SERVICEABILITY PERFORMANCE AND DESIGN CONSIDERATION

W. Ronald Hudson

What is pavement failure? How can pavement failure be defined? How can pavement design be related to quantitative measures of pavement failure? These questions have plagued pavement designers for centuries and are still of concern to us today. Every man involved with pavement design must answer these questions for himself. If a successful, concerted attack is to be made on the problem, however, we must use the same answers or at least compatible answers to these questions.

This problem was illustrated in some detail at the WASHO Road Test, where a panel of experts was involved in establishing a level of failure for the pavement sections being tested. There was a considerable difference of opinion among the experts as to when each section had failed. These problems led Carey and Irick (1) to investigate pavement failure and to define a "pavement serviceability-performance concept" for use at the AASHO Road Test. Acceptance of this concept is not the issue here; rather, our task is to establish a pavement system output function that may be used as the objective function in the systems engineering process for asphalt concrete pavement design.

Previous research has set the stage. The problem has been broken down into logical parts, and papers have been presented at this workshop on material characterization, solutions to boundary value problems, and distress analysis. It is important, however, that we keep in mind the necessity to bridge the gap between these individual effects and the pavement failure.

A crack may be an indicator of the material failure; but it is not the pavement failure. A crack may be undesirable in a pavement (to a certain extent it is not undesirable in continuously reinforced concrete pavements, for example); however, it is not the "failure" of the whole system.

A deflection of 0.25 or 1.0 in. is also not a pavement failure. However, it may be a clue in some cases that the pavement is overloaded and that distress is imminent. Such limiting deflections may have through experience been selected as the design criteria for a particular class of materials in a particular design situation, as in the CBR or other design methods, but these limiting deflections must not be mistaken for pavement failure.

Because the output function is defined in terms of performance and because performance as well as distress mechanisms associated with it have a variety of connotations, a list of definitions is presented to ensure a uniform basis for the ensuing discussion. The definitions are generally based on concepts developed by Carey and Irick (1) for evaluating the performance of the various pavements at the AASHO Road Test and are the same as those used by Hudson et al. (2). It should be noted that inherent in the definitions and the development of the equations for the pavement system is the purpose of the highway facility, which is "to provide a safe, comfortable, and economical method of transporting goods and people."

The following definitions are used in this paper:

1. Performance is a measure of the accumulated service provided by a facility, i.e., the adequacy with which a pavement fulfills its purpose. Performance is often specified by a performance index as suggested by Carey and Irick (1). As such, it is a direct function of the serviceability history of the pavement.
2. Present serviceability is the ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and automobile) traffic in its existing condition.

(The definition applies to the existing condition, i.e., to the condition on the date of rating, and not to the assumed condition the next day or at any future or past date.)

3. Behavior is the reaction or response of a pavement to load, environment, and other inputs. Such response is usually a function of the mechanical state (i.e., stress, strain, or deflection surface properties), which occurs as a primary response to the input.

4. Distress modes are those responses that lead to some form of distress when carried to a limit; e.g., deflection under load is a mechanism that can lead to fracture. Some behavioral responses may not provide distress mechanisms.

5. Distress manifestations are the visible consequences of various distress mechanisms that usually lead to a reduction in serviceability.

6. Fracture is the state of being broken apart or of the member or material being cleft and includes all types of cracking, spalling, and slippage.

7. Distortion is the state of change of the pavement or pavement component from its original shape or condition. Such changes are permanent or semipermanent as opposed to transient, such as deflections.

8. Disintegration is the state of being decomposed or abraded into constitutive elements (i.e., stripping, raveling, or scaling).

With this brief background and these definitions, let us proceed to look at the problem in some detail, keeping in mind that the design of pavements primarily has a functional overtone. At every step of the pavement design or management process, we must keep in mind the function the pavement is to serve.

SERVICEABILITY REVISITED

The primary operating characteristic of a pavement at any particular time is the level of service it provides to the users. In turn, the variation of serviceability with time is some measure of the pavement performance. This performance and the cost and benefit implications are the primary considerations of design and overall management system.

It is important at this point to differentiate between two types of pavement evaluations. They are both important, and neither is designed to replace the other.

A functional evaluation is typified by the serviceability-performance concept and answers the question, How well is the pavement currently serving its function? This is sometimes called a user-oriented evaluation.

