STOCHASTIC MODEL FOR PREDICTION OF PAVEMENT PERFORMANCE

Fred Moavenzadeh, Massachusetts Institute of Technology

A simulation model for predicting the performance of highway pavement is described. The primary modes of distress considered are deformation and cracking. The factors contributing to pavement distress are divided into three categories: (a) physical properties and pavement geometry, (b) vehicular load, and (c) environmental conditions. The damage formulation is handled in two steps. The first step yields the stress and strain fields within the system, which are then used as inputs to the second step. The second step yields damage components or limiting responses. Based on the expected values of the damage component, the road serviceability load after a given time period can be predicted by using a relationship similar to that of AASHO serviceability. The model, then, estimates the change in serviceability and associated reliability of the system due to accumulation of damage. After the changes in serviceability and reliability are determined, several possible maintenance strategies can be examined. An essential part of the model is a relationship among maintenance, change in reliability, and the increase in expected life. Thus for each maintenance strategy there is an associated reliability-life expectancy.

•RATIONAL analysis and design of highway pavements, as with any other engineering system, are normally facilitated by the development of models representative of system behavior under realistic operating conditions. A model, in this context, is an abstract representation of the form, function, and operation of the real or physical system. To develop such models requires that the system be characterized realistically and that information about the system's functions, behavioral interactions, and failure patterns and mechanisms be identified. A major task in this development is choosing the proper model. Different analysts may formulate different models for the same system. This difference may be caused by differences either in formalism or in abstraction. It is also possible that this subjectivity and arbitrariness in problem definitions may result in nonunique solutions for such problems. Consequently, decisions on the configuration and structure of models to represent certain problems may vary considerably among analysts, depending on the interpretations and evaluation of existing information. Because this problem is unavoidable, such interpretations must be based on sound and objective information sources.

One of the major objectives in the area of large-scale modeling of systems is the construction of a causal model capable of handling the interaction among the different components of the system it represents. A causal model is based on an a priori hypothesis of system behavior as well as the interaction of the various system characteristics. Such an interaction occurs in accordance with functional relationships that define the behavior of the system and its responses in terms of physical transfer functions.

This paper discusses the development of a set of causal models for the pavement analysis and design system (PADS). In this context, the design process is viewed as an evolution of analysis in which alternatives are continually synthesized and evaluated to determine the optimal design. The operational policies encountered in handling and maintaining the system are considered as a part of this design methodology. The overall model and its subcomponents, the structural, maintenance, and cost models, are described in detail elsewhere (1) and are reviewed very briefly below.

OVERALL MODEL

PADS consists of three subsets of models: structural model, serviceability-maintenance model, and cost model. When integrated, these models form the basis for selecting and evaluating the optimal design among various alternatives.

The macrostructure of PADS is shown in Figure 1. The structural model uses information on traffic, environment, system geometry, and material properties to yield the specified damage indicators. These are the rut depth, slope variance, and extent of cracking, and they are depicted by their statistical characteristics.

The serviceability-maintenance model uses this information and reduces it to the present serviceability index (PSI) derived from the AASHO Road Test analysis. This model also accounts for the uncertainties and variabilities. The serviceability and reliability in this model are also functions of the degree of applied maintenance.

This information is then relayed into the cost model as is other information on unit costs. The cost model provides a cost estimate for the chosen construction-maintenance strategy, which provides the basis for an optimization of the design.

Structural Model

In the structural model, the pavement is represented by three layers in which the upper two layers have finite depths and the third layer has infinite depth. Each layer may have elastic or viscoelastic properties. The materials in each layer are assumed to be isotropic and locally homogeneous but have statistical variations in space. This scatter results from the mixing, placing, handling, and testing activities, which generate spatial variability in the materials properties. The system is subjected to circular loads of varying intensity and duration. The time intervals between successive load applications are also variable to simulate the traffic conditions on a pavement. The load patterns are also random in space to simulate the channelization of traffic. Environmental changes, i.e., the temperature regimes, are chosen to represent the prevailing regional climatic conditions under which the system is studied. (The effects of moisture and its changes can be incorporated in a similar manner.) These regimes are represented by a set of temperatures that can vary daily, monthly, or yearly as desired in the particular analysis.

Because of the uncertainties and variabilities associated with the operations of a pavement, the inputs and consequently the outputs are described in terms of probabilistic distributions instead of single valued estimates.

A block diagram of the structural model is shown in Figure 2. The model is subdivided into primary and ultimate stages. In the primary stage, the response of the layered system to a static load applied at the surface is obtained by using the layered system theory (2) and closed-form analytic solutions to account for the variabilities in material properties. This stage provides statistical estimates of stresses, strains, and deflections at any point within the pavement structure for a unit load and isothermal conditions. Such system responses are obtained for different temperature regimes. These responses are combined and used as inputs to the ultimate stage, which uses stresses, strains, and deflections to obtain the components of physical damage. The damage components considered are rut depth, slope variance, and extent of cracking, which are used by AASHO to describe the serviceability of the pavement. Probabilistic closed-form solutions are used in this stage of the model.

Input Variables

The inputs to the structural model are system geometry, material properties, load characteristics, and temperature history. System geometry is expressed in terms of the heights of the first and second layers. The material properties assumed to be pertinent here are the constitutive equations and the limiting equations. The constitutive equation for each layer is given as a creep or elastic compliance, and the limiting

equations are given by fatigue curves (strains versus number of cycles to failure). Poisson's ratio is set equal to one-half. The effect of its variation was found to be negligible. The creep or elastic compliances are obtained from triaxial tests and are statistically distributed. Through use of the least squares technique, the creep compliances are fitted to an exponential (Dirichlet) series of the form

$$D(t) = \eta \sum_{i=1}^{N} \overline{G}_i \exp(-t\delta_i) \tag{1}$$

where

$D(t)$ = creep compliance at time t,
δ_i = exponents of the series (generally chosen to be one order of magnitude apart from each other except for $\delta_{N=0}$),
$\overline{G}_i$ = coefficients of the Dirichlet series for the mean creep compliance,
N = number of terms in the series (generally equal to the number of decades of time covered by the experimental data), and
η = random variable with a mean of 1 and a coefficient of variation determined by the scatter of the creep functions.

