RELIABILITY OF HIGHWAY PAVEMENTS

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In a context of systematic analysis of highway pavement systems, the concept of reliability as a design quantity is presented. Reliability is a measure of the probability that a pavement will provide satisfactory service to the user throughout its design service life. The prediction of reliability and its use in providing economically efficient pavements requires consideration of all aspects of service life. A mathematical statement of reliability is discussed for its meaning to pavement design and management, and some methods of application are suggested to demonstrate reliability computation as an operable and useful technique. In particular, Monte Carlo simulation and Markov models are used as examples of useful methods to be applied.

•A PROPERLY designed highway pavement should exhibit satisfactory performance throughout its design service life. Satisfactory performance is defined by the requirements of the transportation system of which the pavement is a part and must be achieved subject to constraints on scarce resources.

In its simplest and, historically speaking, its earliest form, performance was understood primarily as a pavement's ability to support a particular load without showing excessive deflection or cracking. Many current design procedures still use this criterion as a basis. More recently, however, work such as that done by AASHO (1) and the Canadian Good Roads Association (2) has recognized that riding qualities and users' comfort and safety are important in performance evaluation.

Performance may be expressed in terms of 3 principal measures (3) of effectiveness: serviceability, reliability, and maintainability. Serviceability is a measure of the degree to which the pavement provides satisfactory service to the user. Here the term "user" is understood to include not only the direct highway user but also the broad range of recipients of transport benefits. Reliability is a measure of the probability that serviceability will be at an adequate level throughout the design service life. The future behavior of an engineering system is essentially uncertain. Maintainability is a measure of the degree to which effort may be required during the service life to keep serviceability at a satisfactory level. There are 2 aspects of maintenance: normal maintenance, including the regularly scheduled actions directed toward prevention of failure, and repair maintenance, including the actions required to restore adequate serviceability given that a serious loss has occurred or may soon do so.

Reliability is important in the pavement system because of the uncertainty involved in all aspects of the pavement process: planning, design, construction, operation, and maintenance. Uncertainty arises from lack of information and inability to predict the future. It is embodied in the assumptions that must be made to derive analytical models, the limited amount of data available from tests, and the variable quality of the real-world environment (Fig. 1). An unusually heavy rainstorm or a poorly mixed batch of concrete can upset all of the careful planning that went into a pavement.

Traditionally, the uncertainty of prediction of the future behavior of constructed facilities is accounted for by including safety factors in designs. The effectiveness of these safety factors varies with the degree of variation of the parameters they modify.

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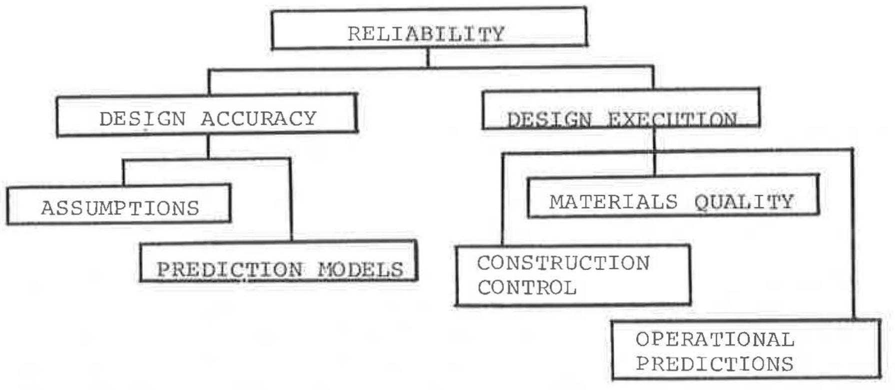


Figure 1. Components of reliability.

The use of higher safety factors when one is less certain (or when the consequences of loss are greater) is an implicit recognition of this fact. In many cases, however, there can be substantial overdesign and misallocation of resources because of safety factors too large for the actual uncertainties involved.

For example, if one is designing concrete and uses a safety factor of 1.2 to obtain 1,000 psi strength (i.e., design a mix with 1,200 psi mean strength), the assumption of a normal distribution of strength will indicate a 5 percent chance that strength will be below 1,000 psi if the coefficient of variation is 10 percent. If the coefficient of variation is 20 percent, the chance of strength being less than 1,000 psi is roughly 20 percent; whereas if the coefficient of variation is only 5 percent, the chances fall to less than 1 percent.