A mechanistic evaluation of the pavement is equally important and is associated with determining the pavement's mechanical condition with the purpose of improving future performance; e.g., a mechanistic evaluation is mainly an indicator of action needed to maintain serviceability and, in that sense, may be a precursor to the serviceability evaluation.

Concept of Serviceability

Many words and methods have been used to describe the concepts of performance and serviceability. One of the best known procedures for defining and obtaining serviceability was established at the AASHO Road Test (1). It was based on subjective evaluation by the road user of the riding quality provided by a pavement at a given (the present) time. To develop the method, the researchers performed correlations with physical measurements of the surface characteristics for a large set of test pavements, and the result was termed the present serviceability index (PSI). This PSI has been extensively used, in its original form and in many modified forms, to predict pavement serviceability. The intergration of PSI over time or over the summation of load applications was termed performance.

Although the serviceability-performance concept represented very real progress and is widely used by many agencies, the ensuing years have seen considerable confusion. This has partially resulted from a proliferation of modifications of the basic method and also from a lack of appreciation and understanding of some of the fundamental considerations of pavement failure. It has further stemmed from a seeming lack of appreciation that, whereas PSI is measured on an objective basis, its purpose is to estimate the subjective opinion of the road users.

Among the purposes of this paper are to define the rationale that underlies pavement performance evaluation, to attempt to clarify some of the concepts underlying serviceability measurements, and to define the role of pavement performance evaluation within an overall pavement management system.

Performance as a Pavement System Output

The process of managing pavements consists of a variety of planning, design, construction, operation, and research activities. Attempts have recently been made by a number of investigators (2 through 8) to define part (including design subsystems) or all of this process in terms of a formal systems framework. These efforts have explicitly recognized that one of the major activities involved is that of performance evaluation or feedback.

If we accept the fact that the currently imperfect state of technology in the pavement field requires such performance evaluation, then we must first define what outputs of the system are to be evaluated. Figure 1 shows the gross output of two alternative pavement strategies in terms of their serviceability-age histories (performance) and the associated value implications. (Pavement strategy includes the structural design, the materials used, the construction processes and control adopted, maintenance procedures, seal coats, and resurfacing.) A large number of traffic, materials, climatic, construction, maintenance, and other variables combine to produce any one such performance profile. These variables are all reflected in the overall pavement strategy that is adopted, and the performance achieved depends on this.

The distinction between serviceability and performance is important. Serviceability (Fig. 1) is a measure only of the pavement's ability to serve its function at a particular time (i.e., at the present). The past record or suspected future capacity of the pavement is not considered in a single PSI measure. Performance is the history of these single PSI measures (called serviceability-age history) of the pavement. Age rather than equivalent wheel load carried (EWL) is taken as the primary abscissa in Figure 1 in order that value implications can be taken into account. Furthermore, it is not sufficient to know or predict only the initial

