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FLEXIBLE PAVEMENT DESIGN AND MANAGEMENT SYSTEMS FORMULATION

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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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This report and its companion, *NCHRP Report 140*, “Flexible Pavement Design and Management—Materials Characterization,” will be of interest and practical value to people of a number of disciplines in highway departments and other agencies. Both reports are the result of research conducted under NCHRP Project 1-10, “Translating AASHO Road Test Findings—Basic Properties of Pavement Components.” From the highway administrator’s standpoint, there should be considerable interest in the systems engineering concept of pavement management described in this report as a method to provide the desired level of pavement service at the most economical over-all cost. The materials characterization investigation, covered in the companion report (*NCHRP Report 140*), is considered to be a phase of a longer-range endeavor aimed at more substantial changes in the structural facet of the pavement design process that will lead to more rational procedures for design of the pavement structural subsystem. Greatest interest in the results will be found among pavement designers, researchers, and engineers involved with materials and soils testing.

The structural design of highway pavements involves empirical techniques based to a large extent on long-time experience of highway agencies and augmented by test programs, the most ambitious of which was the AASHO Road Test conducted near Ottawa, Ill., and completed in the fall of 1960. Because a field test program involving the many variables known to affect pavement performance would become unfeasible, the sponsors of the Road Test chose to include only a limited number of variables in the project. As a result, it is generally recognized that the relationships between traffic loadings and pavement performance developed at the Road Test apply only to the conditions at the test site. Applications of these relationships in other areas of the United States must be based on experimental or other evidence of the effects of differences in subgrade soil, paving materials, construction practices, traffic, environment, and maintenance procedures. A number of early NCHRP projects dealt with extrapolation of Road Test findings to conditions other than those at the test site.

NCHRP Project 1-10 was initiated by a research team from Materials Research and Development, Inc., with the objective of using basic properties of pavement component materials to translate AASHO Road Test findings to other conditions and thus ultimately develop more rational pavement design procedures. In the early stages of the study it was determined that measurement of basic properties of materials and components significant to pavement performance was a highly complex problem requiring (a) development of new testing equipment, and (b) considerable laboratory data collection, followed by (c) field experimentation. It was also recognized that the pavement design decision-making processes involve factors other than the structural ability of a section to support predicted traffic loadings (e.g., maintenance strategies, user considerations, and long-term economics). The concept of considering management of a pavement system throughout its operational life during the initial design process was developing. Consequently, project efforts were divided into two separate but coordinated activities—materials
characterization and systems formulation—with each activity under the direction of a separate research team.

An operational pavement systems model (SAMP5), as described in this report, has been formulated that organizes the over-all influencing factors such as materials characteristics, construction techniques, maintenance requirements, and economics within a suitable framework for flexible pavement design and management. A computer program has been prepared using 58 to 100 input variables and the *AASHO Interim Guides for Design of Flexible Pavements* as the structural subsystem. An earlier version of the system is currently being implemented by the Texas Highway Department. The procedure can be applied to flexible pavement design problems now by any agency having the proper input data and using AASHO design guides. However, for the method to be more easily implemented, detailed descriptions for users' guides, input forms, and data feedback and storage systems are needed. These are being prepared and the procedures are being subjected to a sensitivity analysis and pilot testing during an implementation phase of the study under NCHRP Project 1-10A.

Intermediate and long-range prospects for improvements in pavement design within the systems concept may depend largely on the development of more rational approaches to the formulation of the structural subsystem based on properties of the subgrade and paving materials, rather than on the empirical relationships developed during the AASHO Road Test. A procedure, including the necessary laboratory equipment, has been developed for characterization of materials in terms of stress/strain relationships representative of loading and environmental conditions to which they are likely to be subjected as components of a pavement. The methodology is illustrated in *NCHRP Report 140* by its application to the characterization of an asphaltic concrete, a granular base material, and a cohesive subgrade soil. The description of the testing equipment and accumulated materials characterization data should be of considerable interest to pavement design researchers. Research aimed at application of more rational approaches to solutions of structural subsystem problems is scheduled to be initiated within NCHRP in 1973.

The essential findings of this study, aimed at both immediate and long-range improvements in the pavement design and management process, are further summarized under “Systems Formulation” and “Materials Characterization,” two separate but coordinated activities responsive to over-all project objectives.

**Systems Formulation**

Systems engineering in its broad sense is a codified procedure for attacking complex problems in a coordinated fashion to permit realistic decisions that can be justified on the basis of selected decision criteria. A conceptual pavement systems diagram was prepared primarily to illustrate the interrelation of many inputs and subsystems involved in the pavement design and management process. The inputs to the system include a range of load, environmental, structural, construction, and maintenance variables, all of which are stochastic in nature and are interrelated. Although conceptualizing the over-all pavement system was essential to solving the problem, it was necessary from an application standpoint to develop an operational
system. After a review of the efforts of other researchers in the area of applying systems engineering concepts to pavement design, it seemed desirable to modify and extend the efforts of Scrivner, McFarland, and Carey,* who had developed the first known computer-oriented operational system for the design of flexible pavement, rather than expend time and effort on an entirely new system. Thus, the working method developed on this project, Systems Analysis Model for Pavements (SAMP), is an extension of the algorithms initially conceived by Scrivner et al. In the particular version (SAMP5) described in this report, there are seven classes of input variables, as follows: (1) material properties, (2) environment and serviceability, (3) load and traffic, (4) constraints, (5) traffic delay, (6) maintenance, and (7) program control and miscellaneous. An example problem using the operational model is included. A limited sensitivity analysis and evaluation of the program was conducted, and the feasibility of revising the structural subsystem to permit the use of more rational concepts—such as elastic layered theory—was demonstrated.

The major conclusions and recommendations of this portion of the research are as follows:

1. An uncoordinated attack on the structural design of pavements will not be successful in solving the problem. A systems engineering approach is required that can be used to describe the over-all behavior and performance of the pavement system, as well as the functions of its component parts, during its entire life as a portion of the highway transportation network.

2. A conceptual pavement systems model has been formulated to show the relationships between the many groups of input variables that must be considered.

3. An operational flexible pavement systems model (SAMP5) has been developed, including a computer program using 58 to 100 input variables.

4. Possible improvements to SAMP5 are illustrated, including the use of elastic layered theory and the most recent materials characterization information to provide a more rational structural subsystem.

5. Efforts should be made to: (a) implement the present operational system in several states, (b) modify and improve each of the subsystems, and (c) ultimately upgrade the model toward a true "pavement management system" capable of evaluating the adequacy of the pavement, in terms of providing the intended service over its operational life.

Materials Characterization

Use of the systems approach to pavement design and management requires the description and solution of the various subsystems, one of which is the structural (primary response) subsystem. In theoretical or rational approaches to structural subsystem solutions it is assumed that the primary response of the pavement structure can be defined by its mechanical state. In conventional terms, determining the primary response involves the formulation and solution of appropriate boundary value problems to determine the stress/strain relationships (mechanical state) of each component in a pavement due to applied loads under a variety of environmental conditions. The results obtained from solution of specific boundary value problems are then evaluated in the light of established performance criteria to determine the capability of the pavement system to sustain the input. It is important to recognize the complexity of this task and the iterative nature of the procedure.

For the purpose of determining the mechanical state through the formulation and solution of boundary value problems, materials are currently described by simplified mathematical models. To determine the likelihood of distress, it is necessary to establish performance criteria for the various materials comprising the pavement system. These performance criteria are related to limiting values of stress and strain that can be permitted to occur in the material, the numerical magnitude of the material, the environment, and the loading conditions.

Characterization of materials, as defined for this project, is the selection of constitutive equations to adequately model the response of paving materials to the loading and environmental conditions to which they are likely to be subjected as components of a pavement. In the preliminary model selected for this study, no attempt was made to include environmental factors (e.g., temperature and moisture). However, the effects of these factors on material behavior were taken into account by testing over a range of temperatures and moisture contents likely to exist in actual pavement systems.

No equipment for characterizing materials was found to be capable of fulfilling the desired project requirements, necessitating the design and fabrication of suitable laboratory testing equipment. Essentially, this consisted of modification of conventional triaxial testing apparatus to provide for independent control of axial and radial stresses. Using the modified triaxial equipment, repeated load tests were conducted on two paving materials—an asphaltic concrete and a cohesive subgrade soil. Similar data for a granular base material were available from a previous study. The tests were conducted on the assumption that the materials were elastic, though not necessarily linear; and, hence, the resilient deformations were measured. The data were analyzed on the basis of an incremental formulation of a physically nonlinear elastic constitutive law. In recognition that solution techniques currently available are for linear and “ad hoc” nonlinear problems, the results are presented (in NCHRP Report 140) in terms of an approximate modulus of elasticity and Poisson’s ratio. The variations of these parameters with temperature and stress level have been indicated.

The following findings are considered significant with regard to the response of the particular material tested under the loading conditions of the investigation:

**Asphaltic Concrete**

1. The temperature is the most significant factor in determining the response of asphaltic concrete. This suggests that the characteristics of the asphalt cement are of major significance.

2. At any particular temperature the stress level influences the response of the asphaltic concrete. The asphaltic concrete is less resistant to deformation at higher temperatures. For a constant stress level the deformation increased with increasing temperature.

3. A nonlinear elastic model can provide a suitable representation of the response of asphaltic concrete below temperatures of 55°F for the loading conditions of the study—a repeated load of short duration applied to the material after an initial period of conditioning under repeated load. Above this temperature the time-dependent effects are too significant to neglect; hence, consideration should be given to a viscoelastic model.

4. The data indicate that the asphaltic concrete might initially be isotropic and that anisotropy was induced as a function of the stress state and temperature.
Granular Material

1. The response of granular materials is, for all practical purposes, time-independent and completely recoverable. 
   
   2. The influence of stress level on the resistance to deformation is considerable and is indicated by the dependence of the response under load on the first stress invariant. The resistance to deformation increases with an increase in the value of the first stress invariant. 
   
   3. A nonlinear elastic constitutive law is a reasonable representation of the response of a granular material. 

Cohesive Soil

1. Water content exerts a significant influence on the response of the subgrade soil. An increase in water content causes a decrease in resistance to deformation of the soil. 
   
