n9.95

The Analysis of Highway Pavement Systems

A. C. LEMER and FRED MOAVENZADEH, Department of Civil Engineering, Massachusetts Institute of Technology

This paper presents a model for describing the performance of an engineered facility from the user's point of view. It is suggested that performance may be described in terms of serviceability, reliability, and maintainability. Serviceability is the quality of providing satisfactory service to the user and is evaluated through applications of utility theory. Reliability is the probability that adequate serviceability will be maintained throughout the facility's design life; it may be predicted by use of a semi-Markov process approach. Maintainability is a measure of the effort required during a facility's service life to maintain adequate serviceability. Methods for analysis are suggested and applied to existing data to show how the model may be used in practice to yield engineered facilities having good performance characteristics. The model and its use are viewed in a perspective of the goals of the larger system of which the engineered facility is a part.

•IN PROVIDING a pavement—a riding surface—the engineer is attempting to give a service to the user of a transportation facility. In effect, the real problem the engineer must face is not the design and construction of a physical, structural unit, but rather the satisfaction of the user.

The pavement—in fact, the whole highway system—may be evaluated in terms of three principal parameters: serviceability, reliability, and maintainability. Serviceability is the quality of providing satisfactory service to the user (1). Serviceability is not just a matter of transportation but of transportation in such a fashion as to fulfill the user's needs. Reliability is the probability that serviceability will be maintained at adequate levels, from a user's point of view, throughout the design life of the facility (2). This concept is suggested in recognition of the uncertainty inherent in the systems with which the engineer deals. Maintainability is a measure of the effort required to maintain adequate serviceability throughout the design life. Two types of maintenance effort must be considered: normal maintenance is that regular, day-to-day action planned to keep operation smooth; repair maintenance is an action required to correct a potential or actual loss of serviceability.

This paper attempts to show how these parameters may be evaluated and used by the engineer to provide a facility that will exhibit qualities of satisfactory performance throughout its design life. The framework suggested here is intended to assist the engineer to provide such facilities in a most economical fashion.

SERVICEABILITY

The application of the serviceability concept may be based on utility theory as it is being developed and used in economics and psychophysics. Utility is a general term for the intrinsic value that a person attaches to some stimulus. In the present context, a user would experience the ride over one pavement section as more or less comfortable than that over another section. The relative comfort felt may then be scaled as utility against some objective measure of pavement roughness—for example, a roughometer reading.

Paper sponsored by Committee on Theory of Pavement Design and presented at the 49th Annual Meeting.

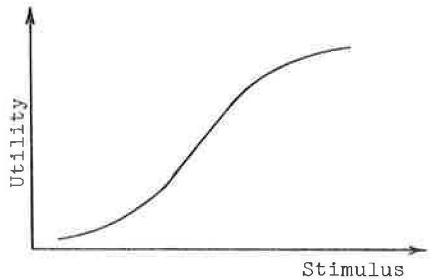


Figure 1. A uni-dimensional utility function.

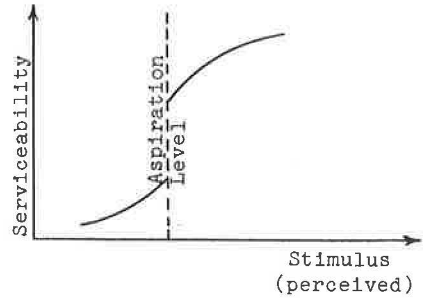


Figure 2. A component of serviceability.

By direct or indirect questioning, one attempts to build up a picture of what the user's utility function is with respect to a stimulus (3). For example, the question might be posed, "How much money would you have to receive in order to make you twice as happy as receiving $10? How much would make you half as happy?" And so on. The utility scale is thus built up on a relative basis.

Figure 1 shows a typical utility function (4). Over a sufficiently broad range of stimulus, this typical s-shaped curve exhibits areas of relative indifference at either end of the stimulus scale and a central portion of maximum sensitivity. For example, consider the changes in user's utility derived from highway lane width. Narrow lanes have a value to the user approaching zero as the lane becomes too narrow for vehicle passage. In the range of typical lane widths, there is a rapid rise in utility up to, say, the size of current Interstate standards. Additional utility derived is small as lanes become oversized—there is more room than the user can appreciate. It is of interest to note that a decrease in overall serviceability may occur as lanes become so wide that safety is affected because weaving by drivers is encouraged.

