DISTRESS MECHANISMS—GENERAL

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At the start, it is desirable to discuss the fundamentals of pavement behavior and performance. The conceptual pavement system illustrates the complex interrelationship that exists among material properties and the geometry (i.e., thickness) of the pavement layers, manifestations of pavement behavior, and pavement performance and failure. Thus, it is necessary to understand the interrelationship of these factors in order to establish concepts and procedures for improving components of the pavement system. The first item, material properties, is not included in this report, but the other two items, pavement behavior and pavement performance, are briefly discussed in the following sections.

PAVEMENT BEHAVIOR

The factors affecting pavement structural behavior have been defined and characterized in different ways by various individuals and groups (2 through 10). Although reasons for these characterizations may vary, it appears that the basic purpose in most cases has been to provide guidelines for design or evaluation. Such descriptions of pavement structural behavior have usually been formulated by defining factors that affect either pavement performance or pavement structure failure. A survey of the literature, however, indicates that there are no clear-cut and generally accepted failure definitions relating to some level of serviceability or performance and that there is no complete set of well-defined and generally accepted failure mechanisms for the pavement components.

In this study, an attempt has been made 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: fracture, distortion, and disintegration. These are given in Table 1. 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.

Also given in Table 1 are the manifestations of each mode of distress, together with a listing of the causes associated with each type of failure. Although the next logical step would be to list the pertinent material properties for each of the failure mechanisms noted, this has not been done because of the lack of suitable constitutive equations for materials and the lack of adequate failure theories. The first may be termed the primary manifestation, and those that occur progressively after it the secondary, tertiary, and so forth. The sequential order of these manifestations would vary depending on load, environmental conditions, and the like. In most cases, a number of these may occur simultaneously.

COMPARISON WITH AASHO MODEL

Technically, if the AASHO equation were all-encompassing, a mathematical model would be present for each of the distress mechanisms given in Table 1. Thus, a model would predict each of the distress modes of fracture, distortion and disintegration by inputing load, environment, construction, maintenance, and structural variables considering space and time. The AASHO model does not have this finesse in that it uses a gross transformation from the input components of a pavement structure, i.e., thickness and strength coefficients, to a present serviceability index (PSI). From

TABLE 1

MODES, MANIFESTATIONS, AND MECHANISMS OF TYPES OF DISTRESS

Mode	Manifestation	Mechanism
Fracture	Cracking	Excessive loading
		Repeated loading (i.e., fatigue)
		Thermal changes
		Moisture changes
		Slippage (horizontal forces)
		Shrinkage
	Spalling	Excessive loading
		Repeated loading (i.e., fatigue)
		Thermal changes
		Moisture changes
Distortion	Permanent deformation	Excessive loading
		Time-dependent deformation (e.g., creep)
		Densification (i.e., compaction)
		Consolidation
		Swelling
	Faulting	Excessive loading
		Densification (i.e., compaction)
		Consolidation
		Swelling
Disintegration	Stripping	Adhesion (i.e., loss of bond)
		Chemical reactivity
		Abrasion by traffic
	Raveling and scaling	Adhesion (i.e., loss of bond)
		Chemical reactivity
		Abrasion by traffic
		Degradation of aggregate
		Durability of binder

prediction of PSI, a performance history can be obtained and failure of the system can be evaluated in terms of a minimum serviceability level and total dollar cost to the system. The performance of the pavement is a measure of the accumulated serviceability provided by the facility and may be expressed as a direct function of the present serviceability history for the pavement (2). A second model is a structural number model that was also developed at the Road Test (11) and subsequently used by the AASHO Design Committee to formulate the Interim Guides (12, 13, 14). These models are expressed as follows:

$$p = 5.03 - 1.91 \log(1 + \overline{SV}) - 0.01\sqrt{C + P} - 1.38\overline{RD}^2 \qquad (1)$$

where

p = present serviceability index,
$\overline{SV}$ = mean slope variance, a summary statistic of wheelpath roughness,
C = area of detrimental cracking per 1,000 sq ft,
P = area of patching per 1,000 sq ft, and
$\overline{RD}$ = average rut depth in the wheelpath.

$$P(\underline{x}, t) = \underset{s=0}{\overset{s=t}{F}} \left[p(\underline{x}, s)\right] \qquad (2)$$

where

$P(\underline{x}, t)$ = performance as a function of space and time,
t = time, and
$\underline{x}$ = position vector of a point referred to a coordinate system.

$$SN = A_1D_1 + A_2D_2 + A_3D_3 \qquad (3)$$

where

SN = structural number of system,
A_i = structural coefficient of the ith layer, and
D_i = thickness of the ith layer.

$$p = P_1 - \left(\frac{W}{\rho}\right)^{\beta} \tag{4}$$

where

P_1 = initial PSI,
W = number of equivalent wheel loads, and
β, ρ = parameters depending on layer thickness and strength coefficient and wheel load magnitude and configuration.