Obviously then, factors that affect the degree of variation in system parameters have a significant effect on reliability. Quality control in construction is a notable case in point. Beyond construction, there are uncertainties of operation and maintenance that are rather removed from the designer's consideration.

Very little attempt is generally made to evaluate and account for the uncertainties of service behavior. More important is the failure to recognize that these uncertainties are of serious consequences for future resources needs. Premature failure may cause the allowances for future service growth to be inadequate.

It would seem logical that adequate performance could best be provided by consideration of the pavement's characteristics throughout its design life. Both the trends of serviceability, as is currently the case, and the pavement's reliability must be predicted. A level of maintainability may be set such that satisfactory service is provided with a high degree of reliability and in an economically efficient manner.

This paper will discuss reliability as a design parameter and will show through an example how this parameter may be used to evaluate the uncertainties in pavement systems. A framework for analysis will first be presented, and techniques for implementing analysis within the framework will be described. The analysis will then be applied to a hypothetical pavement-decision problem to show how reliability considerations will interact with those of economics to influence decision-making.

Reliability Measurement

Reliability is the probability of success or, rather, the probability that the pavement will resist the loads applied to it throughout its design life. To evaluate the pavement's reliability, one must be aware of what the system's possible modes of failure are and, to some extent, how they occur. In general, for each failure mode i, there will be an environmental load D_i placed on the pavement and a capacity R_i of the pavement to resist that load. The loads D_i are determined by a set of environmental qualities (e_1, e_2, ..., e_L). The pavement's response is determined by a set of system characteristics

$(c_1, c_2, \ldots, c_M)$. Then, if there are N possible failure modes, failure is the condition in which one or more of the following inequalities is not satisfied:

$$\begin{aligned} D_1(e_1, e_2, \ldots, e_L) &\le R_1(c_1, c_2, \ldots, c_M) \\ D_2(e_1, \ldots, e_L) &\le R_2(c_1, \ldots, c_M) \\ &\vdots \\ D_N(e_1, \ldots, e_L) &\le R_N(c_1, \ldots, c_M) \end{aligned}$$

That is, if the demand on the system exceeds the ability of the system to resist that mode of failure, such failure will occur.

For example, a highway pavement might fail through loss of safety or through substantial structural failure (loss of structural integrity). Loss of safety would perhaps be described in terms of skid resistance through statistical correlations with observed accidents. Structural failure might mean loss of subgrade support. There would then be 2 failure modes. The pertinent environmental qualities, e_L, might include a number of loadings, temperature, and vehicle speeds. System capabilities, c_M, would include material strengths, subgrade modulus, and surface-course aggregate qualities.

For each failure mode, a model—theoretical or empirical or some combination thereof—is needed to determine how this failure would occur, i.e., how the pavement behaves under load. Theories of stress distribution in pavement systems are examples of such models for deformation, as are the equations produced by the AASHO Road Test for subjective evaluations of ride. That is, these models give a functional relationship between service loads and a parameter that is important to service quality, which is in these cases service deflection or riding quality. It is then possible to describe failure in terms of some maximum or minimum acceptable value of the parameter, which in turn defines the service load that is most likely to result in that value.

The application of these models (which may be uncertain) to data on the system environment characteristics that are probabilistic (and which are uncertain) permit the calculation of the reliability R, which is the probability that all of the previous inequalities are true. Thus, $R = P$ (no failure) $= P(D_i \le R_i)$, where $i = 1, \ldots, N$.

A major task is then to analyze the probabilities that individual failure modes will occur and then to combine these failure modes to compute reliability. It is difficult to attain the initial estimates of failure probabilities because of the complexity of the physical processes involved. It is often impossible to arrive at closed-form mathematical statements of the probabilities involved, and so simulation methods become the only feasible approach.