For the elastic case, all $\overline{G}_i$ equal zero except $\overline{G}_N$. In the general case the instantaneous compliance is represented by $\sum_{i=1}^{N} \overline{G}_i$, and the compliance at very large times is given by $\overline{G}_N$.

In addition to the creep functions, mapping parameters are required to account for the effects of environmental variables such as temperature. When the temperature dependence is accounted for, the creep compliance is given by the following formula:

$$D(t, T) = \alpha_T + \beta_T \, \eta \sum_{i=1}^{N} \overline{G}_i \exp(-\delta_i t/a_T) \tag{2}$$

In equation 2, α_T represents a vertical shift on an arithmetic scale, β_T represents a vertical shift on a logarithmic scale, and a_T represents a horizontal shift on a logarithmic scale of time. In many cases of thermorheologically simple materials $\alpha_T = 0$. β_T is a function of temperature and density but does not vary appreciably from a value of 1, and a_T is referred to as the shift factor and is given for different temperatures. These parameters have to be determined for each type of material. Further theoretical background on the mapping procedures is given elsewhere (1).

To account for plastic deformations other than those due to rate sensitivity, equation 3 is used. These plastic deformations are considered to be principally due to differences in material response to loading and unloading cycles. Thus it is assumed that the unloading function is a certain proportion of the loading function.

$$D_{\text{unloading}}(t, N) = D_{\text{loading}}(t, N) - D_{\text{loading}}(\infty, 1)\, \mu N^{-\alpha} \tag{3}$$

where N is the number of previous loadings.

Therefore, for a unit load applied at time zero and kept for a duration Δt and then removed, the accumulated deformation at time t is

$$\epsilon_{accumulated}(t) = [D(t, 1) - D(t - \Delta t, 1)] + D(\infty, 1)\mu \tag{4}$$

The first term in equation 4 represents the usual linear viscoelastic accumulation, and the second term represents an additional plastic deformation. The exponential factor in N is introduced to account for the decrease in the accumulation rate of plastic deformation as the degree of compaction increases. For a sequence of N loads applied at time t_n and kept for durations of Δt_n, the accumulated response is

$$\epsilon_a(t) \sum_{n=1}^{N} [D(t - t_n, n) - D(t - t_n - \Delta t_n, n)] + \sum_{n=1}^{N} D(\infty, 1)\mu n^{-\alpha} \tag{5}$$

More details are given on the nonlinear rebound function in the literature (1).

Fatigue curves are represented by

$$N_f = K_1 (1/\Delta\epsilon)^{K_2} \tag{6}$$

where

N_f = number of cycles to failure,
$\Delta\epsilon$ = tensile strain amplitude, and
K_1 and K_2 = coefficients related to materials characteristics.

These coefficients are generally sensitive to temperature and are also statistical in nature.

In the present analysis the following expressions were used for the mean values of these coefficients:

$$K_1 = 10^{|-10 - 0.15(70 - T)|}$$

$$K_2 = 4 + 0.04(70 - T)$$

where T is the temperature in deg. The dependency of K_1 and K_2 on temperature will be determined from further experimental data.

The coefficients K_1 and K_2 may be statistically correlated. The coefficient of correlation varies between -1 and +1. This coefficient of correlation has an important effect on the analysis. If this coefficient is -1, an increase of K_1 corresponds to a decrease of K_2; if the coefficient is zero, K_1 and K_2 are statistically independent of each other. These coefficients are given by their means, variances, and coefficient of correlation. The variances and coefficient of correlation determine whether the experimental scatter is best represented by fatigue curves rotated in a given direction or translated with respect to each other. The present analysis assumed different values for the coefficient of correlation to examine its influence.

Other coefficients of correlation that are important but not included in the computer program relate the strain amplitude $\Delta\epsilon$ to the K_1 and K_2. These coefficients of correlation are important because there is certainly a relation between the constitutive equation and the fatigue properties. For instance, a specimen with a higher-than-average modulus probably has a lower-than-average fatigue curve, even though the strains that it will experience will be lower than average (for the same loads).

The spatial coefficient of correlation completes the set of material properties. This coefficient is a measure of the statistical correlation of two points at a given distance

from each other. This coefficient ρ can be represented by

$$\rho = A + B \exp(-X^2/C^2) \tag{7}$$

where X represents the distance between the two points to be correlated.

The values of ρ fall in the range of ± 1. In this case, it is unlikely (not entirely impossible) to be negative. The closer it is to a value of 1, the more homogeneous are the material properties. It should be noted that $\rho = 1$ for $X = 0$, and it approaches zero as X increases. This indicates that two neighboring locations are more likely to have similar properties than two locations that are farther apart. The shape of this curve is a function of the condition of the subgrade as well as the methods of construction. In the numerical examples, the following values were arbitrarily chosen: $B = 1$, $C = 0.12$, and $A = 0$.

The application of traffic load to a pavement system is assumed to be a process of independent random arrivals. Vehicles arrive at some point on the pavement in a random manner both in space (i.e., amplitude and velocity) and in time (of arrival). The arrival process is modeled as a Poisson process with a mean rate of arrival λ. The probability of having any number of arrivals n at time t may be defined as

$$P_n(t) = \frac{\exp(-\lambda t)(\lambda t)^n}{n!} \tag{8}$$

Assumptions of stationarity, nonmultiplicity, and independence must be satisfied for the underlying physical mechanism generating the arrivals to be characterized as a Poisson process. In this context, stationarity implies that the probability of a vehicle arrival in a short interval of time t to $t + \Delta t$ is approximately $\lambda\Delta t$, for any t in the ensemble.

Nonmultiplicity implies that the probability of two or more vehicle arrivals in a short interval is negligible compared to $\lambda\Delta t$. Physical limitations of vehicle length passing in one highway lane support this assumption; it is not possible for two cars to pass the same point in a lane at the same time.