The AASHO equation uses a structural number value (Eq. 3) to compute the present serviceability value (Eq. 4) at the end of a stated time or traffic period. The computed performance at the end of the traffic period does not indicate the relative magnitude of cracking, patching, slope variance, and rut depth (Eq. 1). Rather, some function of their combined values will be equal to the computed PSI at time t. Because these mathematical models are equations statistically derived from AASHO Road Test data, they may be applied successfully within the limits of material types and thicknesses and experiments at the AASHO Road Test. The use of any new materials may be an extrapolation of the equation beyond its boundary conditions; hence, the applicability is questionable and remains to be verified. Thus, one immediate improvement of the AASHO model would be to quantify Eqs. 2, 3, and 4 for fracture distortion and disintegration and their combined value of distress index (Eq. 1) on the basis of theory. With such a model, PSI could be predicted on the basis of the actual output information, i. e., fracture, disintegration, and distortion, rather than through a gross transformation between input variables and performance based on field observations. Such models would make it possible to design for any material and any conditions.

FUNCTIONAL MODELS

The complete quantification of all of the distress manifestations and mechanisms is an extensive undertaking. Therefore, the approach used here is to show a logical method for quantifying several of the distress mechanisms and to demonstrate their applicability in the systems model.

Fatigue or repeated loading has been the subject of considerable research (15 through 23) with the result that there is a great deal of information available for use. Therefore, this distress mechanism has been selected for quantification. The complex interaction of the various distress mechanisms and manifestations was discussed previously. Figure 1 shows the interrelation of several distress manifestations that may be related with load repetitions. In this example, the distress mechanism of repeated loading leads to a primary manifestation of cracking, and the continued repeated load application leads to a secondary manifestation of spalling (fracture) and permanent deformation (distortion). The cracking of the pavement structure may also reduce the load-carrying capacity of the pavement structure, and for the same loads a secondary mechanism of excessive loading results and leads to a secondary distress manifestation of faulting (distortion) and spalling (fracture). In this manner, the initial distress mechanism of repeated loading has caused the distress modes of fracture and distortion to occur in the pavement structure. It is easy to envision the complex interractions that would develop when several distress mechanisms are involved.

The possible progressive development of the distress index due to an initial effect of the distress mechanism of repeated loading and the resulting secondary distress mechanisms is shown in Figures 2 through 5. In Figure 2, the development of the cracking index is conceptually shown in terms of traffic application. For the first period of traffic applications, little or no cracking occurs. When traffic reaches a value of n_c, pro-

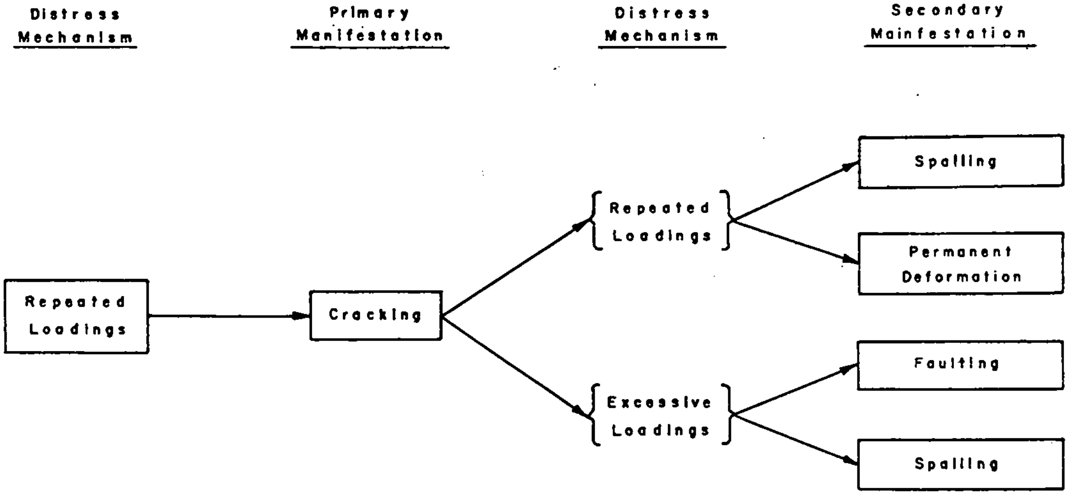

Figure 1. Interrelationship of distress mechanisms and manifestations.