In simulation techniques (particularly the Monte Carlo method), input data are supplied in probabilistic form. These data often consist of statistical information gathered by experimentation. The computerized description of the behavior model is used to compute many samples to build up a statistical description of output. For example, if the model of interest is the standard elastic stress-strain relationship $\epsilon = \sigma/E'$ where E is an experimentally measured random variable, the probability distribution of E is sampled many times, and a corresponding value of ϵ is computed for each (with constant σ). This procedure gives an estimation of the probability distribution of ϵ as a function of E. In complex situations, this simulation method is the only way of obtaining this probabilistic estimate of output.

TIME EFFECTS AND SERVICE LIFE

Reliability will generally be a time-dependent parameter; an obvious example is the failure of a material through fatigue. The events that lead up to the occurrence of a failure are distributed over a period of time. It is often possible to observe certain facility features that imply a deteriorating quality. For example, fine cracks in a rigid pavement may cause no loss in riding quality, but they do warn that water will have access to base materials. That is, pumping and loss of subgrade support are strong possibilities in the near future.

Realistically, then, reliability will be computed by using stochastic models of a facility's service behavior. Stochastic models are generally time-dependent probabilistic representations of physical processes. A facility may be viewed as having a number of possible serviceability states or conditions that it may occupy. Age, use, and renovation are then represented as transitions between states. The previously described models of how failure modes occur are useful for computing the probabilities of particular interstate transitions (Fig. 2).

One particular type of stochastic model that shows promise for use in analyzing pavement behavior is the Markov process. The special feature of the Markov process is that the future state of the process is dependent only on the current state. That is, predictions of the probability that the process will be in any particular state at some future time may be based on observation of the current state. The model has no memory of its past history. If $\rho(n)$ is the probability vector describing the probabilities that the process is in any one of the several possible states at time n, and if $\underset{\sim}{P}$ is the matrix of 1-step transition probabilities, then

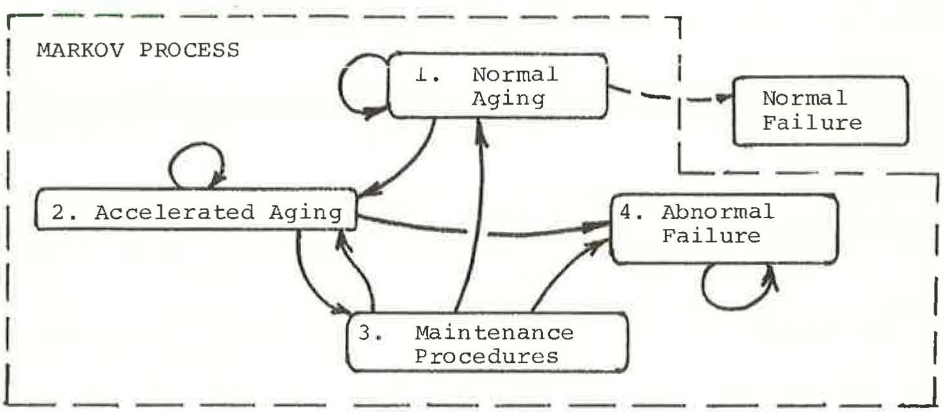
$$\rho(n + 1) = \rho(n)\underset{\sim}{P}$$

Because of the lack of memory, it may be shown through regressive application of this formula that

$$\rho(n) = \rho_0 P^n$$

where ρ_0 is the initial state probability vector. These simple statements describe a Markov process.

For the simple Markov process, the $\underset{\sim}{P}$ matrix is constant. A continuous time process is produced when time-varying functions are introduced into the matrix elements. This modification is often a more accurate, but usually a more difficult to compute, representation of physical behavior.



Transition Matrix

$$\begin{bmatrix} p_{11} & p_{12} & 0 & 0 \\ 0 & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & 0 & p_{34} \\ 0 & 0 & 0 & p_{44} \end{bmatrix}$$

Figure 2. Use of Markov process to analyze changes during pavement service life.

One difficulty is the lack of memory in a simple Markov process. Future predictions depend only on the present. An appropriate counter example in the field of pavements is the memory effect in viscoelastic materials. This feature must be kept in mind when such a model is used.