   2. There is a large influence of stress level on the response of the cohesive subgrade soil. In general, an increase in the axial stress or radial stress caused a decrease in the resistance to deformation. The effect is greatest at stress levels below 3 psi, and appears important for stress levels up to 6 psi. These stress levels are typical of those that exist in the subgrade of a well-designed pavement. 
   
   3. For this particular soil and within the range of water content at which it was tested, a nonlinear elastic constitutive law is a satisfactory representation. 
   
   4. An evaluation of the data indicates that the effects of stress-induced anisotropy may be significant. However, the data are inadequate at this time to be definitive as to the importance of these effects.
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During the course of the study, contacts were maintained with the Federal Highway Administration and other federal and state agencies and individual researchers too numerous to list here. Their cooperation and advice assisted in the development of the concepts utilized in this project.
INTRODUCTION AND RESEARCH APPROACH

Systems engineering is a broad concept with many definitions. Basically, it is a codified procedure for attacking complex problems in a coordinated fashion to permit realistic design developments that can be justified in the face of certain decision criteria. For background in systems engineering and its application to pavement design, Appendix A provides a development of the pavement system, with a discussion of several aspects of the method. Appendix B gives the definitions used in this section.

ANALYZING THE PROBLEM

Figure 1 shows the steps involved in systems engineering. Other authors state the method in different ways, but basically the steps shown here are pertinent.

Too often in the past the narrow view of the pavement design problem has produced unsatisfactory methods of constructing, designing, maintaining, and evaluating pavements. The narrow concepts of design previously used will not suffice for high-speed, high-volume, modern pavement facilities.

As Figure 1 shows, a good understanding of the problem is only the beginning. A concise statement of the objectives of the system (i.e., recognizing the problem) is a necessary step toward a solution. With these objectives in mind, it is possible to establish systems requirements or define the problem. From these requirements, a well-defined model of the problem can be developed and alternate solutions can be generated. From the alternate solutions, the engineer can select the best solution, based on some type of decision criteria, and this solution can be implemented by construction. The method, however, does not end here, because it is necessary to obtain feedback information and check the performance data that have been obtained from the constructed pavement. These feedback data make it possible to modify designs and ultimately to modify the method, if necessary. There is no one, unique, over-all solution, but, in general, this approach can be helpful in solving the problem.

Problem Recognition

Understanding and recognition of the problems facing the pavement designer are essential, as summarized in Appendix A, for the development of solutions.

The specific project objectives, as given in the Project Statement, are:

1. Development of descriptions of significant basic properties of materials used in pavement structures.
2. Development of procedures for measuring these properties in a manner applicable to pavement design evaluation.
3. Development of procedures for pavement design, using the measured values of the basic properties, that would be applicable to all locations, environments, and traffic loadings.

Summarized briefly, the objective of this project seemed to the researchers to be more nearly "to formulate the overall pavement problem in broad theoretical terms," which would enable the solution of numerous problems that have long plagued pavement designers. To achieve these objectives, it has been necessary to broaden the base of the study to include a redefinition and broader understanding of the over-all pavement design process. Such a definition is not uncommon in the application of the systems engineering process.

Problem Definition

The first phase of this project was partially successful in establishing the requirements for pavement systems. A truly useful pavement management system not only must provide a method for understanding the basic properties of the materials, but also must contain a way of using these basic properties together with other pertinent input information (including loads, environment, maintenance requirements, and a wide range of economic factors) to establish a realistic basis for making rational pavement design decisions. It is equally important to keep in mind the constraints imposed on the system and the concomitant
variables—such as air pollution and noise, in the case of the highway system. The system must have a system output function that can be used in the optimization process. The system also must provide the decision maker with a series of possible designs arrayed in some priority order based on the chosen criteria.

Modeling the Problem
There are many ways of modeling the problem, including physical, conceptual, and mathematical models. The conceptual model of the pavement system is shown in Figure 2. It includes not only a particular set of mathematical models or graphs, but also decision criteria and a systems output.
Figure 2. Block diagram of conceptual pavement system.
function. In addition, an implementation plan, equipment, and personnel necessary to implement the system are essential parts of the over-all systems model. Nevertheless, a vital part of the process, particularly in the developmental stage, is the mathematical models, which are in essence the descriptions of the physical problem. These can be in the form of graphs or tables, but more logically are presented as computer programs for rapid solution. These models include such things as the physical relationship relating the factors and materials characteristics, a performance equation relating the traffic factors to predict the load-carrying capacity, and some type of optimization model and economic model, which are used to compare the decision criteria to the predicted performance. Collection and coordination of a particular set of models into an organized package are vital to the systems analysis process.

Generate Alternate Solutions

A working systems analysis must, through the systems model, generate all possible feasible solutions to the particular problem at hand. For example, this might involve 400 or 500 combinations of material strengths and thicknesses to carry a particular set of loads and environments to be considered. A computer program is essential in generating these alternate solutions. In the past, with hand methods, it has been common practice to generate no more than two or three solutions from which to select a design. The probability of obtaining the best design in such a way is remote.

Solution Evaluation and Choice

To select the best possible design criteria for judging, "best" must be established and organized in the computer program. These necessary criteria are often complex and interfere with each other. A series of trade-offs may be involved and must be accomplished in the computer. In any event, a series of designs ranked in some order, based on the decision criteria, should be presented for the decision maker. Because of the complexity of the process, it is difficult to establish precise weighting functions in the decision process. Thus, the decision maker selects the final design for implementation.

Implement Recommended Strategy

After a particular design has been selected, the design must be implemented through preparation of plans, specifications, controls, schedules, etc. After the contract is let, construction must be effectively controlled to ensure that the pavement is constructed as designed. In reality, the final product will vary within normal ranges of reliable construction control; this range of values must be taken into account when evaluating the performance of the system. An essential part of this implementation strategy is the storage of information related to the performance of the system.

Performance Measurement and Evaluation

After a particular design is constructed, performance of the design must be checked and feedback information must be collected and retained throughout the life of the pavement. This vital phase in pavement design processing has often been neglected in previous design methods. Such feedback data not only make it possible to modify and improve the performance of a particular pavement, by providing maintenance and overlays at the proper time, but also provide data from several pavements to evaluate and update the design system. It is the cyclic updating of the working system and its subsystems that ultimately will lead to a solution of the problem at hand.

CONCEPTUAL PAVEMENT SYSTEM

In solving the problem, it is helpful to formulate a conceptual pavement systems diagram, as shown in Figure 2. This figure is not intended to present an exhaustive development of the details of the pavement system. Instead, it attempts to show the interrelation of many of the subsystems involved in the design of the pavement.

The important aspects of the system description include its inputs, physical character, response, output, concomitant variables, system output function, decision criteria, and decision-making process. Other important aspects include feedback and interaction of information and variables in the system.

The inputs to the system include a variety of load, environmental, construction, structural, and maintenance variables. These are not independent variables, but interact with each other, as shown. All of these variables are stochastic in nature; they are difficult to specify and predict, although an attempt is made to specify them in a deterministic way herein. The effect of stochastic variation of parameters is presented in Chapter Two.

The physical characteristics in the system (including geometric measurements such as thickness and arrangement of the layers) can best be represented by mathematical models that represent the structural behavior of the system. It is these mathematical transformations or transfer functions that simulate the behavior of the physical pavement.

The system responses, as shown in Figure 2, involve the behavior of the physical system. These factors usually are measurable and involve the mechanical state (i.e., deflection, stress, and strain). When these so-called primary responses reach some limiting value, distress usually occurs in the form of fracture, distortion, or disintegration. The true output of the system is measured by the goods and people (i.e., load application) actually transported. These factors in combination form a systems performance or output function that can be used as a measure of system adequacy, and which in fact is the objective function of the systems analysis.

Concomitant variables are those factors, desired or not, that accompany the chosen course of action. For example, a typewriter gives prepared copy as desired, but also gives off noise and electrical heat and occupies space. In pavements, for example, use of a chip seal to provide skid resistance might result in flying rocks, or use of crushed stone might deplete natural resources.

Decision criteria are a complex set of factors, many of which involve economics and can thus receive a dollar value. Other factors, however, such as reliability, riding
quality, and maintainability, are difficult to quantify in dollar terms and therefore require trade-off analysis or other systems analysis procedures. Through the use of weighting functions, these must be appropriately combined to select a proper level of acceptability for the system at hand.

BACKGROUND OF OPERATIONAL PAVEMENT SYSTEMS

Although conceptualizing the over-all pavement system is essential and helpful in solving the problem, it is not an adequate stopping place in research. Concepts similar to those previously described have been presented by a variety of authors, including Moavenzadeh (8) and Hutchinson and Haas (7, 9). The next important step in using systems engineering to design pavements is the development of a series of pavement models that can actually be solved to accomplish the steps previously outlined. This task was undertaken in 1962 by Scrivner at the Texas Transportation Institute (6). The Texas study, which terminated in 1968, had as a principal objective the determination of coefficients for Texas materials similar to the coefficients used in the “AASHO Interim Guide for the Design of Flexible Pavement Structures” (10). The details of this research work and of the findings of the Texas project were published in 15 reports made during the life of the study. The findings of the study are presented in those reports (6, 11, 12, 13, 14).

They can be summarized briefly by saying that Scrivner found it necessary to formulate a series of mathematical models describing his findings relative to pavement behavior. He then incorporated these mathematical models into what he called a computerized flexible pavement design method. It is important to reemphasize here, in support of using systems engineering to solve pavement problems, that after eight years of concerted effort and the expenditure of several hundred thousand dollars, the Texas research staff in cooperation with the Texas Highway Department concluded that it was necessary to develop a coordinated computer approach to pavement analysis and design rather than a piecemeal approach such as had been anticipated at the beginning of the project.

The TTI Computer-Based Pavement Design System

In the opinion of many researchers, the work of Scrivner, Carey, and others at TTI is a major accomplishment in the field of pavement design because it represents the first realistic broad-based computer-oriented design method; i.e., the first known operational systems model. The objective of the computer design method is to provide, from several described materials input into the computer, a pavement that can be maintained above a certain minimum level of serviceability over the required design period at a minimum over-all cost.