Finally, independence requires that the number of arrivals in any interval of time be independent of the number in any other nonoverlapping interval of time. In a Poisson process, the time between arrivals is exponentially distributed. This property is used to generate a random number of arrivals within any time interval t.

The amplitudes of the loads in this process are also statistically distributed in space. Traffic studies (3) have shown that a lognormal distribution is suitable to represent the scatter in load magnitude. Means and variances of load amplitudes are used to represent this scatter.

The load duration, as function of its velocity on the highway, is also a random variable. On a typical highway, for example, speeds may vary from 40 to 70 mph (64 to 112 km/h); accordingly, the load duration was assumed to have a statistical scatter represented by its means and variances from distributions obtained through traffic studies.

Figure 3 shows the statistical characteristics of typical load inputs to the model. The required inputs for the loads are as follows:

1. Rate of the Poisson process λ, i.e., rate of load applications per day, month, or year;
2. Proportion of channelized traffic, i.e., the number of considered channels (2 to 10) and the fraction of traffic going into a central path (the remainder of the traffic is equally distributed over the other channels);
3. Duration of the loads in seconds, which is related to the velocity of the vehicle and which can be approximated by the time taken to travel a distance equal to three times the diameter of the loaded area (coefficient of variation of this duration is also

given to account for the variations in velocities);

4. Radius of the loads in inches (mm);
5. Intensity of the loads or tire pressure in psi (kPa); and
6. Load amplitude (optional), which is a linear multiplier of the load's intensity, given by a mean and a standard deviation (accounts for the load spectrum).

The temperature is given by its mean and variance for each basic period, which is usually taken to be a month. Regional weather trends may be established from weather bureau data, and the period over which the temperature has certain statistical properties may be extended or shortened according to local climatic conditions.

Output Variables

The outputs include the statistical estimates of the AASHO damage indicators determined at different times.

1. Rut depth is considered to be primarily due to the channelization of traffic, which causes a differential deformation in the transverse direction. Therefore, certain assumptions must be made about the probability of a certain portion of the traffic flow running in a certain channel. Rut depth is given as a differential settlement between the most traveled channel and its surroundings.
2. Slope variance is an indication of the state of the pavement in the longitudinal direction. It is a measure of pavement roughness and is caused mainly by the variations in the properties of the construction materials. The spatial variations of the material properties may be represented by the degree of correlation between the properties of points separated by a given spacing. When this correlation coefficient is close to 1, the system will be more homogeneous and the pavement will be less likely to become rough. Obviously, the coefficient of correlation will be a function of the spacing. For points that are separated by 1 ft (0.3 m) the coefficient will approach 1, and for points separated by 1 mile (1.6 km) this coefficient will tend to be 0. Points that are far apart are more likely to have been constructed at different times from different materials, and the subgrade is more likely to be different.
3. Cracking is believed to be caused by a fatigue mechanism. Miner's linear law is used to account for the crack accumulation in the top layer. The strains at the first interface are used to determine the fatigue process. There is, however, evidence that some weakening of the base and subgrade under repeated loading may be one of the principal parameters influencing the fatigue behavior of the surface layer. Cracking is given in square yards/1,000 square yards (square meters/1000 square meters).

Operation of the Structural Model

In the operation of the structural model, material creep data are fitted by the curve fitting block so that, for each material type, a creep compliance as a function of time (or elastic compliance) plus mapping parameters such as temperature shift factor a_T can be obtained.

The resulting set of material properties, along with their coefficient of variation and the geometric and load characteristics, is input to the stationary load program. The stationary load program yields the primary responses of the system at the desired locations; these responses are obtained numerically versus time. The curve fitting block is then used again to obtain an exponential series representation of the primary responses.

These exponential series are then used as input to the random load block, along with mapping parameters, traffic and temperature histories, fatigue properties of the materials, and plastic deformation accumulation parameters developed in the stationary load program. A closed-form probabilistic solution for the primary permanent responses (stresses, strains, deflections) is used to predict rutting, cracking, and slope variance of the pavement. The required formulations are given elsewhere (1). This

computation block yields the history of the statistical characteristics of the damage indicators.

Serviceability-Maintenance Model

The serviceability-maintenance model is subdivided into two submodels: a serviceability-reliability (S-R) submodel and a maintenance submodel. The total S-M model is shown in Figure 4.

Serviceability-Reliability Submodel

In the S-R submodel, the distress indicators obtained from the structural model are combined in a regression form suggested by AASHO to provide a subjective measure of the serviceability level of the system at any time period. This measure is referred to as the present serviceability index (PSI), which is expressed as

$$PSI = a_0 + a_1x_1 + a_2x_2 + a_3x_3$$

where x_1, x_2, and x_3 are functions of rut depth, slope variance, and cracking. This expression has been reformulated in light of the uncertainty associated with the damage characteristics in pavements such that statistical estimates of the PSI are obtained. From this, the probabilities of having any value of PSI at any time can be determined. These probabilities are referred to as the state probabilities. In this context, the probability, at any time, of being above some unacceptable value of PSI is defined as the reliability of the system at that time period. This can be viewed as a measure of a confidence level that the system is performing its design functions. The unacceptable limit of serviceability, which is subjectively defined by the user, generally defines some threshold for failure, from which the life expectancy of the system can be determined.

The inputs to this stage, which are the results of the structural model, are the means and variances of the damage indicators (rutting, slope variance, cracking) at different values of time. The outputs include the following.

1. Means and variances of the AASHO present serviceability index at different times are one set of outputs. The model uses the following expression for the serviceability:

$$PSI = a_0 + a_1 \log (1 + SV) + a_2\sqrt{CA} + a_3 RD^2$$

where

SV = slope variance,
CA = cracked area, and
RD = rut depth.

In the case where these damage indicators are statistically independent of each other, the following formula is obtained for the expected value of the serviceability index:

$$E(PSI) = a_1 + a_2 [\log(1 + \overline{SV}) - \tfrac{1}{2}(1 + \overline{SV})^2 \sigma^2_{SV}]$$
$$+ a_3\left(\sqrt{\overline{CA}}^{\,-3/2} \sigma^2_{CA}\right) + a_4 (\sigma^2_{RD} + \overline{RD}^2)$$

The upper bars represent an expected value, and σ^2 represents a variance (1).