For the typical engineering facility there will be several scales of utility that will be pertinent to the satisfaction of the user. For example, in the AASHO Road Test it was acknowledged that features such as grade, alignment, slipperiness, and glare enter into the consideration of how satisfactory a pavement is. But it is found that it is difficult, if not impossible, for the user to judge several dissimilar qualities at once (5), so it is necessary to deal with these qualities separately. In the case of the AASHO Road Test, all aspects of the pavement not directly related to the riding quality of the surface were excluded from consideration. In the case of a systematic analysis of the highway, serviceability is evaluated as a multi-dimensional quantity, a composite of several scales of utility.

A serviceability function of this sort—that is, a vectoral quantity—is difficult to use for comparisons of alternative actions. There are no satisfactory multi-dimensional optimization techniques, and it is somewhat out of the engineer's field of responsibility to make trade-off decisions among the various qualities the user might prefer. The establishment of the aspiration level (6) as a minimum acceptable level of performance, however, may provide the engineer with a measure with which to work. The aspiration level is described as that level of achievement (or performance, in this case) which the user expects, and which he considers reasonable. This level will be based on the user's perception of what is technologically possible and appropriate.

It has been suggested that the idea of an aspiration level may be used to set engineering requirements (4). As shown in Figure 2, part of the region of rapidly rising utility is eliminated from the curve. Specifically, the straight-line portion of the curve having maximum slope is cut, based on psychological considerations involved (6). This action associates a larger loss of serviceability with a small drop in performance at the aspiration level. Thus an effective failure criterion is established at the aspiration level, while optimization above this failure level is still practical.

RELIABILITY

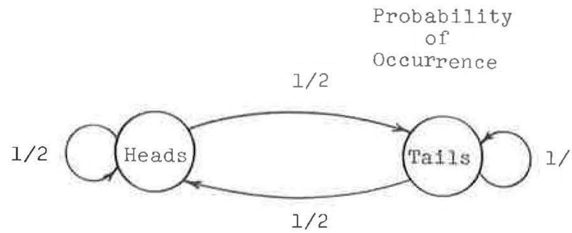


Figure 3. Coin tossing as a Markov process.

In order to say whether a facility is satisfactory or not it is necessary to predict the behavior of the facility, in terms of levels of serviceability, for the duration of its design life. But this prediction can be made only in uncertain terms; reliability is a measure of the degree of this uncertainty. It is suggested that the lifetime behavior of a facility may be approximated by a Markov process. Such an approximation allows the engineer to predict serviceability with a particular degree of reliability throughout the design life.

The behavior of a facility may be represented as a set of states and interstate transition probabilities. The states—in the present context, levels of serviceability—are descriptions of possible conditions of the system being modeled. For example, in flipping a coin, the two states would be "heads" and "tails." The transition probabilities tell the chances that the system, given that it is in a known state now, will occupy a certain state at the next observation. This basic assumption of the Markov process is that the probability that the system will be in any state after a trial is dependent only on the state that is occupied immediately preceding that trial. Figure 3 shows a pictorial representation of such a process for the tossing of a coin.

A variation of the Markov process allows one to describe time spent in a given state at any trial—that is, the time before an interstate transition is made—as a probabilistic variable. With this semi-Markov process, one can approximate the aging behavior of a facility. If the states are thought of as the levels of serviceability that the facility may occupy, this process will allow prediction of the service life history in a probabilistic manner. One then has the reliability of the facility, with respect to some serviceability level, as a function of time. This is the time-dependent probability that the facility will be in a certain state.

MAINTAINABILITY

In describing a facility's behavior as a semi-Markov process, some of the interstate transitions may represent maintenance and repair operations. Normal maintenance will have an influence on the distribution of time before a decrease in serviceability occurs. Repair maintenance is the way in which transitions from one state to another of higher serviceability may occur. The expected time during which the facility will occupy a state that represents failure, relative to the total design life, is a measure of maintainability.