A set of three equations based on empirical data is used to predict the serviceability history of several possible designs meeting the performance criteria; i.e., (1) a specified minimum allowable time from initial construction to overlay must be met, and (2) a minimum specified time between overlays must be accommodated. The costs associated with each design considered by the computer in the analysis include (1) initial construction, (2) routine maintenance, (3) periodic application of seal coats, (4) overlaying with asphaltic concrete to maintain serviceability, (5) traffic delays, and (6) salvage value. All these costs are discounted to present value to form the over-all cost figures for a pavement structure during the analysis period.

From the possibilities considered, the computer selects a set of unique designs and overlay policies meeting the specified criteria and having minimum over-all cost. It prints out a description of each design, the overlay and seal coat policies, and a cost breakdown arrayed in order of least total cost.

Mathematical Models

Three empirical equations are used by Scrivner et al. to predict serviceability history. These are called the deflection model, the traffic equation, and the performance model.

Deflection Equation

From materials properties and thicknesses, the deflection equation predicts a surface curvature index that is assumed to be the characteristic of a deflection basin produced on the pavement by a Dynaffect [after Scrivner et al. (6)]:

\[ S = W_1 - W_2 \]  

in which

\[ W_j = \sum_{k=1}^{n+1} \Delta_{jk} \]

\[ \Delta_{jk} = \frac{C_0}{a_kC_1} \left[ \frac{1}{r_i^2 + C_2 \left( \sum_{i=0}^{k-1} a_iD_i \right)^2} - \frac{1}{r_i^2 + C_2 \left( \sum_{i=k}^{n+1} a_iD_i \right)^2} \right] \]

\[ W_j = \text{the deflection sensed by the } j\text{th sensor of the Dynaffect} \]

\[ \Delta_{jk} = \text{the strength coefficient of the } i\text{th layer of a pavement} \]

\[ C_0 = 0.891; \]

\[ C_1 = 4.503; \]

\[ C_2 = 6.25; \]

\[ a_0 = D_0 = 0; \]

\[ a_i = \text{the thickness of the } i\text{th layer in inches} \]

\[ D_i = \text{the thickness of the } i\text{th layer in inches} \]

\[ W_j = \text{distance in inches from the point of application of either Dynaffect load to the } j\text{th sensor} \]

Traffic Equation

A traffic equation (furnished by the Texas Highway Department) is used by Scrivner to predict the equivalent number of 18-kip axles from certain traffic parameters during the life of the pavement:

\[ N_h = \frac{N_c}{C(r_0 + r_0)} \left[ 2r_0d_h + \left( \frac{r_0 - r_0}{C} \right) t_{1/2} \right] \]
in which

\[ t = \text{time in years since initial construction}; \]
\[ N = \text{total number of equivalent applications of an 18-kip axle that will have been applied in one direction during the time, } t, \text{ in millions}; \]
\[ C = \text{length in years of the analysis period}; \]
\[ N_c = N \text{ when } t = C; \]
\[ N_{k} = N \text{ when } t = t_k; \]
\[ r_0 = \text{ADT (one direction) when } t = 0; \]
\[ r_{c} = \text{ADT (one direction) when } t = C; \]
\[ t_k = \text{the value of } t \text{ at the end of the } k\text{th performance period or the beginning of the next period (} t_0 = 0). \]

Performance Equation

To obtain a performance equation, Scrivner related his deflection data to the performance variables developed from the AASHO Road Test data and then modified the results to include two swelling clay parameters, \( b_k \) and \( P_{2'} \):

\[ Q_2 = \frac{53.6(N_{k} - N_{k-1})S^2}{\alpha} + Q_{2'}(1 - e^{-b_k(t_k - t_{k-1})}) \quad (5) \]

The second term was added to represent the effect of swelling clays. The equation applies to the \( k\)th performance period. The factor \( b_k \) is a swelling clay parameter applying to the \( k\)th performance period. A value between zero and 0.3 must be specified by \( b_1 \), depending on the expected activity of foundation clays:

\[ b_{k+1} = b_k e^{-b_k(t_k - t_{k-1})} \quad (6) \]

\[ Q(\text{the serviceability loss function}) = \sqrt{5 - P - \sqrt{5 - P_1}} \quad (7) \]

\[ Q_2 = Q \text{ when } P = P_2; \]
\[ Q_{2'} = \sqrt{5 - P_{2'}^2 - \sqrt{5 - P_1}} \quad (8) \]

\( \alpha \) (a daily temperature constant) = \( \frac{1}{2} \) (maximum daily temperature + minimum daily temperature) - 32°F.

\( \alpha \) = the effective value of \( \alpha \) for a typical year in a given locality, defined by the formula for the harmonic mean

\[ \alpha = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{\alpha_i} \right) \quad (9) \]

in which \( n \) is the number of days in a year and \( \alpha_i \) is the value of \( \alpha \) for the \( i\)th day of the year.

\( P = \text{the serviceability index at time } t; \)
\( P_1 = \text{the expected maximum value of } P, \text{ occurring only immediately after initial or overlay construction; } \)
\( P_2 = \text{the specified value of } P \text{ at which an overlay will be applied; and } \)
\( P_{2'}(\text{a swelling clay parameter}) = \text{the assumed value of } P \text{ at } t = 0, \text{ in the absence of traffic. In general, } 0 \leq P_{2'} \leq P_2. \]

Economic Considerations

The costs considered in the computer program are those of initial construction, routine maintenance, overlay construction, users' costs, seal coat, and salvage value.

The initial construction costs are computed from a cost per compacted cubic yard. Routine maintenance costs are based on a first-year cost per lane-mile and an incremental increase each year. Seal coat costs are a direct cost per lane-mile for each application. The overlay costs are computed based on the cost of asphaltic concrete, with an additional cost equal to 1 in. of asphaltic concrete as a level-up course. Users' costs are costs to the highway user incurred during overlay construction and are computed based on which one of five traffic handling models is chosen by the program user. The costs are due to delays caused by slowing or stopping of traffic by overlay equipment and personnel, congestion because one or more lanes of traffic are closed, and additional distances traveled due to detours. The salvage value is computed as a percentage of the cost of the structure as it exists at the end of the analysis period.

All costs are discounted to their value at the beginning of the analysis period and then are combined to form the over-all cost of the pavement.

Program Constraints

Constraints are variables provided by the program user and serve two purposes: (1) there may be some restraints that are necessary to make the design practical due to conditions not taken into account in this program; (2) constraints serve to control the operation of the computer program.

The constraints in this program are (1) the maximum funds available for initial construction, (2) the minimum and maximum thicknesses of the materials, (3) the maximum total thickness of initial construction, and (4) the minimum overlay thickness.

Computer Program

A sophisticated computer program was written by Scrivner et al. (6) to solve the models indicated previously and to perform the necessary calculations. Figure 3 is a summary flow chart illustrating the mechanics of the computer program.

Output from the computer program is an ordered list of possible pavement designs that satisfy the requirements specified by the user, based on minimum total cost.
READ IN and PRINT DATA

DO for all designs

IS Initial Design Cost more than Funds Available
  Yes This design is NOT a feasible design. GO TO next design.
  No

IS Design Thickness more than Total Thickness Restraint
  Yes This design is NOT a feasible design. GO TO next design.
  No

Calculate design Life

IS Design Life less than minimum time to first overlay
  Yes This design is NOT a feasible design. GO TO next design.
  No

IS there an Overlay Policy which lasts the Analysis Period
  No This design is NOT a feasible design. GO TO next design.
  Yes

This is a feasible design. Calculate the total cost.

SORT all feasible designs by total cost and PRINT the most optimal designs

Figure 3. Summary flow chart of the Scrivner program. Source (15).
CHAPTER TWO

FINDINGS

In Chapter One an operational pavement systems model, or pavement analysis method, is examined. No other comparable method was found in the literature. A thorough evaluation of the method, comparing it to the conceptual model, shows that it contains most general factors considered in pavement design. In general, systems analysis is a process in which improvements are made with each succeeding cycle of the process. In actuality, most research improvement is a cyclic process, with each cycle adding some new factor or improving some portion of a particular problem.

On this basis it seemed ideal to modify and extend the work developed by Scrivner, in order to fulfill the needs of this project, making any improvement possible within the scope of the funds available. Thus, the working analytical method developed on this project, Systems Analysis Model for Pavements (SAMP), is an extension of the algorithm conceived and developed by Scrivner, McFarland, and Carey (6). Although the algorithm is basically the same, many of the aspects of the SAMP program were developed on this project. SAMP is an operational systems model; i.e., a set of models with its pertinent computer program for making solutions. For easy identification, because improvements are constantly being added to the system, numbers are added to the acronym (i.e., SAMP1, SAMP2, SAMP3, . . . SAMPn) to designate subsequent versions of the same basic program to which improvements have been made.

PURPOSE OF SYSTEMS ANALYSIS METHOD FOR PAVEMENTS

The purpose of the SAMP systems analysis is to design from available input data a pavement that can be maintained above the specified minimum serviceability over the specified design period at a minimum over-all cost. The computer program provides the decision maker with a set of feasible pavement designs arranged in some priority order—in the present case, that of increasing total cost. Other pertinent information necessary for use in making rational design decisions is also provided. A variety of input data is necessary for the solution of the problem. Figure 4 is a typical input data sheet from the computer printout which illustrates an example set of input from the program. Figure 5 shows example output of the program. The information provided for each alternate design includes (1) initial construction configuration, (2) overlay schedule, and (3) a cost breakdown. The cost breakdown includes initial construction, overlays, routine maintenance, salvage value, and users' costs during overlay construction. All costs are discounted to present value using the interest rate selected by the program user.

INPUTS FOR SAMP5

The particular version of the Systems Analysis Model for Pavements described in this report is SAMP5, the fifth in the series. Seven classes of input variables are required by the program, as follows. Each class of variables is important in the solution of a problem by the computer. However, the typical pavement designer probably is familiar with only some of these categories.