2. The reliability of the system at various times assumes that the serviceability index has a normal distribution and that an unacceptable level of serviceability is defined. The reliability of the system at a given time is then the probability of having the system above the failure level.

3. The expected value of the life of the system is the mean time for the system to reach the failure level, in the absence of maintenance activities. The probabilistic distributions of the life, i.e., its probability mass function and its accumulative distribution function, are given also.

4. The marginal state probability is the probability of the system being between specified levels of the serviceability index.

Maintenance Submodel

The maintenance submodel is aimed at generating various maintenance strategies over the operational life of the pavement and evaluating the consequences of these strategies on the serviceability, reliability, life, and economic attributes. In addition, a decision-making algorithm is outlined (1) to select those strategies that provide optimal costs for a given design configuration.

Because of the dynamic nature of this process, the maintenance submodel must be equipped with dynamic feedbacks that loop through the S-R submodel and the cost model. After a maintenance level is generated and defined in terms of some quantifiable items, such as the percentage of ruts to be filled or cracks to be sealed, a feedback loop provides this information to the S-R submodel to modify the current status of the system. The feedback is also transmitted to the cost model to assess the economic consequences of maintenance. The process is repeated throughout the analysis horizon and for various levels of feasible maintenance strategies to determine which strategy provides optimal cost of operation for both the pavement and the vehicles using the road.

Cost Model

The cost model, which has been developed elsewhere (4, 5), determines the total costs of construction, operation, and maintenance of highway systems. It incorporates three components: construction, roadway maintenance, and vehicle operating costs. A schematic representation of its operation is shown in Figure 5. Each component in this model provides estimates of resource consumption and yields the cost estimates of these resources by using separately defined unit prices. This model, therefore, is adaptable to any economy regardless of the relative costs of various resources.

Input variables define the project to be analyzed. Also defined as input is the structural design-maintenance strategy to be evaluated. Grade, alignment, width and depth of surfacing, and maintenance and reconstruction policy are defined; and local unit costs for labor, equipment, and materials are specified. On the basis of this information the submodels estimate the construction, maintenance, and user costs for each analysis period. The model discounts these costs to find the present value of the structural design-maintenance strategy being evaluated. The designer can then compare a number of strategies on the basis of their total predicted cost. The cost model thus provides a basis for decisions on selection and operation of optimal design systems.

RESULTS AND SENSITIVITY ANALYSIS

Illustrative examples and sensitivity analyses designed to demonstrate the ability of the models to predict response of the system and its measures of effectiveness are presented. The analysis conducted in this study involves examining the model sensitivity to changes in the controllable design factors for pavement systems. The factors considered in this study are geometrical configuration, changes in material properties,

Figure 1. Macrostructure of PADS.

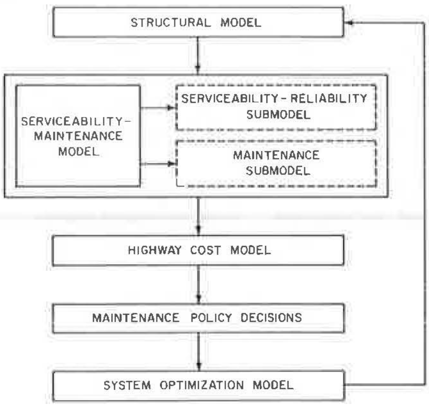


Figure 2. Structural model.

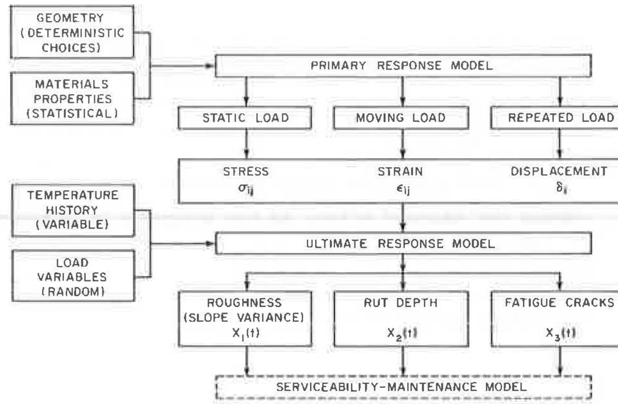


Figure 3. Distribution of load charactersitics.

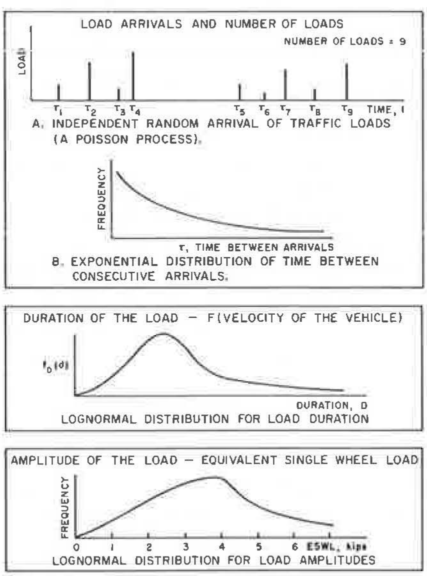


Figure 4. Serviceability-maintenance model.