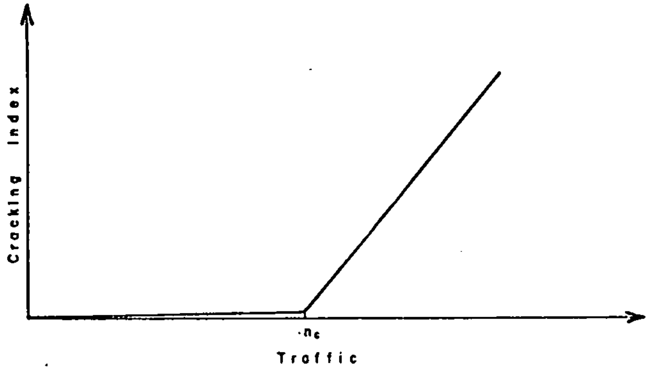

Figure 2. Progressive development of cracking index with traffic.

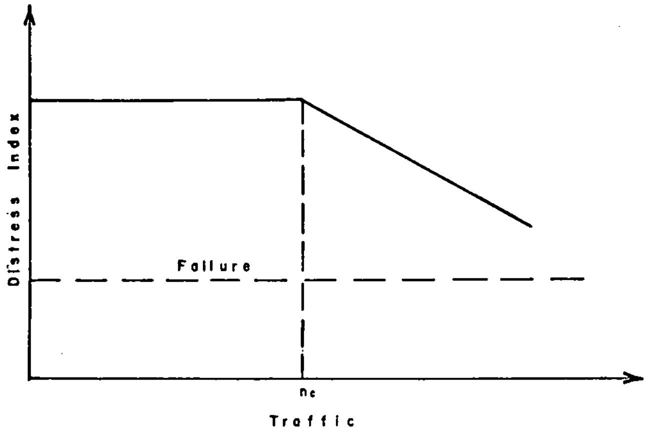

Figure 3. Progressive development of distress index considering cracking.

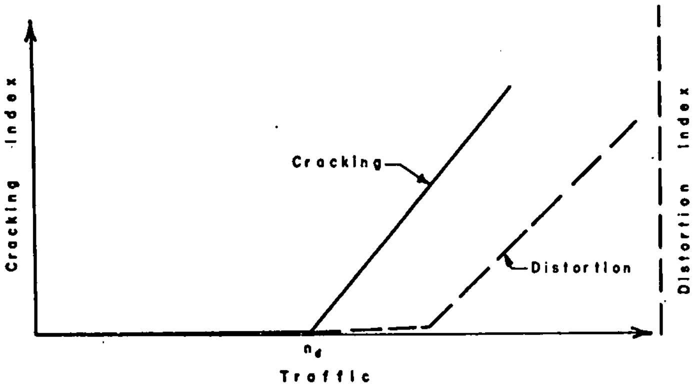

Figure 4. Progressive development of primary cracking and secondary distortion.

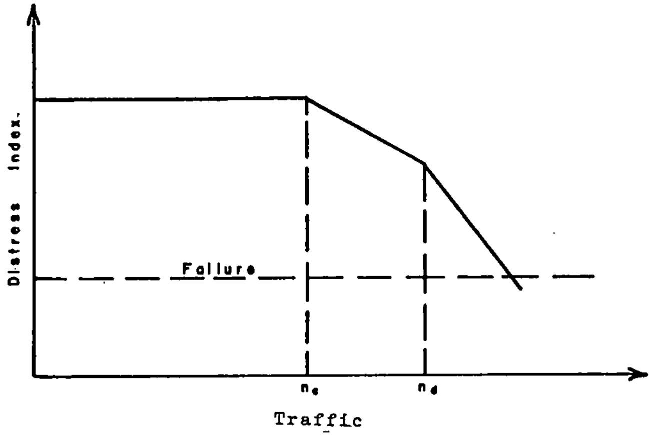

Figure 5. Progressive development of distress index considering both cracking and distortion.

gressive cracking begins, and the cracking index increases rapidly. If it is assumed that only the fracture mode occurs, the cracking index is used with Eq. 6 (Appendix) to compute the distress index. Its history is shown in Figure 3. There is no change in the index until cracking occurs at n_c traffic applications, at which time a progressive decay commences.