1. Material Properties. A great deal of information is required in the program concerning materials available for pavement construction; i.e., their cost, strength, depth control factors, and expected salvage value, as well as the soil support value of the material if it were used as a subgrade. These factors are shown in Figure 4.

2. Program Control and Miscellaneous Parameters. Five input variables are shown in this category in Figure 4.

3. Environmental and Serviceability Parameters. This program considers two types of environmental variables. The most important is involved with evaluating the effect of swelling clay on the performance of the pavement. This effect is calculated with two parameters. The first (called BONE in the program) is a function of the material properties and controls the rate of change of serviceability with time. The other, P_s', is the level of serviceability that the pavement would reach due to the effect of swelling clay alone in the absence of traffic. The second category of environmental variables involves the general climactic and geologic effects of the region, as specified by the "AASHO Interim Guide" (10). This effect has not yet been well quantified, although some states use it in their design methods (16).

Closely related to the environmental variables are the serviceability parameters. These include a serviceability index at initial construction, PSI, the serviceability index after overlay construction, P_s, and the lower limit of the serviceability index or the level when overlay construction or failure occurs, P_s, as shown in Figure 4.

4. Load and Traffic Variables. The load variables used in this program include the total accumulation of the equivalent of 18-kip axle loads expected to be carried by the pavement during the analysis period, and the average daily traffic (ADT) at the beginning and at the end of the analysis. These variables are combined in the program to give a load-time function that distributes the total loads carried throughout the analysis period. The program then uses this information to calculate user cost due to traffic delay (as is discussed later) and uses the loads to be carried in the model to predict pavement life. Two other traffic load variables also are important: (1) the percent of ADT passing through the overlay zone per hour, and (2) the type of road under construction (rural or urban).
PROGRAM SAMPS (SYSTEMS ANALYSIS MODEL FOR PAVEMENTS) REVISED 21 MAY 70
RUN TO SOLVE THE AVERAGE VALUE PROBLEM 6 JUN 70 DLP

PROB 4000. ALL VARIABLES AT ENGINEERING AVERAGE

THE CONSTRUCTION MATERIALS UNDER CONSIDERATION ARE

<table>
<thead>
<tr>
<th>LAYER CODE</th>
<th>NAME</th>
<th>COST</th>
<th>STR.</th>
<th>MIN.</th>
<th>MAX.</th>
<th>SALVAGE</th>
<th>SOIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>ASPHALTIC CONCRETE</td>
<td>10.00</td>
<td>.44</td>
<td>6.00</td>
<td>8.00</td>
<td>50.00</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>CRUSHED STONE</td>
<td>5.00</td>
<td>.14</td>
<td>5.00</td>
<td>8.00</td>
<td>50.00</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>GRAVEL</td>
<td>2.00</td>
<td>.11</td>
<td>5.00</td>
<td>10.00</td>
<td>50.00</td>
</tr>
<tr>
<td>SUBGRADE</td>
<td></td>
<td>-0.00</td>
<td>-0.00</td>
<td>-0.00</td>
<td>-0.00</td>
<td>-0.00</td>
<td>4.25</td>
</tr>
</tbody>
</table>

PROGRAM CONTROL AND MISCELLANEOUS VARIABLES

NMB - THE NUMBER OF OUTPUT PAGES FOR THE SUMMARY TABLE (10 DESIGNS/PAGE). 3
NM - THE TOTAL NUMBER OF MATERIALS AVAILABLE, EXCLUDING SUBGRADE. 3
CL - THE LENGTH OF THE ANALYSIS PERIOD (YEARS). 20
ALW - THE WIDTH OF EACH LANE (FEET). 12
RATE - THE INTEREST RATE OR TIME VALUE OF MONEY (PERCENT) 5.0

ENVIRONMENTAL AND SERVICEABILITY VARIABLES

R - REGIONAL FACTOR. 1.7
PSI - THE SERVICEABILITY INDEX OF THE INITIAL STRUCTURE. 4.2
P1 - THE SERVICEABILITY INDEX OF AN OVERLAY. 4.2
P2 - THE MINIMUM ALLOWED VALUE OF THE SERVICEABILITY INDEX. (POINT AT WHICH AN OVERLAY MUST BE APPLIED). 2.5
P2P - THE LOWER BOUND ON THE SERVICEABILITY INDEX WHICH WOULD BE ACHIEVED IN INFINITE TIME WITH NO TRAFFIC 1.5
NONE - THE RATE AT WHICH NON-TRAFFIC FACTORS REDUCE THE SERVICEABILITY INDEX. .120

LOAD AND TRAFFIC VARIABLES

RO - THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE BEGINNING OF THE ANALYSIS PERIOD 10000
RC - THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE END OF ANALYSIS PERIOD. 20000
XNC - THE ONE-DIRECTION ACCUMULATED NUMBER OF EQUIVALENT 18-KIP AXLES DURING THE ANALYSIS PERIOD. 5000000
PROP - THE PERCENT OF ADT WHICH WILL PASS THROUGH THE OVERLAY ZONE DURING EACH HOUR WHILE OVERLAYING IS TAKING PLACE 6.0
ITYPE - THE TYPE OF ROAD UNDER CONSTRUCTION (1-RURAL, 2-URBAN). 1

CONSTRAINT VARIABLES

XTTU - THE MINIMUM ALLOWED TIME TO THE FIRST OVERLAY 2.0
XTOU - THE MINIMUM ALLOWED TIME BETWEEN OVERLAYS. 3.0
CMAA - THE MAXIMUM FUNDS AVAILABLE FOR INITIAL CONSTRUCTION 5.00
ICMAX - THE MAXIMUM ALLOWABLE TOTAL THICKNESS OF INITIAL CONSTRUCTION 32.0
OVMIN - THE MINIMUM THICKNESS OF AN INDIVIDUAL OVERLAY. .50
OVMAX - THE ACCUMULATED MAXIMUM THICKNESS OF ALL OVERLAYS 2.5

TRAFFIC DELAY VARIABLES ASSOCIATED WITH OVERLAY AND ROAD GEOMETRICS

ACPR - ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR). 75.0
ACCO - ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/COMPACTED CY). 1.80
XLSN - THE DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE OVERLAY DIRECTION. .60
XLSL - THE DISTANCE AROUND THE OVERLAY ZONE (MILES) 0.00
HPD - THE NUMBER OF HOURS/DAY OVERLAY CONSTRUCTION TAKES PLACE 8.0

TRAFFIC DELAY VARIABLES ASSOCIATED WITH TRAFFIC SPEEDS AND DELAYS

PP02 - IN THE OVERLAY DIRECTION THE PERCENT OF VEHICLES THAT WILL BE STOPPED BECAUSE OF THE MOVEMENT OF PERSONNEL OR EQUIPMENT. 5.00
PPN2 - IN THE NON-OVERLAY DIRECTION. 5.00
DDG2 - IN THE OVERLAY DIRECTION (HOURS). .150
DDN2 - IN THE NON-OVERLAY DIRECTION (HOURS) .150
AAS - THE AVERAGE APPROACH SPEED TO THE OVERLAY AREA, 50
ASO - THE AVERAGE SPEED THROUGH THE OVERLAY AREA 30
ASN - IN THE NON-OVERLAY DIRECTION (MPH), 50
MODEL - THE TRAFFIC HANDLING MODEL USED. 3

MAINTENANCE VARIABLES

X2-THE NUMBER OF DAYS PER YEAR THAT THE TEMPERATURE REMAINS BELOW 32F. 60
CLW - THE COMPOSITE LABOR WAGE 2.05
CERR - THE COMPOSITE EQUIPMENT RENTAL RATE. 2.50
CMAT - THE RELATIVE MATERIAL COST (1.00 IS AVERAGE) 1.00

Figure 4. Typical computer listing of input data, SAMPS.
**SUMMARY OF THE BEST DESIGN STRATEGIES IN ORDER OF INCREASING TOTAL COST**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATERIAL ARRANGEMENT</strong></td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>ABC</td>
<td>ABC</td>
<td>ABC</td>
<td>ABC</td>
<td>AB</td>
<td></td>
</tr>
<tr>
<td><strong>INIT. CONST. COST</strong></td>
<td>2.153</td>
<td>2.222</td>
<td>2.014</td>
<td>2.083</td>
<td>2.639</td>
<td>2.917</td>
<td>2.917</td>
<td>2.708</td>
<td>2.708</td>
<td>2.639</td>
</tr>
<tr>
<td><strong>OVERLAY CONST. COST</strong></td>
<td>1.127</td>
<td>1.092</td>
<td>1.309</td>
<td>1.262</td>
<td>.825</td>
<td>.558</td>
<td>.570</td>
<td>.802</td>
<td>.802</td>
<td>.863</td>
</tr>
<tr>
<td><strong>USER COST</strong></td>
<td>.271</td>
<td>.252</td>
<td>.303</td>
<td>.297</td>
<td>.203</td>
<td>.130</td>
<td>.138</td>
<td>.201</td>
<td>.202</td>
<td>.208</td>
</tr>
<tr>
<td><strong>ROUTINE MAINT. COST</strong></td>
<td>.588</td>
<td>.633</td>
<td>.594</td>
<td>.592</td>
<td>.624</td>
<td>.710</td>
<td>.714</td>
<td>.631</td>
<td>.633</td>
<td>.627</td>
</tr>
<tr>
<td><strong>SALVAGE VALUE</strong></td>
<td>-.510</td>
<td>-.550</td>
<td>-.510</td>
<td>-.523</td>
<td>-.576</td>
<td>-.602</td>
<td>-.602</td>
<td>-.589</td>
<td>-.589</td>
<td>-.576</td>
</tr>
<tr>
<td><strong>NUMBER OF LAYERS</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>LAYER DEPTH (INCHES)</strong></td>
<td>D(1)</td>
<td>7.75A</td>
<td>8.00A</td>
<td>7.25A</td>
<td>7.50A</td>
<td>6.00A</td>
<td>6.00A</td>
<td>6.25A</td>
<td>6.25A</td>
<td>6.00A</td>
</tr>
<tr>
<td></td>
<td>D(2)</td>
<td>6.00B</td>
<td>5.00B</td>
<td>5.00B</td>
<td>5.00B</td>
<td>5.00B</td>
<td>5.00B</td>
<td>5.00B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D(3)</td>
<td>6.00C</td>
<td>10.00C</td>
<td>8.75C</td>
<td>5.00C</td>
<td>8.25C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NO. OF PERF. PERIODS</strong></td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
<td></td>
<td>1(2)</td>
<td>5.797</td>
<td>7.734</td>
<td>5.266</td>
<td>5.844</td>
<td>8.469</td>
<td>11.625</td>
<td>11.344</td>
<td>9.063</td>
<td>9.234</td>
</tr>
<tr>
<td></td>
<td>1(5)</td>
<td>20.656</td>
<td>20.125</td>
<td>22.062</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>OVERLAY POLICY (INCH)</strong></td>
<td>(INCLUDING LEVEL-UP)</td>
<td>0(1)</td>
<td>1.5</td>
<td>2.5</td>
<td>2.0</td>
<td>2.0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
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<td></td>
<td>0(2)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
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<td>1.5</td>
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<td></td>
<td>0(3)</td>
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<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0(4)</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 5. Typical computer output of SAMP5.*
5. Constraint Variables. Figure 4 lists six variables as constraints on the operation of the program. They must be chosen by the pavement designer (program user) because they control certain decisions in the pavement system. These variables probably are new to the reader because they are implicit in other design methods, or are ignored completely. The minimum and maximum thicknesses of the construction materials listed under material properties also are constraints on the system and limit the range of feasible designs.