Figure 4 shows two possible expected life histories for two similar facilities. It is expected that one will experience a greater number of failures than the other, but a failure in the second case will take much longer to repair than the multiple failures of the first. The second facility would have a lower maintainability. That this time lost—and hence the maintainability—is directly related to user cost and comfort may be realized by considering the case of a bridge that must carry heavy traffic. The execution of a difficult maintenance action may require the closure of a lane, resulting at least in the slowing of traffic flow and losses of time

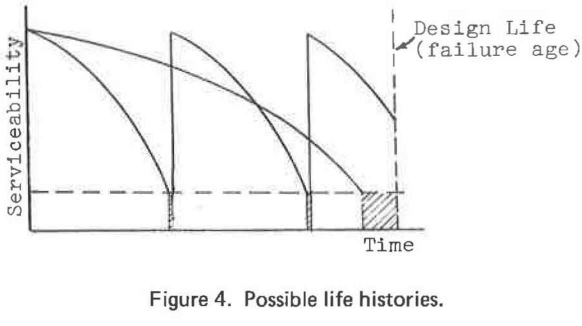


Figure 4. Possible life histories.

to the commuter or, quite likely, the disruption of traffic patterns within a sizable radius of the bridge.

It should be noted that in both cases it is possible for the facility to give adequate service throughout its design life, with no failures. Life history is probabilistically predicted. This point admits the possibility that one may learn by experience, changing planned normal maintenance and operating policies to suit the exhibited performance of the facility. The most efficient selection and adjustment of such policies is essentially a problem in statistical decision theory and is beyond the scope of this paper.

AN EXAMPLE OF APPLICATION

The foregoing discussion has been directed toward describing what is basically a systems analytic approach to engineered facilities. A brief example should help to illuminate the way in which these ideas fit together. What follows is rough, intended only to present in outline of how the engineer might proceed to use this approach.

It has been suggested that a satisfactory highway pavement will be one which is rideable, safe, and possesses structural integrity (2). This goal statement gives three components of serviceability for the highway pavement; the first step is to develop the functions for evaluating these components.

Rideability is the most apparent quality for the immediate user of the road, and the most complex. A variety of evaluation schemes have been suggested, ranging from purely subjective (8) to very objective (9). For this example the AASHO Road Test is a useful source of information. The AASHO definition of serviceability is essentially what is meant here by rideability (10). Figure 5a shows a plot of the percentage of people finding a pavement to be acceptable vs. a subjective scale of rideability. This function may be interpreted as a mean value utility function for rideability. It would be more correct to show the variations among individuals and to say that there is a certain probability that a given percentage of people will find a pavement of given rideability satisfactory. Figure 5b shows how this function may be transformed (4) for use in an engineering context. The aspiration level is defined and the curve adjusted. The serviceability scale is derived by a geometric (and in this case quite direct) transformation of the utility scale.

In trying to predict pavement safety, one faces a wide assortment of studies and conclusions as to what is important and how pavement affects accidents and vehicle driver characteristics. It is beyond the scope of this example to try to formulate a coherent definition of when and why a pavement is safe. For purposes of illustration it will be assumed that skid resistance, as affected by pavement roughness, is of primary importance because of its influence on accidents.

It has been suggested that characteristics of the microscopic roughness of the pavement surface may be related to the coefficient of friction (11), which in turn may be related to the occurrence of accidents (12). With this rationale, approximations may

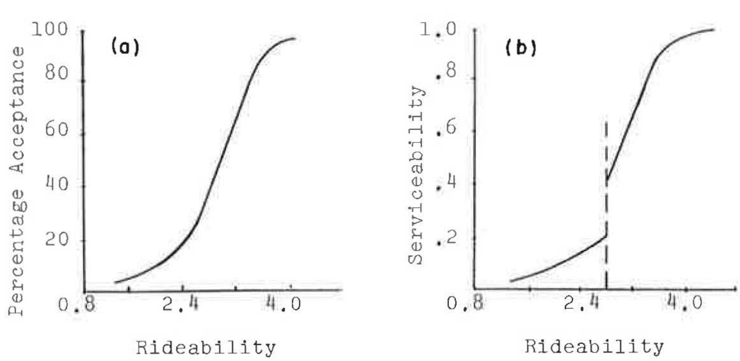


Figure 5. Rideability component of serviceability.