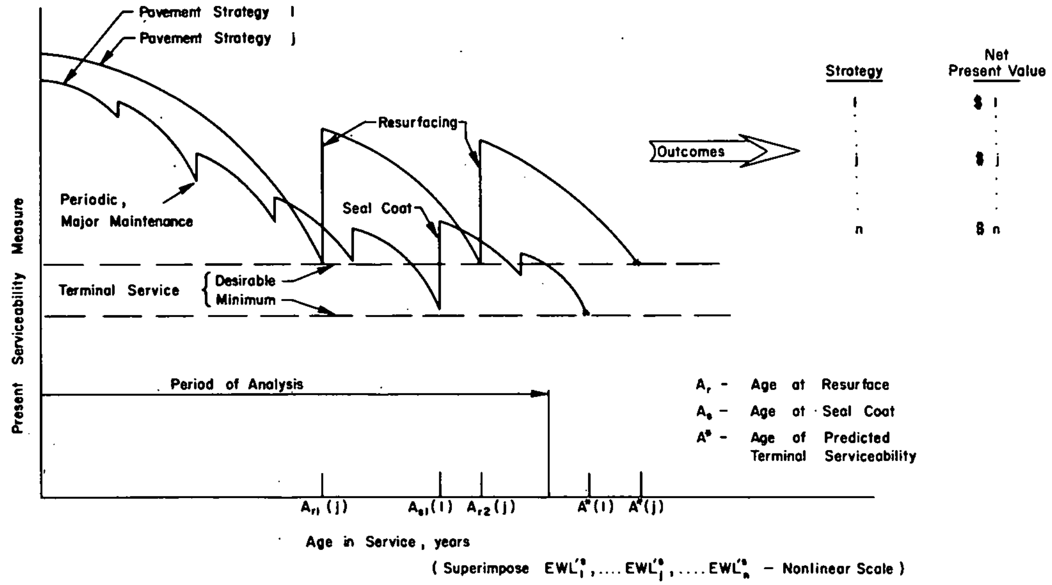


Figure 1. Gross output of a pavement system in terms of performance and value implications.

serviceability or the terminal age. Without knowing the intermediate portion, we cannot adequately check the design strategies, their plans, or programs for maintenance and resurfacing; nor can we explore the implications of raising the terminal serviceability level.

Role of Performance Evaluation in the Pavement Management System

The measurement of the outputs of a pavement system during its time in service, i. e., the evaluation of its performance, has previously been noted as a major management activity. Figure 2 shows the principal elements of this activity as a portion of the overall pavement management system and the information flows that result in a continuous process of feedback. The development and implementation of the performance evaluation subsystem as a portion of the management system or of its components can be a comprehensive and major systems problem within itself. Several aspects of this are subsequently discussed in more detail.

EVALUATING PAVEMENT DISTRESS

Distress is normally evaluated by the two basic approaches: the functional evaluation of the effect of distress on the function of the roadway (i. e., how well it is serving traffic today) and the mechanistic evaluation of distress with an eye toward future performance (i. e., what the current physical condition of the pavement is, what its causes are, and what effect this condition will have on the future performance of the pavement).

The difference between these two approaches is the key to the problem of relating pavement behavior to pavement performance. A crack in the pavement surface may have minor or no effect at all on how well the pavement is serving traffic today. On the other hand, the maintenance engineer and the design engineer, who look at this existing crack in terms of mechanistic evaluation, immediately think of it as a local failure. The design engineer may be concerned if he did not expect the crack to occur. The mainte-

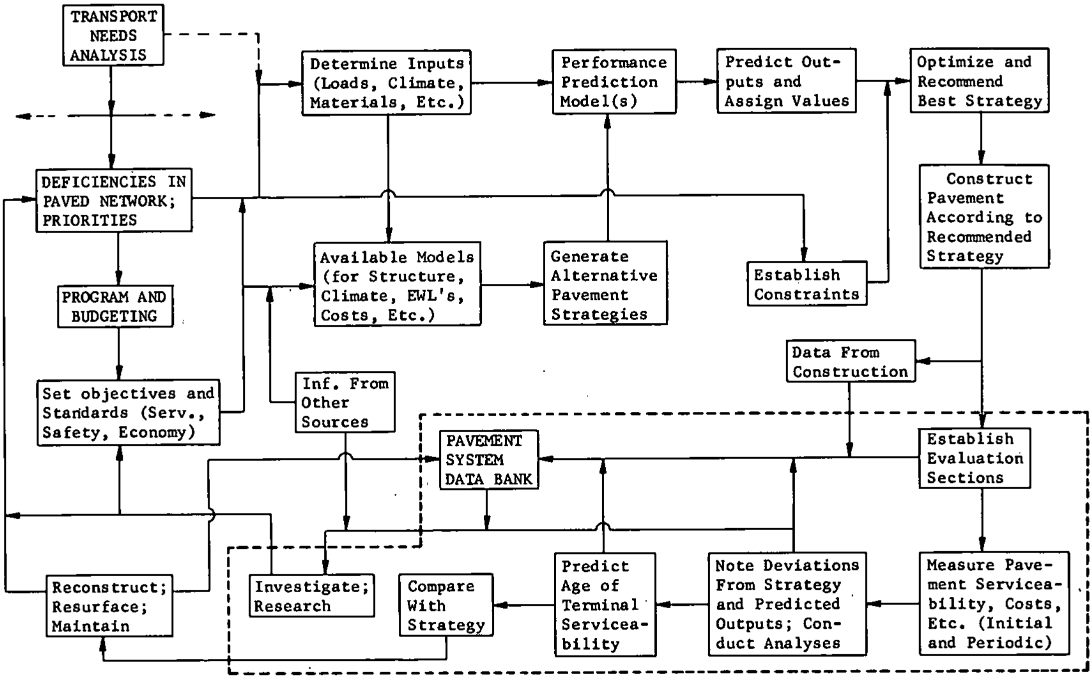


Figure 2. Role of performance evaluation in a generalized pavement management system.