6. Traffic Delay Variables. These are divided into two parts. The first contains those variables associated with the overlay procedure and the road geometrics. There are six such variables, as shown in Figure 4.

The second category contains those associated with the traffic speed and delays. There are five such variables (Fig. 4).

These variables are used to calculate user vehicle costs during the overlay of the various proposed pavement designs. They are discussed further by Scrivner et al. (6).

7. Maintenance Variables. Four maintenance variables are required to implement the NCHRP maintenance study that is used as the basis for calculating projected maintenance costs in this program (17) (Fig. 4). The exact formulation of their use in this program is shown in Appendix C.

PROGRAM OPERATION

The SAMP5 computer program uses an algorithm similar to the system discussed in Chapter One. The main differences involve the model used for calculating routine maintenance cost, the performance models, and the use of seal coats.

The operation of the program, as shown in Figure 6, can be divided into four sections, as follows:

1. Initial Construction. The variables used in this phase of the program are material strengths, thickness ranges, and initial serviceability level. The material strengths include the AASHO strength coefficients as well as soil support values as described in NCHRP Report 128 (16). The system takes the thickness ranges of the materials and increments through all possible layer and thickness combinations, calculating the structural number for each layer selection. The asphaltic concrete is incremented by ¼-in. steps; the increment of the other layers is in steps equivalent in cost to ¼ in. of asphaltic concrete rounded off to the nearest ¼ in. (i.e., if the cost of asphaltic concrete is $10 per cubic yard and the cost of gravel is $2 per cubic yard, the increment for gravel is ¼ (10/2) = 1¼ in.) Each structural number then is combined with the loading and nontraffic deterioration parameters in the performance model to determine the first period of the performance history.

Each initial construction design must first satisfy three constraints: it must (1) cost no more than the maximum funds available for initial construction, (2) be no thicker than the total thickness constraint, and (3) have a life (length of time until the serviceability index reaches the minimum allowed, \( P_0 \)) at least as long as the minimum time to the first overlay. For each design that meets these requirements the program continues to the overlay phase.

2. Overlay Design. The variables used in the overlay calculations are (1) the lower bound on the serviceability index, (2) the length of the analysis period, and (3) minimum and maximum overlay thickness constraints. If the serviceability of a pavement reaches a minimum value, \( P_0 \), as determined by the performance model, an overlay must be applied. It is assumed that overlays will be constructed of asphaltic concrete in multiples of \( \frac{1}{2} \) in. starting the minimum overlay thickness constraint. All possible combinations of thicknesses (in \( \frac{1}{4} \)-in. increments) and numbers of overlays are then tried to determine which overlay policy is most economical for each initial construction design. This interaction with the cost computation is shown as optimization feedback in Figure 6. The number of possible overlay policies is controlled by the maximum overlay thickness constraint and by the length of the analysis period.

3. Cost Computation. The computed costs in the SAMP programs are those of initial construction, overlay, maintenance, traffic delay, and salvage value. Initial construction, overlay, and traffic delay (users') costs are calculated as discussed in Chapter One. Salvage value in SAMP5 is based on a percentage of the structure existing at the end of the analysis period. A different percentage may be used for each material. Maintenance cost is calculated by the road and shoulders model of NCHRP Report 42 (17). Each cost is then discounted to its present value using the interest rate input into the program. The sum of these discounted costs is called the total cost.

4. Optimization. The main part of the optimization in the SAMP program is in the overlay procedure. The remainder of the optimization is to sort each initial construction design, together with its optimal overlay policy, in order of increasing total cost. Then the “ten best” designs are printed out in a summary table (Fig. 5). The number of pages in the summary table (10 designs per page) is specified by the program user.

PERFORMANCE MODEL

The performance model used in SAMP5 consists of three equations and a set of inequality restraints, as follows:

1. Traffic Equation. This is the same as the one shown in Chapter One.

2. Structural Number Equation. This is from the AASHO Road Test (27):

\[
SN^* = A_1D_1 + A_2D_2 + \ldots + A_nD_n
\]

in which

\( SN^* \) = structural number of the pavement;

\( A_i \) = AASHO strength coefficient of the \( i \)th layer;

\( D_i \) = thickness of the \( i \)th layer; and

\( n \) = number of layers above subgrade.

3. Performance Equation. This is from NCHRP Report 128 (16) but is modified to take into account the effects of nontraffic-associated deterioration.
Figure 6. Block diagram of SAMP pavement system.
in which

\[ SN = \left[ \frac{1.051(W_1 \cdot R)^{0.1048}}{10^{0.03971(88-3)} \cdot 10^{0.0136} \cdot (g-g')^i} \right] - 1 \] (11)

\[ SN = \text{structural number required of a pavement structure}; \]
\[ W_1 = \text{total equivalent 18-kip single-axle loads expected during the design life of the facility}; \]
\[ SS = \text{soil support term for the existing material}; \]
\[ R = \text{regional factor}; \]
\[ R = \frac{P_1 - P_2}{P_1 - 1.5} \] (13)
\[ g = \frac{M^2 + 2MV5-P_1}{P_1 - 1.5} \] (14)
\[ M = \left( \sqrt{5} - P_1^2 - \sqrt{5} - P_1 \right) \left( 1 - e^{-b_n \cdot t_n} \right) \] (15)

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\[ M = \left( \sqrt{5} - P_1^2 - \sqrt{5} - P_1 \right) \left( 1 - e^{-b_n \cdot t_n} \right) \] (15)

\[ \beta_n = 0.4 + 0.081(19)^{3.25} \] (12)

where

\[ P_1 = \text{initial serviceability index}; \]
\[ P_2 = \text{nontraffic deterioration lower limit}; \]
\[ b_n = \text{nontraffic deterioration rate at the beginning of the kth performance period}; \]
\[ t_n = \text{length of the kth performance period}. \]

4. Inequality Restraints. These also are from NCHRP Report 128 (16):

\[ D_i \geq \frac{SN_i}{A_i} \] (16)
\[ SN_i^* = A_i D_i \geq SN_2 \] (17)
\[ D_i \geq \frac{SN_i^* - SN_i}{A_i}, i = 2, \ldots, n \] (18)
\[ SN_i^* = SN_i + A_i D_i \geq SN_i + 1, i = 2, \ldots, n \] (19)

Solution of Performance Model

The first step in the solution of the performance model is to determine which inequality restraint is limiting; i.e., which layer interface has the shortest life. This is done by solving Eq. 11 for \( W_1 \), assuming that Eq. 14, the term for nontraffic deterioration, is equal to zero. The interface with the smallest \( W_1 \) is the one that will produce the shortest life. This is true because traffic and nontraffic deterioration are assumed to be independent.

When it has been determined which interface will produce the shortest life, the traffic and performance equations are solved simultaneously by an iterative process.

DEMONSTRATION OF FEASIBILITY OF REVISIONING THE PAVEMENT SYSTEMS MODEL

A prerequisite of any satisfactory systems model is that it can be readily revised as experience and research provide new input. The SAMP developed in this report is only a beginning in pavement systems design methods. As new tools and techniques are developed, they can be incorporated into the system. The feasibility is demonstrated here for using improved materials characterization studies, such as those described in NCHRP Report 140, to improve the structural subsystem of the model.

It is desirable to discuss first the fundamentals of pavement behavior and performance. The conceptual pavement system diagram in Figure 2 shows the complex interrelationship that exists between:

1. Material properties and the geometry (i.e., thickness) of the pavement layers.
2. Manifestations of pavement behavior.

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. Because material properties are discussed in NCHRP Report 140, they are not discussed here. Pavement behavior and pavement performance are discussed briefly in the following sections. A more detailed discussion of these two factors appears in Appendix E.