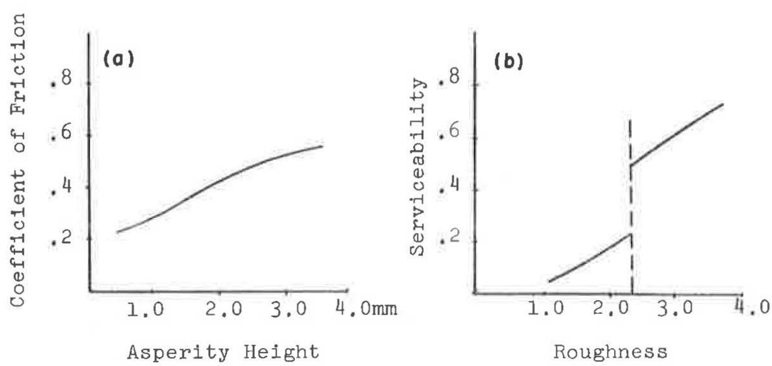


Figure 6. Safety component of serviceability.

be made to give Figure 6. Relative safety is meant to relate to skidding resistance at a given speed and to accident frequency; the roughness scale is related to asperity height. Figure 6b gives the converted serviceability function.

Structural integrity is the classical problem of the engineer. Does the structure resist the loads to which it is subjected? The safety factor with respect to loads is an adequate prediction of this component of serviceability. Figure 7 shows this function. When the ratio of applied load to structural capacity rises above unity—a factor of safety with respect to load of less than unity—a structural failure may be expected. Such a failure will represent a complete loss of structural integrity and a decline of serviceability effectively to zero. As long as the system can resist the loads applied, full serviceability with respect to structural integrity would be retained. In cases where a partial loss of serviceability is possible—for example, some plastic yielding without complete structural collapse—this serviceability function would not be such a severe single step.

The specification of the multi-dimensional serviceability function in such a way as to allow comparisons of alternative actions is another difficult problem that cannot be adequately treated here. For the purposes of this example, the product of the three scales can represent gross serviceability. Failure occurs when this gross serviceability falls to an unacceptably low level.

Having set up serviceability measures, one next uses these measures as a basis for describing the service behavior of a facility. In a detailed study, the various physical conditions and processes leading to losses of serviceability might be represented in the Markov process. For this example, however, the representation has been simplified to include only discrete steps in rideability, without regard to cause. Figure 8 shows a state transition diagram for pavement aging. Dashed lines indicate maintenance actions. Numbers for the states are taken from Figures 5, 6, and 7.

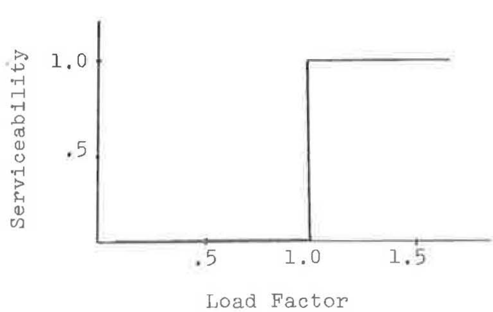
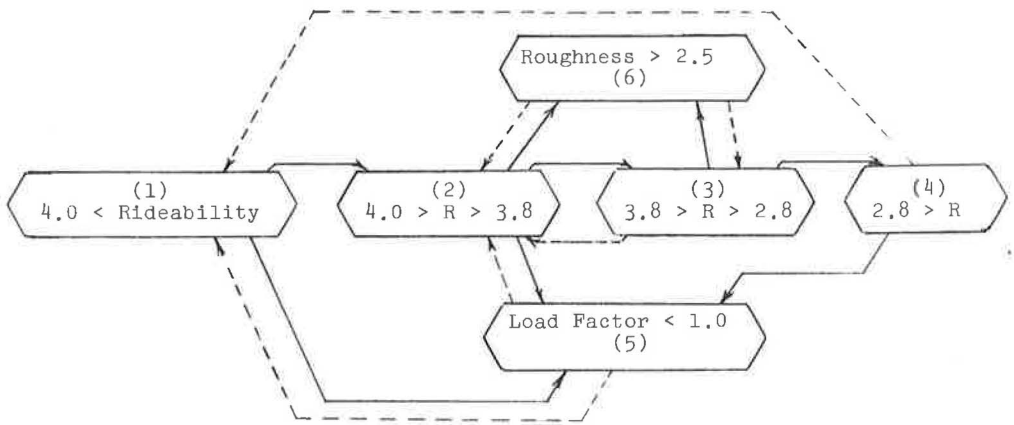