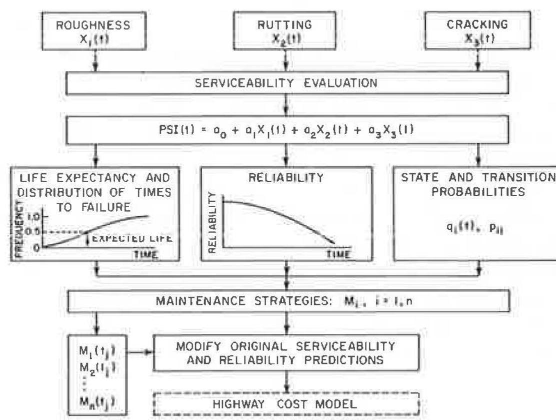
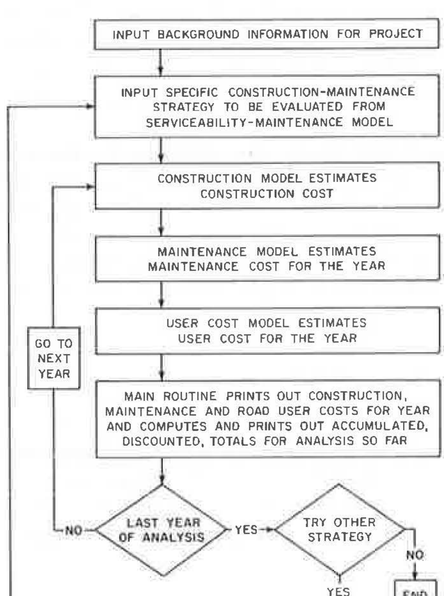


Figure 5. Operation of cost model.



influence of quality control aspects on the damage progression within the system, and its serviceability, reliability, and life expectancy. These are essentially the parameters over which an engineer has control when designing a pavement.

To establish a common yardstick for comparison among the different systems at hand, these systems were subjected to similar load and temperature histories.

Input Descriptions

The temperature was assumed constant and equal to the reference temperature, 70 F (21 C). Hence, all the time-temperature shift factors were unity. For the fatigue curves described above, the coefficients K_1 and K_2 were assumed to have a correlation of zero, i.e., linear independence. The mean load intensity in the random loading program was 80 psi (550 kPa), with a variance of 400 psi^2 (19 000 kPa^2). The mean duration of the load is 0.05 sec with a variance of 0.0004 sec^2. The mean traffic rate was 0.01 load/sec or 864 loads/day. The coefficients of normal deflection and radial strain accumulation were taken as 0.0002 and 0.00004 respectively, and the exponents were taken as 0.6 and 0.5 respectively. The radius of the applied loading was 6.4 in. (16.2 cm). The spatial autocorrelation function assumed a coefficient of 1.0 and an exponent of 0.12. The serviceability failure level was set to 0.46 on a normalized 0-1 scale.

The usual single parameter influence on pavement behavior was not analyzed; instead, the trade-offs and interactions of several parameters were revealed by using three-dimensional plots. Accordingly, three system geometries, three sets of physical properties of the material constituents, and three levels of quality control on the system fabrication were analyzed.

The geometry of the system is expressed in terms of the thicknesses of its first and second layers; the third layer is infinitely deep. The thickness of the layers in inches (2.54 cm) is as follows:

Geometry	Layer 1	Layer 2
Thin	3	5
Medium	4	6
Thick	5	9

The physical properties of the materials can be characterized as weak, medium, and strong, depending on the creep functions of their constituent materials. These creep functions are shown in Figure 6, where the infinite time compliance of the third layer is taken as 0.001.

The levels of quality control can be characterized as poor, medium, and good. The percentage of statistical scatter in material properties is as follows:

Quality Control Level	Layer 1	Layer 2	Layer 3
Good	0	10	20
Medium	20	30	40
Poor	40	60	70

Effects on Rut Depth

Figure 7 shows the mean rut depth histories as functions of time, material quality, and system thickness (given good quality control), indicating that the mean rut depth is roughly inversely proportional to the system thickness and the material quality; there is a slight positive correlation between thickness and material quality. This agrees quite well with intuition, although the relationships may not be quite so linear. Quality

Figure 6. Creep function for (a) weak, (b) medium, and (c) strong material properties.

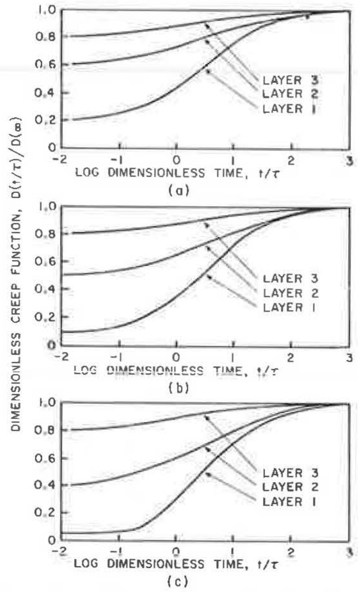


Figure 7. Rut depth as a function of material quality for (a) thin, (b) medium, and (c) thick systems.

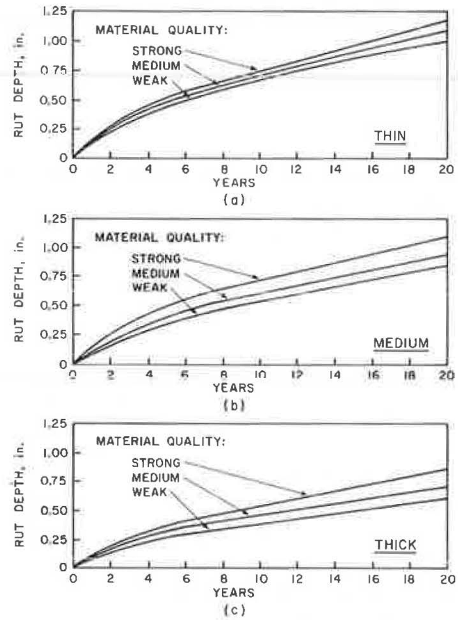


Figure 8. Slope variance as a function of quality control and time for (a) weak, (b) medium, and (c) strong material quality.

