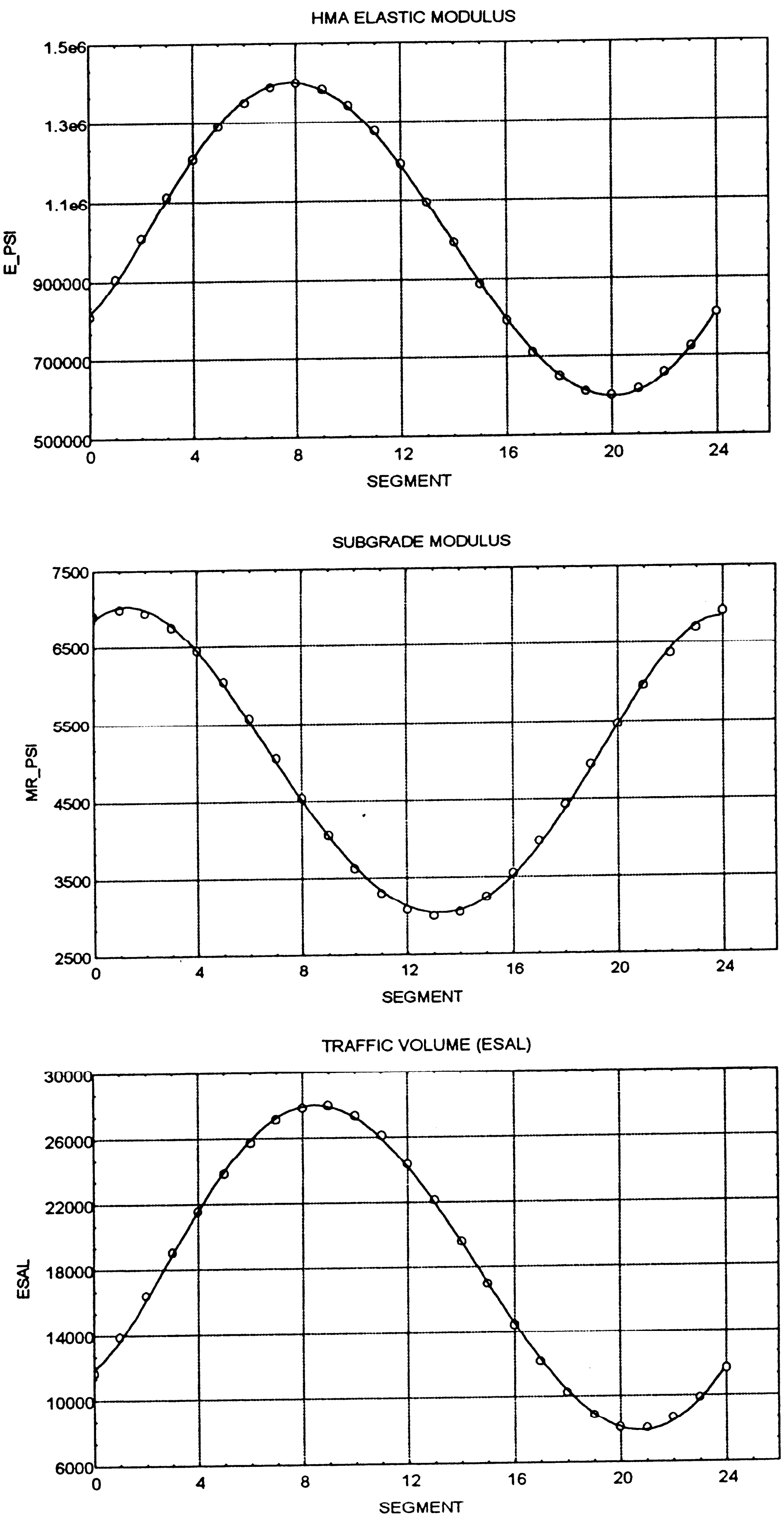

FIGURE 4 ESAL and pavement moduli time functions (psi = 6.9kPa).