Figure 7. Structural integrity component of serviceability.

Some additional simplification concerning transition probabilities will be used here to ease computation. It was stated earlier that interstate transitions are in general stated as time-dependent-probability functions. Work is currently under way to develop such functions from theoretical and statistical analysis of data such as laboratory tests and those gathered in the AASHO



States

Ageing

Maintenance Transitions

The Transition Matrix

$$\begin{bmatrix} 0 & .95 & 0 & 0 & .05 & 0 \\ 0 & 0 & .90 & 0 & .05 & .05 \\ 0 & .40 & 0 & .45 & .10 & .05 \\ .10 & 0 & .65 & 0 & .25 & 0 \\ .25 & .75 & 0 & 0 & 0 & 0 \\ 0 & .50 & .50 & 0 & 0 & 0 \end{bmatrix}$$

Figure 8. A Markov process for highway pavement.

Road Test. It is expected that these techniques will be described in future papers. For current purposes, it will be assumed that these functions are given. Further, this example deals only with the overall probabilities that a particular transition will occur, given that a transition does occur. That is, it may be assumed that pertinent convolution integrals have been computed for the transition functions, yielding the numerical probabilities shown in Figure 8. Parentheses indicate that a decision regarding maintenance activity has been made for the case shown. The aspiration level is defined and the curve adjusted. Also shown in Figure 8 is the transition matrix for this process. Each entry P_{ij} in this matrix is the probability that the system will be in state j after the next transition, given that it is in state i now. The picture (a flow graph representation) and matrix are equivalent. Implicit in all of the numbers are decisions regarding operating policies, expected traffic, economic design life, etc. What remains after these assumptions is a simple Markov process.

Computations may be made using flow-graph or matrix methods in the transform domain (13). It may be shown that the probability matrix P_{ij} (n), where P_{ij} is the probability that the system will be in state j after n transitions, given that it starts in state i, is given by the inverse transform of

$$P^g(z) = [I - Pz]^{-1}$$

where P is the transition matrix. This expression applies to the current example and uses geometric transforms. Analogous results are obtained using Laplace transforms for the continuous time case.

In this example, probabilities refer to continuous time processes reduced to the facility's design life, as described above. The overall lifetime behavior to be expected of the system is given as the steady-state limit of this process. Expected serviceability, reliability, and a coefficient of maintainability (equal to one over the relative time used in maintenance) may thus be computed. Table 1 summarizes the results of

TABLE 1

SUMMARY OF CASES

Case	Transition Matrix						Evaluation Parameters
Normal	0	0.95	0	0	0.05	0	Expected Serviceability = 0.49
	0	0	0.90	0	0.05	0.05	
	0	0.40	0	0.45	0.10	0.05	Reliability = 0.72
	0.10	0	0.65	0	0.25	0	
	0.25	0.75	0	0	0	0	Coefficient of Maintainability = 3.58
	0	0.50	0.50	0	0	0	
Normal Maintenance-Intensive	0	0.95	0	0	0.05	0	Expected Serviceability = 0.50
	0	0	0.9	0	0.05	0.05	
	0	0.6	0	0.25	0.1	0.05	Reliability = 0.81
	0.1	0	0.8	0	0.1	0	
	0.25	0.75	0	0	0	0	Coefficient of Maintainability = 5.25
	0	0.5	0.5	0	0	0	
Innovation	0	0.95	0	0	0.05	0	Expected Serviceability = 0.34
	0	0	0.9	0	0.05	0.05	
	0	0.5	0	0.3	0.05	0.15	Reliability = 0.45
	0.1	0	0.65	0	0.25	0	
	0.25	0.75	0	0	0	0	Coefficient of Maintainability = 1.82
	0	0.5	0.5	0	0	0	