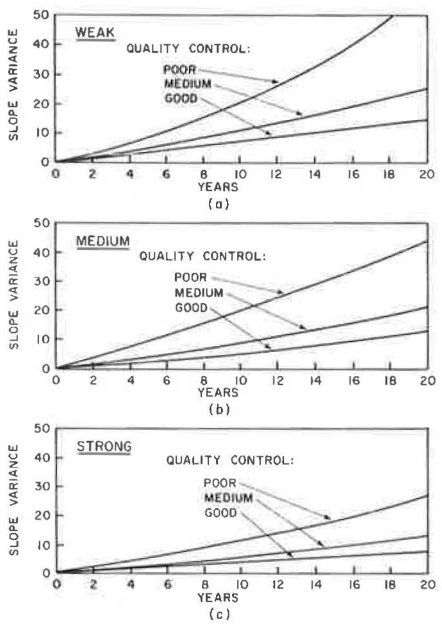
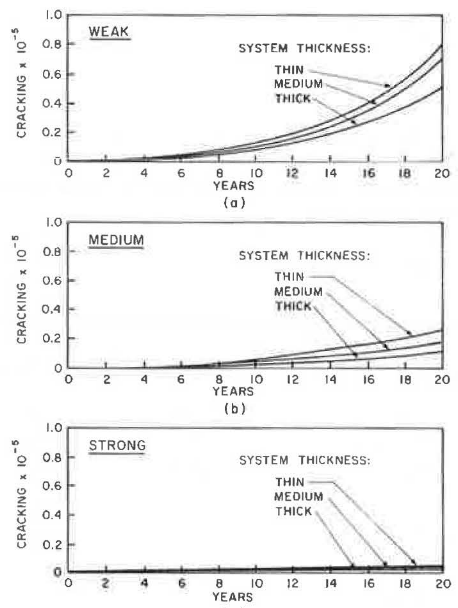


Figure 9. Cracking as a function of system thickness and time for (a) weak, (b) medium, and (c) strong material quality.



control level has a relatively insignificant effect on the mean rut depth but does influence the variance of rut depth (which is related to roughness). This is due primarily to the assumed symmetry of the creep function distributions about the mean.

Effects on Slope Variance

Figure 8 shows the mean slope variance as a function of time, material quality, and quality control (given a thin geometry). The data indicate that the mean slope variance is roughly proportional to the square of the quality control (expressed as a percentage variation) and inversely proportional to the material quality. Iterations over the system thickness reveal also that the mean slope variance is roughly inversely proportional to system thickness. The slope variance also depends on the spatial autocorrelation function, which was held constant during this analysis.

Effects on Cracking

Figure 9, which shows the mean cracking damage histories as functions of time, material quality, and quality control (given a thin geometry), indicates that the mean cracking damage is roughly inversely proportional to the system thickness and the material quality of the system (the material quality being the more dominant variable). Iterations over quality control have indicated that the mean cracking damage is relatively unaffected by quality control, but the variance of the cracking damage is highly affected, for reasons similar to those for mean rut depth.

Effects on Serviceability

Figure 10 shows the mean present serviceability histories as functions of time, material quality, and quality control (given a thin geometry) and indicates that the mean serviceability is inversely proportional to the quality control (expressed as a percentage variation) and proportional to the material quality of the system. The effects of quality control enter the serviceability index primarily through the slope variance component, but the material quality and system thickness affect all mean damage components.

Effects on Reliability

Figure 11 shows the system reliability histories as functions of time, material quality, and quality control (given a thin system geometry), indicating that the reliability is proportional to the material quality and inversely proportional to the square of the quality control (expressed as a percentage variation). Iterations over system thickness indicate that the reliability is also proportional to the square of the system thickness.

Effects on Marginal Probabilities

The marginal state probabilities as functions of time and system thickness are shown in Figure 12, which indicates that the thicker the system is the slower it deteriorates. Figure 13 shows the marginal probabilities as functions of material quality, indicating that the stronger the materials are the slower the pavement deteriorates. Figure 14 shows that quality control has a similar prolongation effect.

Effects on Life Expectancy

Figure 15 shows the life expectancy of the pavement as a function of material quality,

Figure 10. Serviceability as a function of quality control and time for (a) weak, (b) medium, and (c) strong material quality.

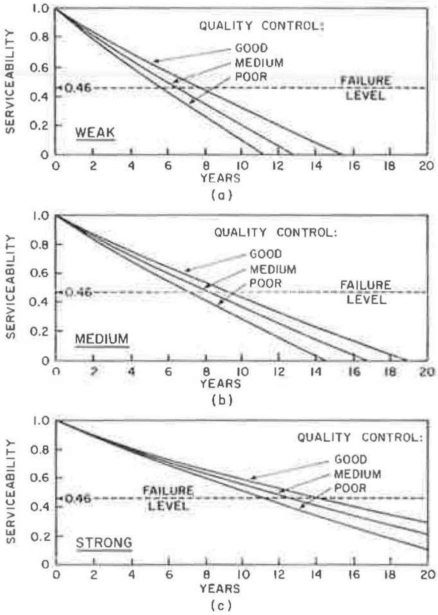


Figure 11. Reliability as a function of quality control and time for (a) weak, (b) medium, and (c) strong material quality.

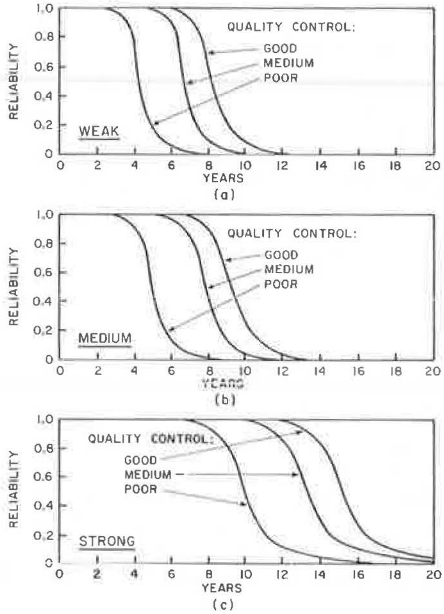


Figure 12. Marginal probabilities for (a) thin, (b) medium, and (c) thick systems.