In spite of this difficulty, there are 2 primary justifications for using a Markov process to analyze pavement reliability and service life behavior. First, for the periods of time considered by the analyst for planning and design, the Markov process may provide reasonable models of pavement behavior. That is, any memory the facility might have of how it reached its present state will often have faded by the time a measurably new state is predicted. Second, in a context of statistical decision theory, a Markov process may serve as a first estimate that is to be modified as more data become available. With this point of view, the Markov model may serve to test initial operation and maintenance policies and check how they interact with design.

To use a Markov model, one must first describe the service behavior of the facility in terms of states and possibly interstate transitions, then estimate the values of probabilities in the P matrix, and with this information present the entire process in the transition matrix (Fig. 2).

APPLICATIONS

The applicability of reliability analysis and of Monte Carlo and Markov simulation models in this analysis may best be illustrated by an example. For this example, a pavement for a low-volume highway is considered. Two pavement sections were designed for the expected traffic and are shown in Figure 3. The asphalt and concrete

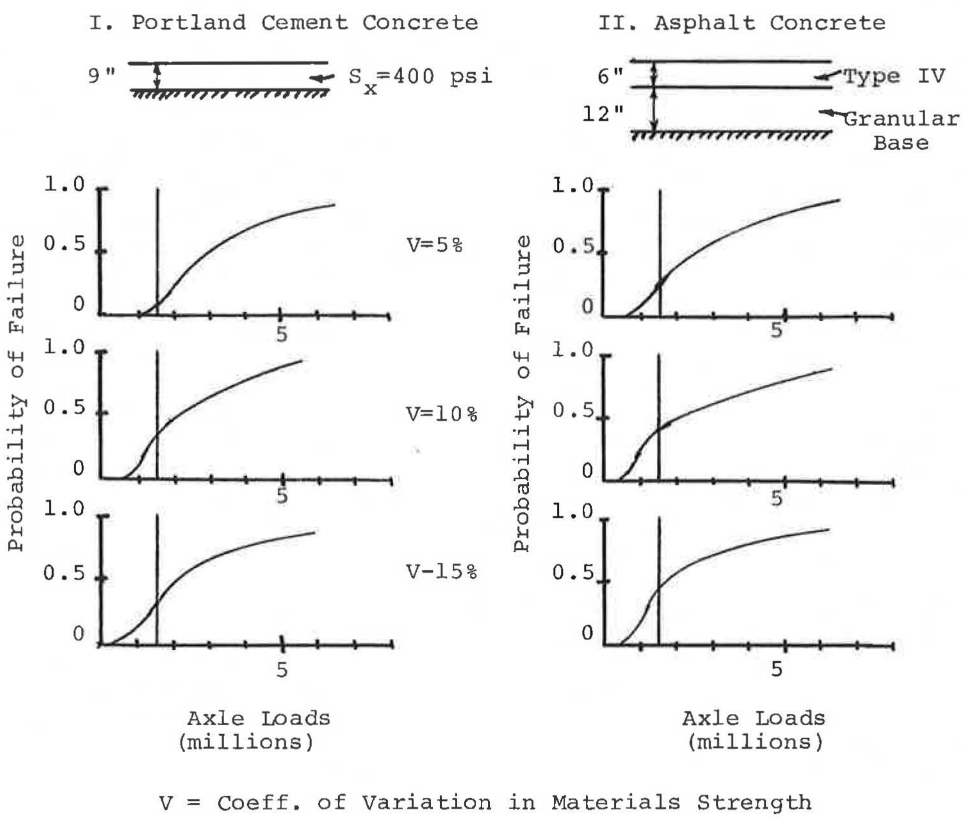


Figure 3. Design alternatives: initial daily traffic, 200 VPD (equivalent 18-kip loads); traffic growth rate, 4 percent per year; design life, 15 years; soil (subgrade) - CBR = 3, k = 100 pci.

sections were designed according to The Asphalt Institute (4) and extended AASHO (5) formulas respectively. Soil conditions and traffic predictions (in this case, total number of loads) were taken as external constraints not subject to change.

It has been suggested (3) that serviceability for highway pavement is measured by 3 components—rideability, safety, and structural integrity. Rideability applies to the quality of ride experienced by people and goods traveling the road and is analogous to the original AASHO serviceability concept. Safety applies to the likelihood of accidents and is related to skidding and to road hazards. Structural integrity describes gross load-bearing characteristics of the pavement.