nance engineer may be concerned if he thinks the crack will permit intrusion of water, increased deflection, spalling, and additional cracking that may occur and can result in rapid deterioration of the pavement. If on the other hand the pavement is designed to contain cracks, their presence will be of no concern to the designers or the pavement users involved.

However, if the roughness of the pavement, either as constructed or induced by changes in the pavement surface profile, is undesirable in character, i. e., excites poor response from the pavement user or is excessive in nature and provides an undesirable ride, the designer and the maintenance engineer may not be concerned at first, and yet the pavement will be a poor one.

OBTAINING A SYSTEM OUTPUT FUNCTION

Figure 3, as presented by Hudson et al. (2), shows that the expected output of a structural systems model is a behavioral characteristic, deflection or strain, that results at some limiting value in distress. The terms rupture, distortion, and disintegration have been used to describe all types of distress. The figure indicates that these are combined with appropriate weighting functions to yield a wear-out curve or system output function for the pavement. It is no easy task to develop a method of relating these factors.

A research team from Texas (10) has developed a working pavement design system that accomplishes this purpose, as shown in Figure 4. In effect, the team simplified the problem by using a deflection model for relating inputs to output—in this case surface deflection under the load. As indicated in the figure, the tie between expected deflection and expected performance was made empirically from equations developed at the AASHO Road Test relating deflections to performance. Such empirical methods are often used to bridge the gap between predictions of behavior and expected performance. Other researchers (11) have bridged this gap by using the AASHO Road Test

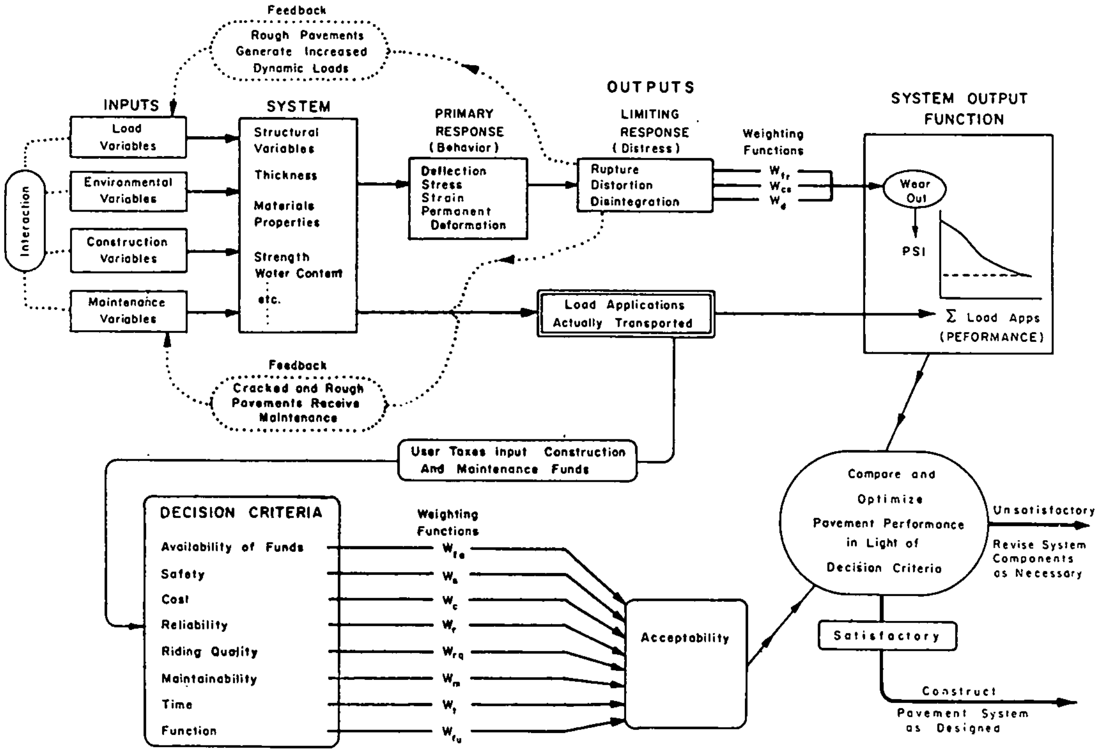


Figure 3. Ideal pavement system.