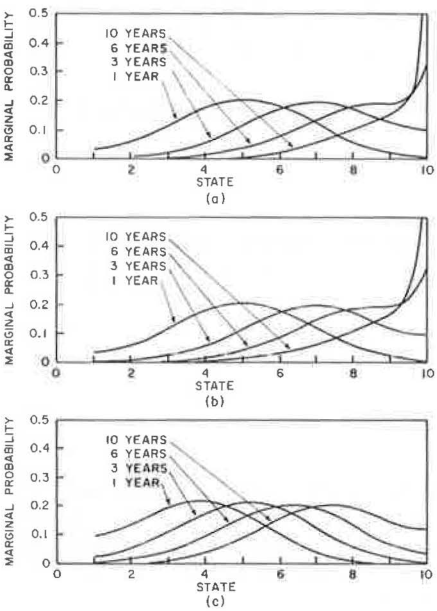


Figure 13. Marginal probabilities for (a) weak, (b) medium, and (c) strong material properties.

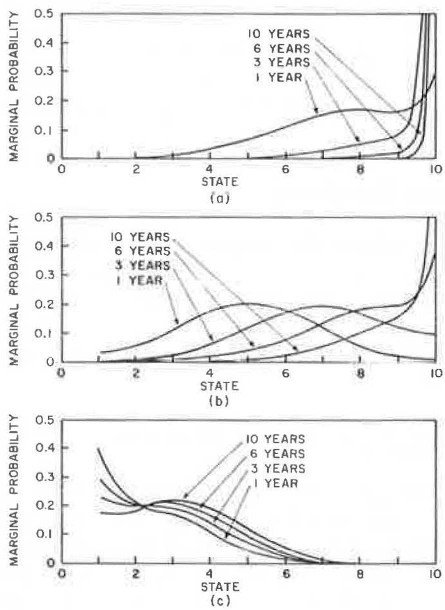


Figure 14. Marginal probabilities for (a) poor, (b) medium, and (c) good quality control levels.

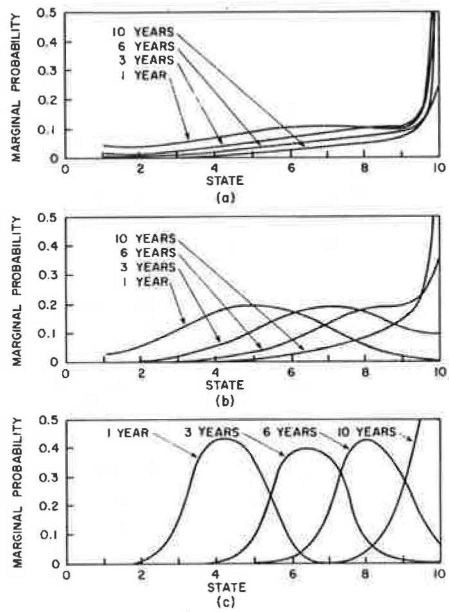


Figure 15. Life expectancy as a function of system thickness and quality control for (a) weak, (b) medium, and (c) strong material quality (given a 20-year observation period).

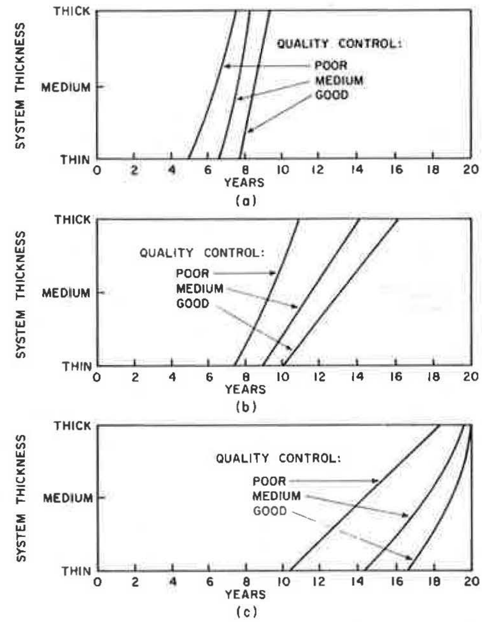


Figure 16. Serviceability as a function of system quality for the environment differing from the reference temperature (70 F, 21 C) by (a) -10, (b) 0, and (c) +10 deg.

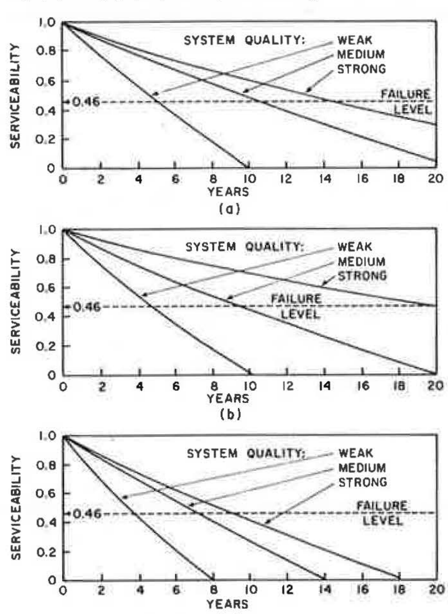
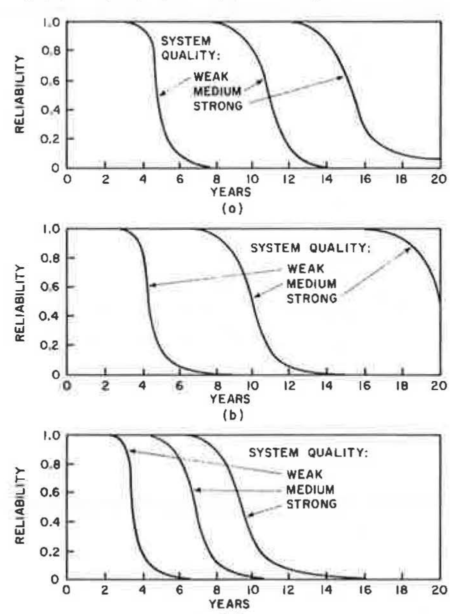


Figure 17. Reliability as a function of system quality and time for the environment differing from the reference temperature (70 F, 21 C) by (a) -10, (b) 0, and (c) +10 deg.



quality control, and system thickness (given a 20-year observation period). The life expectancy is roughly proportional to system thickness and the square of the material quality and is inversely proportional to quality control (expressed as a percentage variation).