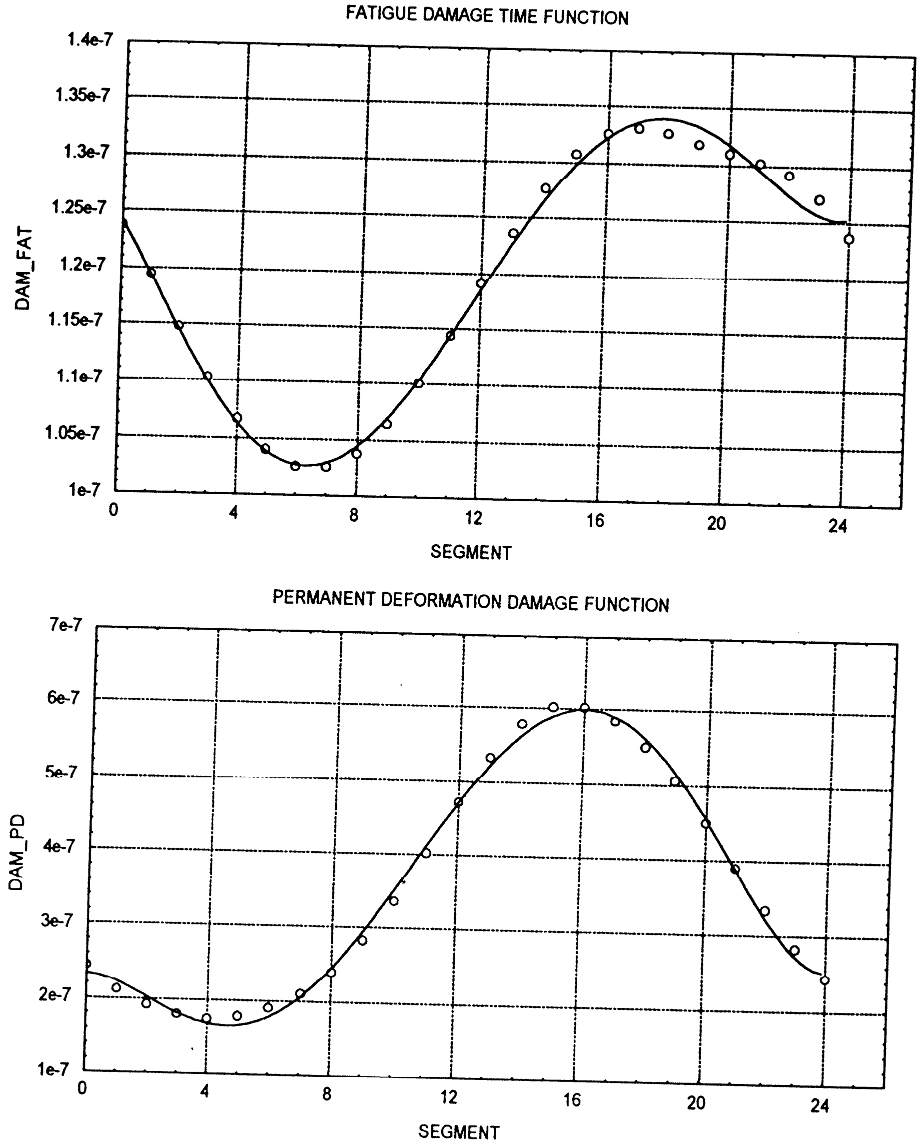

FIGURE 5 Damage functions, example 2.

CONCLUSIONS

On the basis of the analysis of SMP data for Sites 48SA and 48SF, both located in a no-freeze zone, pavement layer elastic moduli were accurately modeled using sinusoidal periodic models. A two-step process is proposed to consider seasonal variations in the design of flexible pavements. The first step is to characterize seasonal changes of moduli of pavement layers using periodic functions. The second step is to use such periodic functions in pavement design equations.

A computer program, SVPD, was written to carry out the required calculations and facilitate the comparison between the previously listed design methods.

In empirical design method, AASHTO equation, material and traffic variables are substituted by time functions. The equation is then solved for the required structural number. The solution is achieved using numerical optimization techniques. The required *SN* value is the value that minimizes the objective function (in this case it is the squared deviation between the cumulative damage and unity). SVPD carries out these calculations, plots the objective function, and finds the required structural number.

In mechanistic-empirical design methods, given a pavement structure, SVPD subdivides the year into small increments; calculates the expected ESALs, the AC = layer elastic modulus and subgrade resilient modulus values in each increment, and the critical stresses (or strains); uses superposition to calculate cumulative damage; and solves for (*N*) performance life of the pavement as determined separately by fatigue and permanent deformation. Two examples are presented to illustrate how each variation component affects the outcome of the design algorithm.

The essence of the effective modulus concept in the AASHTO design procedure (*6*) is the recognition of the sensitivity of the M_R to seasonal variations. However, the underlying assumption in its present application is that traffic is uniformly distributed throughout the year. Mechanistic damage analysis procedures (*13*) opened up the prospects of matching traffic variations to seasonal variations to yield conceptually more accurate pavement performance predictions. SVPD advances the state of the art of pavement design and performance another step by suggesting a methodology for simulating the joint impact of seasonal variations in pavement-layer properties and traffic loading. By extension SVPD could also become a valuable decision support tool for pavement management as well as traffic restriction in environmentally sensitive areas.

Time series analysis is used to characterize the seasonal variations of interest. It should be noted, however, that deployed in simulation mode, the SVPD methodology would be capable of accommodating any periodic function, continuous or piecewise, linear or nonlinear, time variant or time invariant.

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