The development of the secondary manifestations of faulting and permanent deformation is shown in Figure 4 in terms of the distortion mode of distress. The distortion index might begin at a traffic value n_d, which is greater than n_c inasmuch as distortion is a secondary manifestation in this case. The shape of the distress function changes with the addition of distortion (Fig. 5), and the decay or slope of the distress index will be greater when the secondary manifestations of distortion and fracture occur, because of their compounding effect.

Failure of the system occurs when the distress index decreases below a minimum acceptable value. The preceding discussion illustrates the functional concepts involved in quantifying the distress index. The next step is to utilize the necessary constitutive equations to solve the functional equations.

SELECTION OF BOUNDARY VALUE PROBLEMS AND CONSTITUTIVE EQUATIONS

Detailed steps for characterizing materials and using the results in boundary value problems are discussed in other papers in this report. As a precursor to such complex improvement, this example illustrates the application of the best developed constitutive equation and boundary value problems in the present state of the art. The constitutive equation for linear elastic theory (24) and layered theory (25, 26) probably represent the most advanced state of the art available for use at the present time.

Figure 6 shows a typical pavement structure cross section and the elastic parameters, i. e., modulus of elasticity and Poisson's ratio, and the pavement geometry value, i. e., thickness, required in the layered system program. These values are used with the layered program to compute the mechanical state of stress and strain in the pavement structure. These computed values may then be compared with the corresponding limiting values to predict cracking. If the computed stress is greater than the strength, then cracking is assumed to occur.

The computed values of stress and strain are deterministic in nature inasmuch as the input values are considered to be exact quantities. Thus, a deterministic solution does not consider the possibility of variations in properties, as required by conceptual Eq. 6. With the absence of stochastic concepts, a deterministic approach implies that, when the stress is greater than the strength, failure will occur at every point in the pavement where a wheel load causing the limiting stress passes over. Of course, experience and studies show that cracking does not occur in this manner but, rather, on a progressive basis (11). Thus, it is necessary that the stochastic concepts be injected into the approach in order to predict progressive cracking more accurately. One method previously developed assumes that, if the stress is independent of strength, the probability of distress may be stated as

$$P\{C\} = P\{\text{stress} > b\} + P\{\text{strength} < b\} \tag{5}$$

where

$P\{\}$ = probability of an event occurring, and

b = a value defining the point where stress and strain values overlap.

A stochastic equation permits one to quantify this functional notation. The use of Eq. 5 allows the percentage of surface area of a roadway experiencing cracking to be predicted for certain stress and strength variations around the mean value shown.

In addition to these properties, the fatigue characteristics of the materials are an input property required in predicting cracking due to the repeated load distress mechanism. A typical fatigue curve for portland cement concrete and asphalt concrete (Fig. 7) indicates that, the greater the stress level is, the fewer will be the number of load repetitions required to failure. The solid line in Figure 8 is an average fatigue line for the data. Monismith, Kasianchuk (27), and others have shown that the stochastic variation in

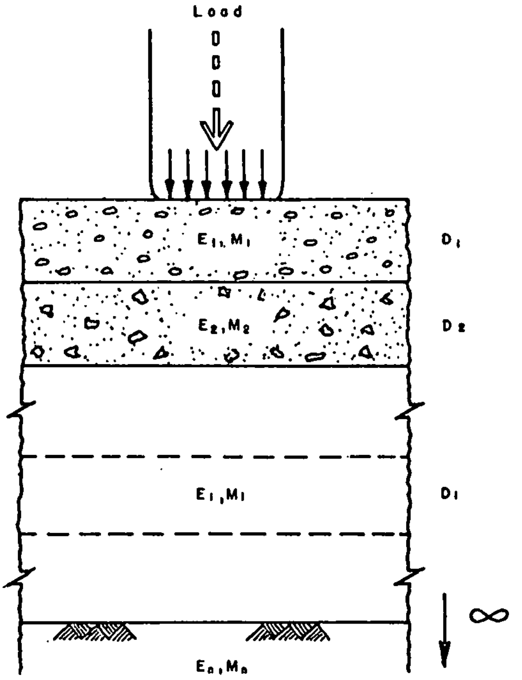

Figure 6. A typical pavement structure cross section showing the elastic parameters.