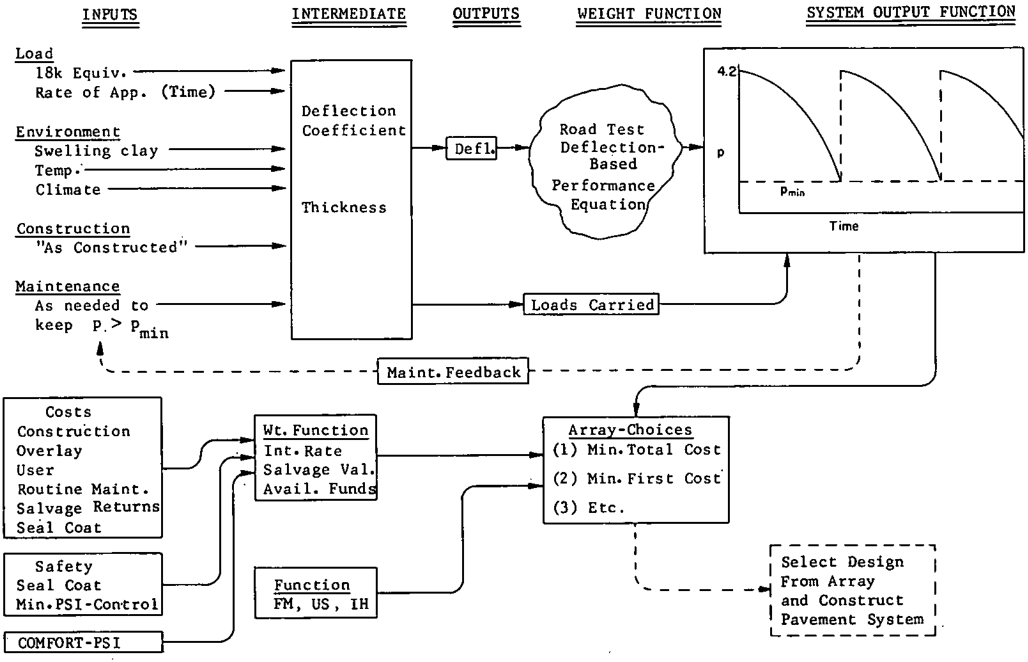


Figure 4. Working pavement system.

structural number concept to empirically predict performance from material properties in layers and their thicknesses. In both cases, the effect of system environments, in these cases the effect of subgrade swelling clay on pavement roughness, is evaluated and integrated into the serviceability-deterioration function by empirical evidence obtained in a study of Texas pavements.

RELATIONSHIP BETWEEN BEHAVIOR AND PERFORMANCE

Examination of the conceptual pavement system shown in Figure 3 illustrates the complex relationship that exists among the following:

1. System inputs,
2. Materials composing the system,
3. Pavement behavior, and
4. Pavement performance.

It is necessary to compare the performance or system output function against various decision criteria in order to make rational pavement designs and management decisions. It will ultimately be necessary to do this comparison on a stochastic basis; however, at the present time, it is adequate to make the comparison deterministically to illustrate the concept.

Hudson et al. (2) has attempted to associate material properties with modes of failure or distress through considerations of the various mechanisms and manifestations of distress. Limiting response (i.e., distress) modes have been divided into three categories: rapture or fracture, distortion, and disintegration. With the exception of pavement slipperiness associated with the surface coefficient of friction, all forms of pavement distress can be related individually or collectively to these modes.

The next logical step might be to list the pertinent material properties for each of the failure mechanisms associated with each manifestation of failure; however, this is beyond the scope of this paper.

SUMMARY

The concepts of performance and the solution to pavement design are complex problems. The application of systems engineering techniques appears to offer a reasonable approach to the solution. In this process, certainly materials characterization, theoretical analogies, solutions to boundary value problems, and distress analyses are important aspects of the problem. However, it is essential to pavement design that consideration be given to the functional requirements of the pavement and that pavement failure be defined in terms of the function of the pavement and not merely in terms that are convenient to analyze and predict from some mechanisms of failure.