Effects of System Quality and Environment on Performance

The effects of the difference between the environmental temperature and the reference temperature and of system quality on pavement performance were examined. The following three levels of system quality were selected: strong (strong material, good quality control, medium geometry); medium (medium material quality, medium quality control, medium geometry); and weak (weak material quality, poor quality control, thin geometry). The environment differed from the reference temperature by +10, 0, -10 deg F. Other variables remained as before.

Figure 16 shows the mean serviceability history as a function of time, system quality, and difference of the environment from the reference temperature. The data indicate that the mean serviceability is proportional to the system quality and is a rather complex function of temperature. This is reflected largely by the amount of creep (i.e., temperature sensitivity) of the system and by the temperature dependence of cracking damage, which appears to be minimized at the reference temperature.

Figure 17 shows reliability as a function of time, system quality, and difference from the reference temperature of the environment, indicating that the reliability is proportional to system quality and, again, a very complex function of temperature, depending on the amount of creep of the system.

Effects of System Quality and Traffic Volume on Performance

The influences of traffic volume and system quality of performance were examined. The weak, medium, and strong systems described previously were retained, and the traffic volumes were 432, 864, and 1,728 loads/day. The other inputs remained as before.

Figure 18 shows mean serviceability as a function of time, system quality, and traffic volume, indicating that the mean serviceability is more than linearly proportional to traffic volume and proportional to system quality. The degree of nonlinearity in traffic volume depends on the serviceability equation (in this case, the AASHO equation) used.

Figure 19 shows reliability as a function of time, system quality, and traffic volume. Reliability is proportional to the system quality and is a complicated function of traffic volume.

Figure 20 shows life expectancy as a function of system quality and traffic volume. There is a more than linear proportionality to system quality and an inverse proportionality to traffic volumes.

Traffic speed variations showed very little effect because of the relative constancy of the creep functions used in this time range and at the reference temperature. However, it is known from the structure of the model that the load duration influences performance measures similarly to the way environmental temperature does.

SUMMARY AND CONCLUSIONS

The basic framework and its associated models offer a very useful capability for analysis and design of highway pavements. The limited sensitivity analysis conducted so far shows some of the potentials and capabilities of the model and reveals some of the improvements necessary for full implementation of the models as a design tool.

The structural model satisfactorily accounts for the infinitesimal strains and deflections and is therefore most useful in predicting the onset of failure, although it becomes rather inaccurate as failure progresses and the system undergoes major distortions

Figure 18. Serviceability as a function of system quality and time for (a) light, (b) medium, and (c) heavy traffic volume.

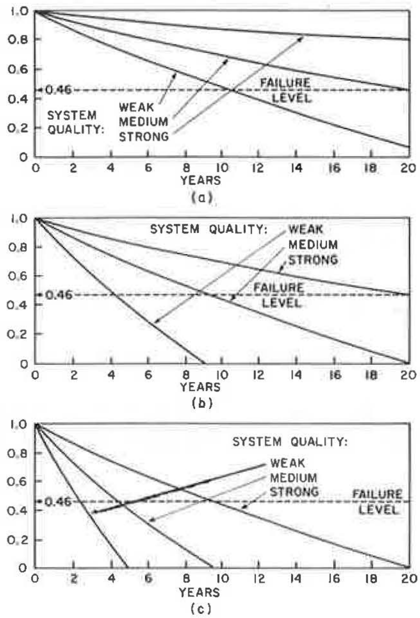


Figure 19. Reliability as a function of system quality and time for (a) light, (b) medium, and (c) heavy traffic volume.

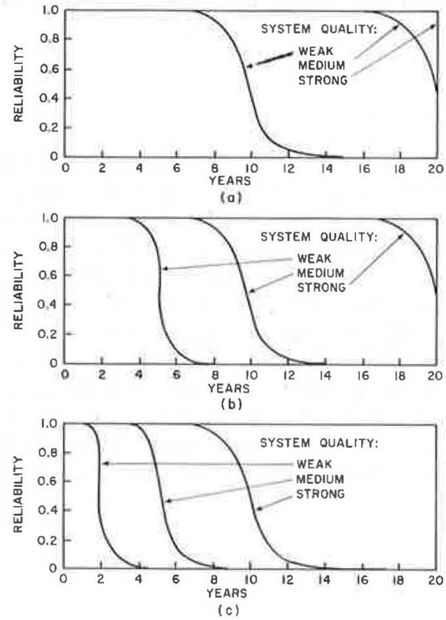
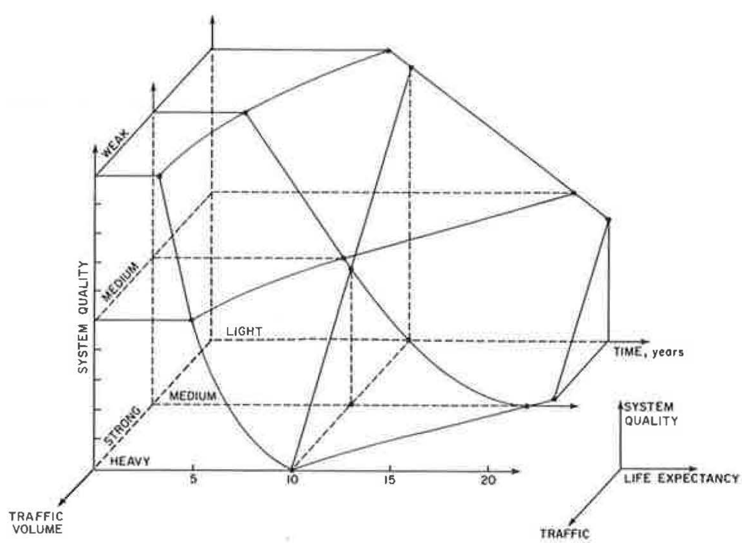


Figure 20. Life expectancy as a function of system quality and traffic volume (given medium traffic speed).



that invalidate the basic assumptions underlying the development of the models. Based on these limitations, the models may be used to compare various design alternatives. The effect of geometry, load area and intensity, random interarrival times of vehicles, statistical variations in the materials properties, and temperature histories can be accounted for by the models.

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