Failure could then occur through loss of any one or more of these qualities. That is, the pavement could become rough and bumpy, causing the user dissatisfaction with riding qualities; the pavement could become slippery or develop large potholes; or, finally, large-scale subsidence or large deformations under a heavy vehicle might occur.

The statement of failure modes for reliability computation would then have 3 basic inequalities. Failure in the first of these, which is adequate rideability, is assumed to be due solely to the cumulative effects of axle-load repetitions and is the basis for the designs shown in Figure 3. This mode will be referred to as normal failure because, according to the design assumptions, this mode is the only one that may occur.

The distribution of probability of normal failure as a function of axle load repetitions was found for each of the pavements and for a variety of assumptions regarding construction quality control by using Monte Carlo simulation of the design equations. Where the initial designs were developed by using fixed expected values of the pertinent parameters such as strength, these parameters were now input as probability distributions. Quality control was characterized by the coefficients of variation of the materials strength parameters. Examples of distributions so derived are shown in Figure 3.

It is interesting to note that decreased construction control may lead to higher mean values of loads to failure. This is because the looser control leads to more spread in the strength distributions, which leads in turn to higher probabilities of very high values of strength as well as low values of strength. Thus, the mean value of the computed factor may rise, but the overall distribution spreads out considerably and reliability falls. In the analysis, losses of safety and of structural integrity are considered, in this case, to be abnormal failures. Because something may happen during the life of the pavement to cause such failures, they must be considered in analysis. Based on such considerations, the service life of the pavement in this example might be partially modeled by a 4-state Markov process. This model is partial because it is linked with a normal failure model for rideability losses (Fig. 2).

Four states will be used in the Markov model. Normal aging (1) is the condition that leads to normal failure. Load applications cause slow and steady deterioration of rideability. Accelerated aging (2) is a state caused, for example, by the initiation of cracking or surface polishing. Such conditions will represent accelerated losses of serviceability because they could precede losses of structural integrity or safety respectively. Maintenance procedures (3) will be initiated when the accelerated aging conditions are detected and can be successful by returning the pavement to normal aging. Abnormal failure (4) will eventually occur if maintenance efforts fail or are never undertaken. Design decisions determine the probabilities of aging and maintenance activities.

The probability matrices for the Markov process must now be formulated. That is, transition probabilities must be assigned to the arrows shown in Figure 3. Table 1 gives several alternative plans that might be considered. It should be noted that terms such as "high maintenance" in the plan descriptions signify greater maintenance activity and, thus, higher probability of going from the accelerated aging state to the maintenance state.

The probabilities are postulated for 6-month computation periods. That is, each probability refers to the state in which the process might be in 6 months, given knowledge of the present state. The normal failure distributions refer to a 15-year design life, so probabilities in the Markov "subprocess" must be computed for 30 transitions. The reliability values given in Table 2 were computed as the probability that neither normal nor abnormal failure states occur in the 15-year design service life.

TABLE 1

OPERATING AND MAINTENANCE POLICIES AS A MARKOV SUBMODEL

Policy No.	Policy Description	P-Matrix
I	Standard operating policies	$P_I = \begin{pmatrix} 0.95 & 0.05 & 0 & 0 \\ 0 & 0.40 & 0.20 & 0.40 \\ 0.60 & 0.30 & 0 & 0.10 \\ 0 & 0 & 0 & 1 \end{pmatrix}$
II	High maintenance activity, standard quality	$P_{II} = \begin{pmatrix} 0.95 & 0.05 & 0 & 0 \\ 0 & 0.40 & 0.50 & 0.10 \\ 0.60 & 0.30 & 0 & 0.10 \\ 0 & 0 & 0 & 1 \end{pmatrix}$
III	Standard maintenance activity, high quality	$P_{III} = \begin{pmatrix} 0.95 & 0.05 & 0 & 0 \\ 0 & 0.40 & 0.20 & 0.40 \\ 0.80 & 0.10 & 0 & 0.10 \\ 0 & 0 & 0 & 1 \end{pmatrix}$
IV	High maintenance activity, high quality	$P_{IV} = \begin{pmatrix} 0.95 & 0.05 & 0 & 0 \\ 0 & 0.40 & 0.50 & 0.10 \\ 0.80 & 0.10 & 0 & 0.10 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