At the present time, most theories associated with pavements predict pavement behavior and pavement distress. Available work on pavement performance involves primarily empirical relationships between measurements on pavements and observed serviceability. The most complete example of this type involves use of the AASHO Road Test data.

It is recommended that, as research effort continues toward the development of a better pavement design method, adequate attention be given to combining various pavement behavior and distress factors into an overall performance function because it is only through adequate definition of this function that the pavement problem will ultimately be solved.

Generalized Failure Concept

To accomplish the design of the pavement system requires that a definition of failure be fully specified. The term "failure" as used here refers to a failure of the pavement system and not the material failure. A key point in this discussion is that failure of a pavement material is generally not a catastrophic occurrence, as is the case of a steel rod rupturing in tension. Failure of pavement is, instead, a condition that develops gradually over a span of time generally measured in years. In this framework, the output of the pavement system exceeds some limiting value formulated by the decision criteria. A pavement designated as having "failed" in some respect may still be capable of carrying traffic at a reduced service level and may still have a high salvage value in an economic analysis for a pavement rehabilitation program.

The conceptual pavement system (Fig. 3) provides the framework for development of a generalized model of pavement failure. Figure 3 shows that the pavement system output and the decision criteria should be considered together because the decision criteria are used to evaluate the system output and to make a judgment of pavement performance. Thus, failure may be defined by the decision criteria as some limiting value of the system output.

Distress Index

The behavior of a pavement structure may be quantified in terms of its response. Figure 3 also shows that the limiting response is known as distress (i.e., rupture, distortion, or disintegration) and may be expressed conceptually as

$$\underline{DI}(\underline{x}, t) = \underset{s=o}{\overset{s=t}{\underline{F}}} \left[\underline{C}(\underline{x}, s),\ \underline{S}(\underline{x}, s),\ \underline{D}(\underline{x}, s)\underline{x},\ t\right] \tag{1}$$

where

t = time

$\underline{x}$ = a space variable;

$\underline{DI}(\underline{x}, t)$ = distress index, a function of space and time;

$\underline{C}(\underline{x}, t)$ = measure of fracture, a function of space and time;

$\underline{S}(\underline{x}, t)$ = measure of distortion, a function of space and time; and

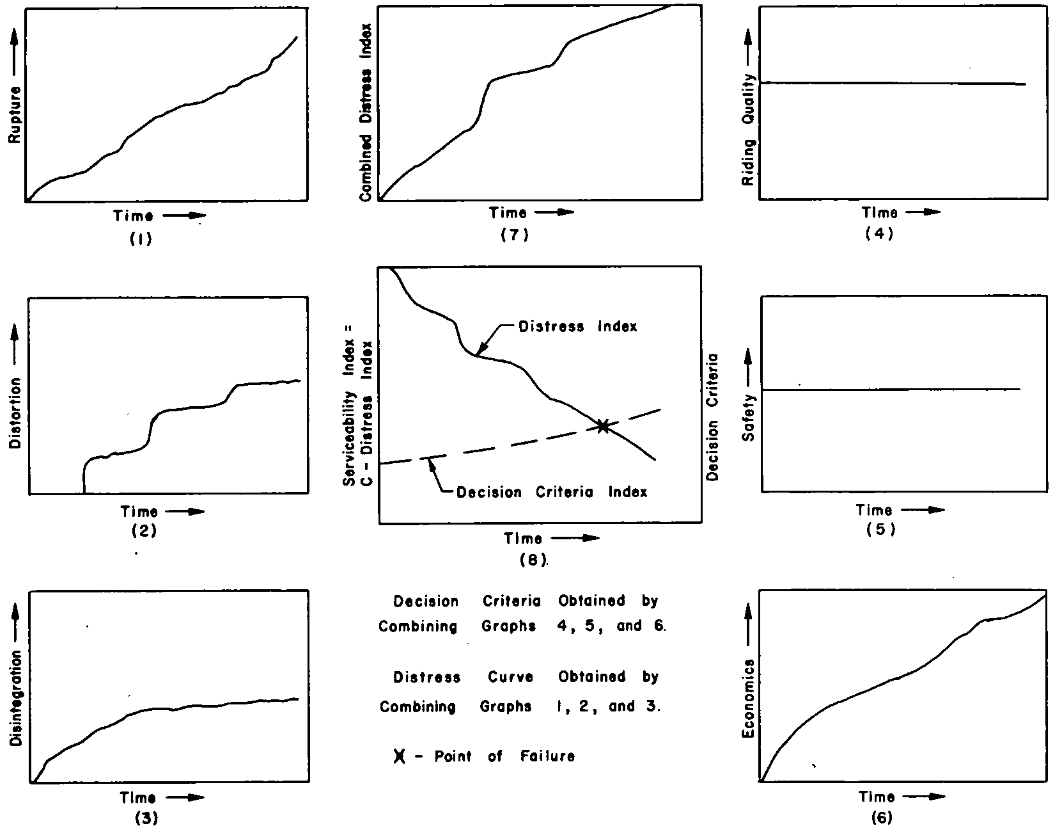
$\underline{D}(\underline{x}, t)$ = measure of disintegration, a function of space and time.