Pavement Behavior

The factors affecting pavement structural behavior have been defined and characterized in different ways by various individuals and groups (18-26). 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 usually have been formulated by defining factors that affect either pavement performance or failure of the pavement structure. A survey of the literature, however, indicates that there are no clear-cut and generally accepted definitions of failure that relate 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 is 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: (1) fracture, (2) distortion, and (3) disintegration. These are shown in Figure 7 and are defined in Appendix B. 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. Figure 7 also shows the manifestations of each mode of distress, and lists the mechanisms associated with each manifestation of failure. Although the next logical step would be to list the pertinent material properties for each failure mechanism noted, this has not been done because of a lack of (1) suitable constitutive equations for materials, and (2) adequate failure theories. The complexity of the former aspect is discussed in NCHRP Report 140. The first may be termed as the primary manifestation; those that occur progressively after it are termed secondary, tertiary, etc. The sequential order of these manifestations
Distress Mode | Distress Manifestation | Examples of Distress Mechanism
---|---|---
Cracking | | Excessive loading
 | | Repeated loading (i.e., fatigue)
 | | Thermal changes
 | | Moisture changes
 | | Slippage (horizontal forces)
 | | Shrinkage
Fracture | | Excessive loading
 | | Repeated loading (i.e., fatigue)
 | | Thermal changes
 | | Moisture changes
Spalling | | Excessive loading
 | | Repeated loading (i.e., fatigue)
 | | Thermal changes
 | | Moisture changes
Permanent deformation | | Time-dependent deformation (e.g., creep)
 | | Densification (i.e., compaction)
 | | Consolidation
 | | Swelling
Distortion | | Excessive loading
 | | Densification (i.e., compaction)
 | | Consolidation
 | | Swelling
Faulting | | Adhesion (i.e., loss of bond)
 | | Chemical reactivity
 | | Abrasion by traffic
Stripping and Raveling and scaling | | Adhesion (i.e., loss of bond)
 | | Chemical reactivity
 | | Abrasion by traffic
 | | Degradation of aggregate
 | | Durability of binder

Figure 7. Categories of pavement distress.

would vary depending on load, environmental conditions, etc. In most cases, a number of these may occur simultaneously.

Comparison with SAMP Program
Technically, if the SAMP program were all-encompassing, a mathematical model would be present for each of the distress mechanisms shown in Figure 7. Thus, a model would predict each of the distress modes of fracture distortion and disintegration, respectively, in a manner described by conceptual Eq. E-1 (App. E) by inputting load, environment, construction, maintenance, and structural variables considering space and time. The models used in the SAMP program do not have this finesse, because the program uses a gross transformation from the input components of a pavement structure (i.e., thickness and strength coefficients) to a present serviceability index. From prediction of present serviceability index, 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. A number of mathematical models are contained in the SAMP program, but the ones of primary interest here are the performance models developed at the AASHO Road Test (27). One model is the present serviceability equation, which indicates the ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and auto) traffic in its existing condition (18). 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 (18). A second model is a structural number model that also was developed at the Road Test (27) and subsequently was used by the AASHO Design Committee to formulate the “Interim Guides” (10, 16, 28). These models are:

\[ p = 5.03 - 1.91 \log(1 + SV) - 0.01\sqrt{C} + p - 1.38RD^2 \]  

(20)

in which

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

in which
\[
P(x, t) = F[p(x, t)]
\]

(21)

The SAMP program uses a structural number value (Eq. 22) 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. 20). Rather, some function of their combined values will be equal to the computed serviceability value (Eq. 22) to compute the present serviceability value (Eq. 23).

\[
SN = A_1D_1 + A_2D_2 + A_3D_3
\]

(22)

in which
\[
SN = \text{structural number of system;}
\]
\[
A_i = \text{structural coefficient of the ith layer; and}
\]
\[
D_i = \text{thickness of the ith layer.}
\]

(23)

in which
\[
p_i = \text{initial PSI;}
\]
\[
W = \text{number of equivalent wheel loads; and}
\]
\[
\beta, \rho = \text{parameters depending on layer thickness and strength coefficient, wheel load magnitude and configuration, etc.}
\]

The development of the secondary manifestations of fracturing and permanent deformation is shown in Figure 11, in terms of the distortion mode of distress. The distortion index might begin at a traffic value \( n_a \), which is greater than \( n_c \) because distortion is a secondary manifestation in this case. The shape of the distress function changes with the addition of distortion (Fig. 12), and the decay or slope of the distress index will be greater when the secondary manifestations of distortion and fracture occur, due to 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 use the necessary constitutive equations to solve the functional equations.
Figure 8. Interrelationship of distress mechanisms and manifestations.

Figure 9. Progressive development of the cracking index with traffic.

Figure 10. Progressive development of the distress index, considering only cracking.
Selection of Boundary Value Problems and Constitutive Equations

In the materials characterization section of this project (5), detailed steps for characterizing materials and using the results in boundary value problems are discussed. At some time in the future it would be desirable to use this information in the SAMP computer program. 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 equations for linear elastic theory (38) and layered theory (39, 40) probably represent the most advanced state of the art that is now available for use.

Figure 13 is a typical pavement structure cross-section showing 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, cracking is assumed to occur.

The computed values of stress and strain are deterministic in nature because 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 Eq. E-1. 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. Experience and studies show that cracking does not occur in this manner, but rather on a progressive basis (27). Thus, to predict progressive cracking more accurately, it is necessary that the stochastic concepts be injected into the approach. Appendix F describes a method for predicting cracking on a stochastic basis. The method assumes that if the stress is independent of strength, the probability of distress is:

\[ P(C) = P(\text{stress} > b) + P(\text{strength} < b) \]  \hspace{1cm} (24)

in which

\[ P(\cdot) = \text{probability of an event occurring; and} \]

\[ b = \text{a value defining the point where stress and strain values overlap.} \]

An equation is developed in Appendix F to quantify the foregoing functional notation. The use of this equation 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 pre-

---

**Figure 13.** Typical pavement structure cross-section showing the elastic parameters.

**Figure 14.** Typical fatigue diagram for a pavement material.
dicting cracking due to the repeated load distress mechanism. A typical fatigue curve for portland cement concrete and asphaltic concrete (Fig. 14) indicates that the greater the stress level the fewer the number of load repetitions required to failure. Although it is not stated by investigators, the solid line is an average fatigue line for the data. Monismith and Kasianchuk (41) and others have shown that the stochastic variation in asphaltic concrete may be described by lines parallel to the average fatigue line, as shown in Figure 14. 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 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, the material will last \( N_i - 80 \) load repetitions, which is greater than \( N_i - 99 \) (42).

Prediction of Cracking Index

In this section, data are used to numerically predict a cracking index history that might be developed in a pavement structure due to the repeated load distress mechanism, assuming that only the primary distress mode occurs. The cracking index then is used to predict the distress index history of the pavement. For this example, a full-depth asphaltic concrete pavement that is divided into three layers (Fig. 15) is selected; the upper layer is a wearing course; the second layer, an asphaltic concrete base; and the third layer, a subgrade.

![Diagram of pavement structure](Image)

Figure 15. Geometry and material properties used in the example problem.
The first step in the analysis is to characterize the material properties of the pavement structure. The stiffness of the asphaltic concrete may be obtained using the pavement temperature and mixture properties with the procedure described by Finn in NCHRP Report 39 (43). Values of 100,000 psi and 600,000 psi are used to represent summer and winter conditions, respectively, for the wearing course. These values are designated as the modulus of elasticity of the wearing course in the layered program. Because the base course temperatures will generally be lower than in the wearing course during the summer, a value of 500,000 psi is used for this illustrative problem. The modulus of elasticity for the subgrade layer may be characterized using the resilient modulus procedures described by Seed et al. in NCHRP Report 35 (44). Values of 3,000 psi and 10,000 psi are selected for the resilient modulus to represent poor and medium support conditions, respectively. The values of Poisson’s ratio shown in Figure 15 are based on previous experience.

A wheel load of 12,000 lb, representing a medium heavy load, is used in the example. To simplify the presentation, only one load value is used. Mixed traffic such as that experienced on a highway may be readily taken into account by procedures advanced by Kasianchuk (41) and McCullough (42) and described in Appendix F.

The fatigue properties of the asphaltic concrete may be characterized by the repeated flexural test procedures described by Deacon (30) and Epps (31). Figures 16 and 17 show a typical asphaltic concrete that was characterized in fatigue by Epps (31). Figure 16 shows the distribution expected with good quality control; Figure 17 represents poor quality control. Note that in both cases the average line is identical, but the spread in Figure 17 is considerably greater than in Figure 16. These two variations are used to predict the variation in performance for asphaltic concrete with the same average values, but representing substantially different degrees of quality control. A conventional deterministic procedure would predict that these two asphaltic concretes would have the same performance history, but it would be recognized immediately that a considerable difference in performance could be expected.

Material properties, wheel load, and layer thicknesses are used with the computer program to predict stresses in the pavement structure. Figures 18 and 19 show for poor and good soil, respectively, the tensile stress in the asphaltic concrete at the interface of the subgrade with the asphaltic concrete layer that is directly beneath the wheel load, in terms of the base stiffness. This location was selected because it represents the maximum tensile stress in the pavement structure, the area where a tensile failure may initiate. Observations of asphaltic concrete taken from in-service pavements by Monismith et al. (29) confirm the reasonableness of this hypothesis. Both figures show stress is highly dependent on the stiffness of the base, although when a thickness of 12 in. is reached the effect becomes nil, and the tensile stress becomes nil. Furthermore, it may be noted that the tensile stress decreases with increased base thickness, as would be expected. Note also that the stresses are high for summer conditions, because the wearing course loses some of its carrying capacity (i.e., stiffness) with increasing temperature. A comparison of Figures 18 and 19 shows that the stresses are substantially lower for good support condition, as would be expected.

For this example, the stress is assumed to be deterministic (i.e., zero variance) and the fatigue strength is assumed to vary around the mean value, as shown in Figures 16 and 17. This simplifying assumption does not affect the logic or concepts being illustrated, but it will influence the shape of the performance history curve. Variations in both stress and strength may be taken into account, as described in Appendix F. To be compatible with the values for cracking used in Eq. 20, the cracking index equation (Eq. E-2) in Appendix E is quantified for use hereafter as follows:

\[ CI(x, t) = \frac{\sum_{s=0}^{\infty} P(C(x, s))}{1,000} \]

in which

- \( P(\cdot) \) = probability of an event occurring; and
- \( C(x, s) \) = cracking of space and time.

The right side is defined as

\[ \sum_{s=0}^{\infty} P(C(x, s)) = \left\{ \sum_{j=1}^{k} N_j \geq 1.0 \right\} \]

in which

- \( n_j \) = the actual number of the \( j \)th stress repetitions experienced; and
- \( N_j \) = the allowable number of \( j \)th stress repetitions permissible.