The reliability calculations give the probabilities of no failure in a 15-year design period. It should be pointed out that the differences in reliability between concrete and asphalt pavements are due more to the form of the equations used than to any other factor. Fewer variables in the equation lead to greater effect of variations in each variable on the final result. Hence, quantitative measurements are most valid within a single design type. Only relative evaluations may be made between different designs.

An alternative type of information one might want would be a description of possible failure age. Because the failure depends on traffic volume, failure age will depend on the growth rate of traffic. Figure 4 shows these data for the concrete pavement and standard operating conditions. Data such as these would be useful in the planning stage for making construction staging and financing decisions. An attempt could be made to choose an optimal design life, based on possible traffic growth and costs of service.

The standard way these results would be used is with respect to cost data. A balance between cost and reliability would be struck to achieve a good design. For example, similar results in this case, not of similar magnitude but of improved reliability, are obtained for the concrete pavement by improving maintenance with constant quality control or by improving quality control with constant maintenance activity. The former alternative would require higher initial outlay of funds, whereas the latter would represent deferred outlays. In terms of net costs and timing, it is likely that one of these 2 alternatives would be preferred, given that the increased reliability is desirable.

By taking another point of view, one might decide that the greater expected lifetime of a concrete pavement with reliability equal to that of a comparable asphalt pavement might justify an increased construction cost. On the other hand, lower expected

TABLE 2

RELIABILITY VALUES

Design Type	Construction Quality (percent)	Operating Policy	Reliability
Asphalt	15	I	0.24
		II	0.46
		III	0.25
		IV	0.48
	10	I	0.25
		II	0.48
		III	0.26
		IV	0.50
	5	I	0.30
		II	0.57
		III	0.31
		IV	0.60
Concrete	15	I	0.31
		II	0.61
		III	0.33
		IV	0.64
	10	I	0.34
		II	0.66
		III	0.36
		IV	0.70
	5	I	0.35
		II	0.67
		III	0.37
		IV	0.71

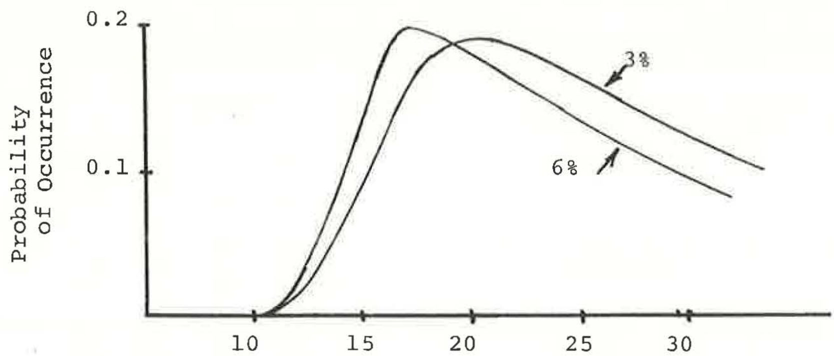


Figure 4. Distribution of failure age as a function of traffic growth rate.

life might be preferred as a means of obtaining flexibility in an urban system.

SUMMARY AND CONCLUSIONS

The previous discussion illustrates how the concept of reliability may be used in pavement analysis and decision to account for uncertainty. It is felt that the traditional use of safety factors is inadequate on 2 counts. First, the safety factor has no clear relation to the true uncertainty in the system. The use, for example, of a single standard load factor on all Interstate roads makes no allowance for the fact that traffic growth patterns could differ substantially with patterns of regional economical development. Second, safety factors that represent overdesign are wasteful of economic resources and can be a cause of loss to society just as premature failure would be.

The use of reliability is a practical means of overcoming these 2 inadequacies. Techniques such as Monte Carlo simulation and Markov modeling are suggested to demonstrate how one might implement reliability analysis. In a context of systematic analysis of highway pavements, reliability is an important factor.

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