Distress is spatial in nature and is best considered on a unit volume basis. The notation in Eq. 1 indicates that the distress index is a function of the history of the variables shown from time zero to current time t.

Each of the parameters in Eq. 1 must be quantitatively predicted from the input parameters and the system models. Considering the systems framework, we may express rupture, distortion, and disintegration in general as functions of five classes of variables. For rupture, $\underline{C}(x, t)$ is a function of load, environment, construction, maintenance, and structural $\overline{\text{variables}}$ and of space and time. For distortion, $\underline{S}(x, t)$ is a function of load, environment, construction, maintenance, and structural $\overline{\text{variables}}$ and of space and time. For disintegration, $\underline{D}(x, t)$ is a function of load, environment, construction, maintenance, and structural $\overline{\text{variables}}$ and of space and time.

These expressions predict the three modes of distress in terms of five classes of variables. The variables are all expressed as a function of space and time with one exception. Construction variables enter at the beginning of the time history. After a pavement is constructed and opened to traffic, it is no longer time-dependent on the methods of construction.

The next development step is to substitute these expressions into Eq. 1, which conceptually describes the upper region of Figure 3. When the proper weighting functions are used, Eq. 1 would represent the system output function, which may then be evaluated in terms of various decision criteria.



Decision Criteria Obtained by Combining Graphs 4, 5, and 6.

Distress Curve Obtained by Combining Graphs 1, 2, and 3.

X - Point of Failure

Figure 5. Failure concept.

Decision Criteria Index

Basically, an engineer's criterion for judging a pavement structure is how well it is accomplishing its purpose. The decision criteria should therefore include, among other things, riding quality, economics, and safety. These decision criteria may be expressed in terms of a decision criteria index, or DCI(x, t), as DCI(x, t) is a function of riding quality, economics, safety, maintainability, and other factors and of space and time.

All the parameters included in the decision criteria index are functions of space. The time term is not included in riding quality because there is a minimum allowable rideability for any given type of roadway regardless of time. The safety term is also time-invariant because it, too, has some minimum acceptable level, for given conditions, that should not be exceeded during the life of a pavement. Because a highway represents a capital investment that may be depreciated over some time period, there is need for considering time in the economics term.

Each of the parameters in this expression must be quantified. Thus far, there has been little attempt to do so. Generally, these factors are considered subjectively, either directly or indirectly, by highway administrators.

System Failure

Failure of the pavement structural system may be expressed as a condition where the distress from the system output has exceeded an acceptable level based on the decision criteria. Figure 5 shows the principles of this failure definition. Through a model similar to that shown in Eq. 1, rupture, distortion, and disintegration may be combined into a distress index as shown by the solid line in graph 7 of Figure 5. The serviceability curve is then some constant minus distress function depending on the scaling factors involved.

An illustration of what acceptable levels might be for each decision criterion is presented to the right in Figure 5. The decision criteria are represented by a combined function expressed by the dashed line in graph 8. The point at which these two curves intersect might then represent failure for the system, i.e., when the pavement is performing at less than the desired level. Other functions of the variables such as the area between the curves may also be appropriate measures of the performance.

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