The limiting value of the cracking index is 1,000 for the boundary conditions of Eq. 26. This value in essence means that 100 percent wheel path area is experiencing cracking. To demonstrate the flexibility of the approach being developed, the cracking index history is shown in considering a number of parameters in Figures 20 through 23.

Effect of Structural Variables

Figure 20 shows the possible effect of base thickness (structural variable) and season (environmental variables) on the cracking index. Note in all cases the cracking index starts at zero and, after a given number of applications, reaches the value of 1,000. In general, the cracking index rate increases as the base thickness decreases. Because the pavement structure has a lower load-carrying capacity in summer than in winter, the rate of increase is greater for summer conditions than for winter conditions. Note that for 100 percent of the wheel path area to experience cracking, 600 applications would be required for the 4-in. base thickness and 120,000 applications would be required for the 12-in. thickness.

Figure 21 shows possible effect of the subgrade stiffness on the cracking index. The poor subgrade condition is the same as a 4-in. thickness in Figure 20, and the good subgrade condition was computed for a subgrade stiffness of 10,000 psi. Figure 21 shows the difference in performance with poor and good soils. The figure also can be used to
Applications to Failure — $N_f$

Figure 16. Fatigue diagram for an asphaltic concrete with good quality control.

Figure 17. Fatigue diagram for an asphaltic concrete with poor quality control.

illustrate the effect of environmental variables. For example, the good curve could represent a condition where the subgrade is dry, and the poor support condition represents a condition where considerable moisture is present in the subgrade. Substantially greater rates of deterioration are experienced with the poor support conditions, as expected. Most pavement structures cycle between poor and good subgrade conditions during the year, and a true performance curve for a pavement would have to be the culmination of these support conditions. If the designer is capable of expressing the degree of support as a function of time, the performance history may be predicted.
Figure 18. Tensile stresses at soil-base interface with poor soil support for varying conditions of base thickness, base modulus, and seasons.
Effect of Environmental Variables

Figure 22 shows the effect of the seasonal distribution of wheel loads (load variables) on the cracking index history. The two curves marked summer and winter are identical to the 6-in. base curve in Figure 20. Owing to the decreased stiffness of the asphaltic concrete, a greater rate of deterioration is experienced in summer than in winter. These conditions represent the extremes of pavement performance. The three intermediate curves represent distributions between these extremes. For example, if 75 percent of the wheel loads occur during summer conditions and 25 percent occur during winter conditions, the rate of deterioration would be less than for summer but greater than for winter conditions. Carrying the example further, if only 25 percent of the wheel loads are experienced during summer conditions and 75 percent are experienced during winter conditions, the rate of deterioration would be less than the one previously described, but greater than for the winter condition.

Effect of Construction Control Variables

Figure 23 shows the effect of quality control (construction variables) on the distress index history of a pavement. The good and poor quality control curves are developed from Figures 16 and 17, respectively. In both cases, distresses for the 4-in. base course in Figure 15 were used. Note that
Figure 20. Effect of base thickness and season on cracking index.

Base Modulus = 600,000 psi
Subgrade Modulus = 3000 psi
Log S.D. = 0.40 Poor Control
Base Thickness = 4"  
Base Modulus = 600,000 psi  
Poor Subgrade Modulus = 3000 psi  
Good Subgrade Modulus = 10,000  
Weather Summer  
Log S.D. = 0.40 (Poor Quality Control)

Figure 21. Effect of subgrade support on computed cracking index.
the cracking index increases rapidly for the condition of poor quality control, but both curves obtain a cracking index value of 500 at the same number of load applications. This is to be expected, because the mean value lines for the two distributions are identical. From 225 applications on, the good quality control curve increases relatively more rapidly than the poor quality control curve. Again, this is to be expected, because for poor quality control some high as well as low values would be expected. It is emphasized that under conventional design procedures the predicted curves for these two conditions would be identical because stochastic variations are not considered. This figure shows that a considerably different performance history would be expected. Furthermore, if the primary cracking manifestation leads to other distress mechanisms, decay of the distress curve will be increased, and performance will be relatively poor.

The cracking index histories shown in Figures 20 through 23 may be used with Eq. 20 to compute the distress index history for the conditions prescribed. Assuming that only the primary distress mechanism of repeated loading is causing distress, Eq. 25 may be used with Eqs. 20 and 21 to define the distress index quantitatively, as follows:

\[
DI(x, t) = 1.0 - 0.0002 \sum_{i=1}^{k} \frac{n_i}{N_i} \geq 1.0 \times 1,000
\]

in which terms are as defined previously.

Figure 24 is the distress index history based on the cracking index history presented in Figure 20 for base thicknesses of 6, 8, and 12 in. for summer conditions.
Because the cracking index has only a small influence on the distress index, the change in magnitude in Figure 24 is relatively small. However, this magnitude is irrelevant, because the important point here is that the distress index has been predicted using a distress mechanism. For example, if these same cracking index values were used in the rigid equations, the relative effect would be much greater. The data in Figures 21 through 23 also could be used to predict the distress histories similar to Figure 24 if desired.

Summary
In the foregoing, the feasibility of using research findings and results to improve a systematic pavement design procedure is demonstrated—in this case with the SAMP computer program. The specific improvement of the SAMP program selected was putting the gross transformation between input variables and distress history (i.e., pavement performance) on a sound, rational basis. This particular gross transformation is a limiting feature of the SAMP program design procedure and for most other existing design procedures in that the procedures cannot be extrapolated beyond the limits in which they were derived. This has presented numerous problems in terms of performance and design in the past.

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

1. Predict a distress manifestation based on a primary distress mechanism (Fig. 7).

2. 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 (Fig. 8).

3. The effect of the primary, secondary, and higher order distress mechanisms must be defined and combined to predict a distress index history (i.e., performance) for the pavement (Fig. 12).

Only the first step is accomplished in this chapter, but the feasibility of the approach was demonstrated by actually quantifying the cracking index history based on the repeated load distress mechanism. This index then was used to predict the distress index history. In the process, material, structural, load, and construction variables were used to quantify the distress index, defining the interrelationship between these variables, as shown in the conceptual pavement design system (Fig. 2). In addition, the findings and results of a number of NCHRP research proj-
Figure 24. Effect of base thickness on distress index and $N_t$. 

Summer Weather
Poor Q.C. Log S.D. = 0.4
Subgrade Mod. = 3000 psi
$DI = 1.0 - 0.002 \sqrt{CI}$
were used as state-of-the-art procedures to specifically improve the transformation. This demonstrates the feasibility of using research results from various studies, but it also demonstrates that this work needs to be conducted in a coordinated fashion, based on priorities and the sensitivity of the parameters.

Logically, the next step in using the information developed would be to incorporate the mathematical models for predicting distress index history into the SAMP program. No attempt was made in this study to actually incorporate the repeated load distress mechanism for predicting performance into the model, because a number of other key distress mechanisms must be quantified first. When this is accomplished, these various distress mechanisms can be combined to rationally predict the distress index history or performance of a pavement structure.

Dynamic Effects
Another major area that is largely ignored in the present working model is the dynamics of the system. Existing pavement design methods largely treat the pavement design as a static problem. In reality, most of the loads applied to a pavement structure are moving. The effect of these moving loads in the dynamic sense has not been fully evaluated and is not considered in most pavement design methods. It is highly desirable that the study of these effects be continued. The probability of their importance is particularly high on heavily loaded vehicles, such as trucks, and on new jumbo jet aircraft for airfield pavement.

CHAPTER THREE
INTERPRETATION AND APPLICATION OF FINDINGS

EXAMPLE PROBLEM
A so-called average problem was chosen to best illustrate the program. A complete output list of this example problem is shown in Appendix D. The core portion of the computer input and output is shown in Figures 4 and 5.

Using the input data shown in Figure 4, the computer generated an array of possible pavement designs, the first ten of which are shown in Figure 5. Of these designs, four are one-layer designs, one is a two-layer design, and five are three-layer designs. The total predicted cost for these ten designs ranges from $3.63 to $3.76. The actual designs available to the administrator for choice range widely, as shown by the differences in Design 1 and Design 7 (Fig. 25). The cost for Design 1 is $3.63, with a smaller amount of the investment going into initial construction and additional funds employed in four subsequent overlays. On the other hand, Design 7 involves a substantial initial construction investment with a total thickness of 20 in. overall with only two overlays subsequently applied. Within the cost differential shown, the designer or administrator is free to select a design, because variability in costs probably will discount this possible cost differential, and, for practical purposes, the cost of the two designs could be considered equal.

Figure 26 shows the predicted performance histories of these two designs. Many people would consider Design 7 to be superior because only two periods of overlay are involved. However, this is a subjective weighting function not presently considered by the program.

SUBSEQUENT PROGRAM USE
SAMP5 is valuable not only as an initial design tool, but also for its use for pavement evaluation and maintenance programming. For example: the designer chooses a design—say, either Design 1 or Design 7. Based on the best information available, it is predicted that an overlay will be required after five years. At the end of four or five years, however, it will be possible for the maintenance engineer to take additional data on the section; reevaluate the conditions as they exist at that time; and, using the information as input to the program, update the predicted performance history of the section. In this way a more exact estimate of maintenance cost and predicted future cost can be made, and thus programming of maintenance funds can be more realistically applied.

SENSITIVITY ANALYSIS AND EVALUATION OF THE OPERATIONAL SYSTEM
SAMP5, an operational pavement systems model, is presented and examined in Chapter Two. As indicated in the discussion of pavement systems analysis, the evaluation of the model is an important step in the solution of the problem. Therefore, a preliminary evaluation of SAMP5, both subjective and objective, is attempted here, to provide a better understanding of the model and its various subsystems.

One effective method of evaluating the parameters in a complex model is to perform a sensitivity analysis, which
is basically an evaluation of the amount of response in a model due to a unit change in the parameters of the model. In simple linear models such as Newton's law, $f = ma$, it is easy to recognize that the output (force) is directly proportional to the input mass or the input acceleration. In more complex models it is sometimes possible to differentiate the output with respect to each input separately to obtain the rate of change of the output with respect to the specific input; i.e., for $y = x^2$, $dy/dx = 2x$. For a linear equation this represents the slope of the plot of one variable with respect to the other.