several design options for the process described. In the maintenance-intensive case, normal maintenance-type transition probabilities are set higher. The "normal" case is as shown in Figure 8. The "innovation" case involves a supposition that some new material of higher initial cost is used that gives this pavement a very low probability of going from a rideability of 3.2-2.8 to the failure state—i.e., improved durability, at the expense of maintenance funds, after initial deterioration, something like work hardening.

It is now up to the engineer to consider the costs involved in the various alternative actions and the benefits derived from varying levels of serviceability—all in terms of the specific goals for the pavement under consideraction—and to arrive at a decision. The decision problem is made very complex by the multitude of non-engineering factors that must be considered. A benefit-cost type of analysis must be undertaken with care (14).

CONCLUSIONS

This paper has attempted to present a framework for the systematic analysis of constructed facilities such as highway pavements. It is expected that this approach will benefit not only the engineer, by helping him to order problems and solutions, but also the user of the engineer's services. With the increasingly wide recognition of a need for a systems approach to engineering problems, it is hoped that the approach described here will be of some modest use in filling an apparent lack of operationally useful suggestions.

ACKNOWLEDGMENT

The work reported herein is being carried out under a grant from the Sloan Fund for Basic Research, under the direction of M. I. T.'s Urban System Laboratory.

REFERENCES

1. Carey, W. N., Jr., and Irick, P. E. The Pavement Serviceability-Performance Concept. HRB Bull. 250, 1960, pp. 40-58.
2. Moavenzadeh, F., and Lemer, A. C. An Integrated Approach to the Design and Analysis of Highway Pavement. Report R68-58, M. I. T. Dept. of Civil Engineering, 1968.
3. Galanter, E. Direct Measurement of Utility and Subjective Probability. Amer. Jour. of Psychology, Vol. 75, 1962, pp. 208-220.
4. Lifson, A. Evaluation Technology. Unpublished notes, U. C. L. A., 1968.

5. Stevens, S. S. Measurement, Psychophysics, and Utility. In Measurement: Definitions and Theories (Churchman and Ratoosh, ed.), Wiley, New York, 1959.
6. Siegel. Level of Aspiration and Decision Making. Psychological Review, Vol. 64, 1957, pp. 253-262.
7. Shepard, R. N. On Subjectively Optimum Selections Among Multi-Attribute Alternatives. In Decision-Making (Edwards and Tversky, ed.), Penguin, Baltimore, 1967.
8. Canadian Good Roads Assn. Pavement Evaluation Studies in Canada. Proc. Internat. Conf. on the Structural Design of Asphalt Pavements, Ann Arbor, 1962.
9. Quinn, B. E., and Wilson, C. C. Can Dynamic Tire Forces Be Used as a Criterion of Pavement Condition? Report 32, JHRP, Purdue Univ., 1963.
10. The AASHO Road Test: Report 5—Pavement Research. HRB Spec. Rept. 61E, 1962.
11. Colley, B. E., Christensen, A. P., and Nowlen, W. J. Factors Affecting Skid Resistance and Safety of Concrete Pavements. HRB Spec. Rept. 101, 1969, pp. 80-99.
12. Beaton, J. L., Zube, E., and Skog, J. Reduction of Accidents by Pavement Grooving. HRB Spec. Rept. 101, 1969, pp. 110-125.
13. Howard, R. Dynamic Programming and Markov Processes. M. I. T. Press, Cambridge, 1960.
14. Marglin. Criteria for Evaluation of Public Investment. M. I. T. Press, Cambridge, 1968.