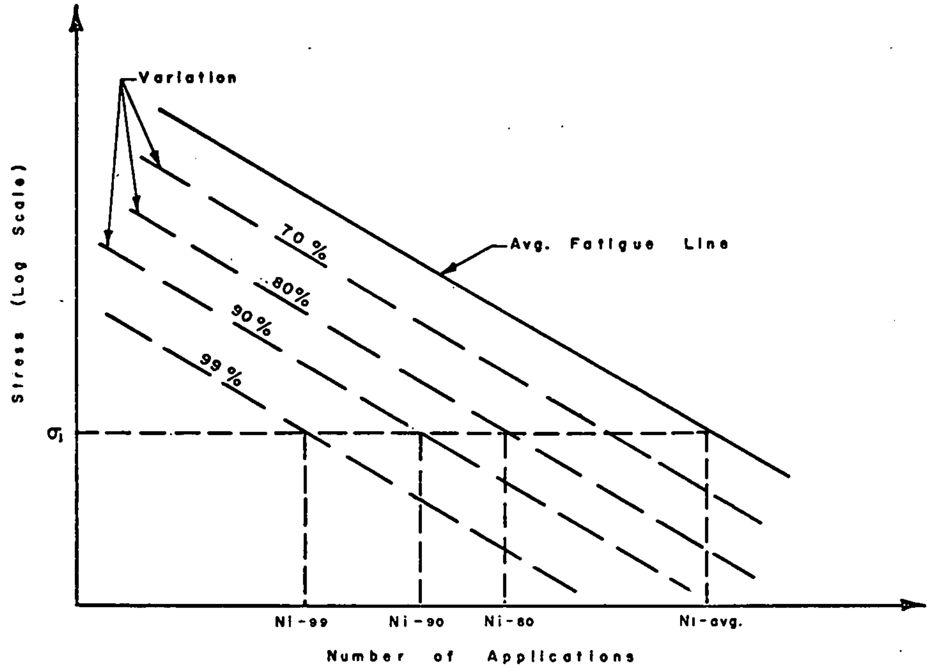

Figure 7. Typical fatigue for a pavement material.

asphalt concrete may be described by lines parallel to the average fatigue line as shown in Figure 7. Each line indicates the probability that a pavement subjected to a given stress level will last a given number of applications. In essence, this principle implies that, for a given stress level, the less risk of cracking one is willing to take, the smaller will be the allowable number of load repetitions. For example, the ith stress level will go N_i - 99 applications with a probability of 99 percent, i. e., only 1 percent chance of failure. However, if the user is willing to accept the probability of 20 percent failure, then the material will last N_i - 80 load repetitions, which is greater than N_i - 99 (28).

SUMMARY

In this report, the feasibility of using research findings and results to improve a systematic pavement design procedure is demonstrated.

The conceptual sequence for modifying the gross transformation between input variables and performance may be developed as follows:

1. Predict a distress manifestation based on a primary distress mechanism (Table 1).
2. Note that the occurrence of a primary distress manifestation leads to the initiation of a secondary distress mechanism which in turn leads to secondary distress manifestations. This process may occur for several additional levels, i. e., secondary, tertiary, and so on (Fig. 1).
3. Define the effects of the primary, secondary, and higher order distress mechanisms, and combine them to predict a distress index history, i. e., performance, for the pavement (Fig. 5).

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APPENDIX

DISTRESS INDEX

$$\underline{DI}(\underline{x}, t) = \underset{s=o}{\overset{s=t}{\underline{F}}} \left[\underline{C}(\underline{x}, t),\ \underline{S}(\underline{x}, t),\ \underline{D}(\underline{x}, t)\ \underline{x}, t\right] \tag{6}$$

where

t = time;
$\underline{x}$ = position vector of a point referred to a coordinate system (space);
$\underline{DI}(\underline{x}, t)$ = distress index, a matrix function of space and time;
$\underline{C}(\underline{x}, t)$ = measure of fracture, a matrix function of space and time;
$\underline{S}(\underline{x}, t)$ = measure of distortion, a matrix function of space and time; and
$\underline{D}(\underline{x}, t)$ = measure of disintegration, a matrix function of space and time.

$\underline{C}(\underline{x}, t)$ is a function of load, environment, construction, maintenance, and structural variables and of space and time.

$\underline{S}(\underline{x}, t)$ is a function of load, environment, construction, maintenance, and structural variables and of space and time.

$\underline{D}(\underline{x}, t)$ is a function of load, environment, construction, maintenance, and structural variables and of space and time.

$\underline{DCI}(\underline{x}, t)$, or Decision Criteria Index, is a function of riding quality, economics, safety, maintainability, and other factors and of space and time.