Unfortunately, with a model or set of models as complex as SAMP5 it is impossible to evaluate the sensitivity of the parameters this simply. However, it is possible to evaluate quickly the effect of the parameters by using a computer. By writing a series of computer solutions, changing the level of one variable from one solution to the next, it is possible to compare the effect of a unit change in any given variable. By running combinations of solutions in the proper manner, it is possible to evaluate the interactions of the variables in the model. It is highly desirable to run a complete factorial analysis in this fashion, to examine the behavior of the model over its complete range. Such a large-scale undertaking was impractical for this project, and a small sensitivity analysis was undertaken.

**Analysis Conducted**

The problems for this analysis were chosen to study the effects of what are considered to be important variables in several different models. These variables are (1) the nontraffic deterioration parameter for the rate at which the pavement structure reaches equilibrium, (2) the accumulated number of equivalent 18-kip axles during the analysis period, (3) the number of days the temperature remains below 32°F, (4) the strength coefficient of the asphaltic concrete layers, and (5) the soil support value of the subgrade. For each of these variables, engineering averages and extremes were chosen. The extremes were designated as either high or low, depending on whether they produced total costs above or below that of the basic average solution for the example problem previously described.

In addition to the basic average solution (all variables at their engineering averages), ten additional problems are included in this phase of the study. With all other variables at their average level, a problem was run with each of the five variables to be studied varied individually to its low value and then to its high value. The values used for each of the five variables are given in Table 1.

The effects of these variables in the projected design are analyzed by examining the optimal solution of each problem for differences in total cost and for any changes in the design strategy. Table 2 gives a summary of this information for the 11 solutions.

Plotting the total cost vs the variable level (Table 1) gives a set of curves showing the over-all effect of each variable in the region of the basic average solution. These curves are shown in Figure 27.
To get a numerical rating of the variables, the average slope of the curves of Figure 27, in cents for each change of 10 percent in the range of the variable, has been calculated for the low-to-average and average-to-high ranges as well as for the low-to-high range. These slopes and a percentile rating are given in Table 3; this shows that the soil support of the subgrade and strength coefficient of the asphaltic concrete are the most important of the variables evaluated, while the nontraffic deterioration parameter is least important as far as total cost is concerned.

Table 2 indicates that all but one variable had an effect on the initial and overlay construction designs; variable 3 (number of days maximum temperature remained below 32°F) did not. For that variable, the only difference between these solutions and the basic average solution is the cost, from which it can be inferred that variable 3 is independent of the number or the length of the performance periods. This cannot be said of the other four variables.

**Detailed Sensitivity Analysis**

To accomplish an analysis similar to the one presented previously for all the variables in the SAMP program, about 500 solutions would be required. Several thousand solutions would be needed to study completely the interactions among the variables. It is also possible to investigate the parameters in factorial form over the range of interest and to use fractional factorial solutions. Several of the variables can be shown to be independent of some of the others; thus, partitioning of the solutions can be accomplished.

It is also desirable to study each model in the system independently, evaluating each variable at two or three levels.

Breaking the computer program down into its component parts can greatly reduce the computer time required for the analysis of the individual variables. The time subroutine, for example (see program listing in Appendix C), solves the performance function for the length of each performance period. Included in this subroutine are approximately ten variables that appear at no other place in the program. To study the interactions of these ten variables would require $2^{10}$ original solutions, or 1,024 solutions. To solve a single design problem in the SAMP program, the time subroutine must be called from 5,000 times.
TABLE 1
VALUES OF VARIABLES USED IN SENSITIVITY STUDY

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nontraffic deterioration parameter</td>
<td>0.0 0.12 0.24</td>
</tr>
<tr>
<td>Accumulated number of equivalent 18-kip axles</td>
<td>$2 \times 10^4$ $5 \times 10^4$ $8 \times 10^6$</td>
</tr>
<tr>
<td>Number of days the temperature remains below 32°F</td>
<td>0 60 120</td>
</tr>
<tr>
<td>Strength coefficient of the asphaltic concrete layer</td>
<td>0.33 0.44 0.77</td>
</tr>
<tr>
<td>Soil support value of the subgrade</td>
<td>2.00 4.25 6.50</td>
</tr>
</tbody>
</table>

Subjective Analysis

The subjective analysis of the model by current individual users and potential users also is important. No user will be satisfied with the model until he truly understands more than the general facts about its working mechanisms and operation. For example, many users will object to the use of AASHO Road Test equations for structural information. Others will object to the way in which the swelling clay parameters have been formulated. All these are valid objections, because the various subsystems in the system are not perfect. In fact, many improvements and changes are needed now, and will be needed in the future, to make the model truly applicable to pavement design and evaluation.

However, it is important that some type of working model be formulated and put to use. By using the model, observing its use in the field, and beginning to develop feedback information on the results on the performance of pavements designed with the method, it will be possible to update the model, change its various subsystems, and, thus, provide a method that uses the measured values of material properties and be applicable to all locations, environments, and traffic loadings.

TABLE 2
OPTIMAL SOLUTIONS FOR SENSITIVITY STUDY PROBLEMS

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>INITIAL THICKNESS</th>
<th>INITIAL NO. OVERLAYS</th>
<th>TOTAL COST/ SQ YD ($)</th>
<th>HIGH THICKNESS</th>
<th>INITIAL NO. OVERLAYS</th>
<th>TOTAL COST/ SQ YD ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nontraffic deterioration parameter</td>
<td>8.00A 2</td>
<td>3.266</td>
<td>5.25A 3</td>
<td>3.842</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accumulated number of equivalent 18-kip axles</td>
<td>7.25A 3</td>
<td>3.220</td>
<td>6.00A 3</td>
<td>3.860</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of days the temperature remains below 32°F</td>
<td>7.75A 4</td>
<td>3.049</td>
<td>7.75A 4</td>
<td>4.307</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength coefficient of the asphaltic concrete layer</td>
<td>6.00A 2</td>
<td>2.703</td>
<td>6.00A 2</td>
<td>3.965</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil support value of the subgrade</td>
<td>6.75A 2</td>
<td>2.857</td>
<td>8.00A 3</td>
<td>4.438</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average value solution: 7.75A 4 3.628

* A, B, and C refer to material type in example problem.
Figure 27. Cost of optimal design vs variable level for solutions in sensitivity study.

VARIABLES

(1) Non-traffic deterioration parameter
(2) Accumulated number of equivalent 18-kip axles
(3) Number of days the temperature remains below 32°F
(4) Strength coefficient of the asphaltic concrete layer
(5) Soil support value of the subgrade
TABLE 3
NUMERICAL RATING OF VARIABLES

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>LOW TO AVERAGE</th>
<th>AVERAGE TO HIGH</th>
<th>LOW TO HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PERCENT-TILE RATING *</td>
<td>PERCENT-TILE RATING *</td>
<td>PERCENT-TILE RATING *</td>
</tr>
<tr>
<td></td>
<td>10% CHANGE</td>
<td>10% CHANGE</td>
<td>10% CHANGE</td>
</tr>
<tr>
<td>1. Nontraffic deterioration parameter</td>
<td>8.04</td>
<td>43.5</td>
<td>4.28</td>
</tr>
<tr>
<td>2. One-direction accumulated number of equivalent 18-kip axles</td>
<td>8.16</td>
<td>44.1</td>
<td>4.64</td>
</tr>
<tr>
<td>3. Number of days the temperature remains below 32°F</td>
<td>11.58</td>
<td>62.6</td>
<td>13.58</td>
</tr>
<tr>
<td>4. Strength coefficient of the first material (asphaltic concrete)</td>
<td>18.50</td>
<td>100.0</td>
<td>6.74</td>
</tr>
<tr>
<td>5. Soil support value of the subgrade</td>
<td>15.42</td>
<td>83.3</td>
<td>16.2</td>
</tr>
</tbody>
</table>

* Based on 100 percent for variable 4; low to average range.

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

The work presented herein, and that of Scrivner, Hutchinson, Haas, and others, shows that systems engineering must be applied to the pavement design problem if more rational realistic pavement design methods are to be developed. In this day of modern, heavy, high-speed traffic it is no longer satisfactory to use a three-variable nomograph for pavement design. As new and more complex materials continue to be used, pavements must be designed much more precisely.

This research revealed a considerable lack of coordination within the various national highway pavement and materials research programs and among the many agencies involved. It shows, however, that it is possible to develop a coordinated framework into which research from many sources can be entered. The findings also point out that the pre-planning of research to fulfill a specific priority need within the pavement system could result in greater over-all economy in the effort.

The most significant result of this phase of Project 1-10 is that an operational pavement systems model (SAMP5) was formulated and is presented for use and future development.

RECOMMENDATIONS

In using SAMP5 it will be important to have good sources of input data. There is now a dearth of good information on highway maintenance costs, various categories of highway users' costs, and other factors. It is recommended that methods for improving this data base be initiated as rapidly as possible.

It is recommended that SAMP5 be studied and used by others in an attempt to evaluate it thoroughly. Such use is essential for proper step-by-step improvement of the system. In conjunction with such implementation, it will be necessary to collect and store for future analysis and use the feedback data from routine pavement design and performance histories. Because no really good coordinated program for storing such data is presently available, one is urgently needed.

Considering all aspects of the problem (literature searches, consultation with recognized authorities, findings within the project, and the factors listed previously) it appears essential that a long-term, well-coordinated pavement management project be continued in the future to accomplish the goals of the project statement. Such
research should result in over-all economies in the national highway construction and maintenance program.

NEEDED RESEARCH

Subsequent research in this area should attempt to finalize the basic working systems formulation as a design and pavement research management tool. This would include specification of various subsystem research needs based on a complete sensitivity analysis of SAMP5.

A second major research need is to integrate the best available elastic theory into the working system as a structural subsystem. This would lead to implementation of the research accomplished in the materials characterization portion of this project (5).

A continuing effort should be made to implement the working system in several states. This effort requires national coordination, and can be accomplished best through the NCHRP.

REFERENCES

26. Monismith, C. L., "Design Considerations for Asphalt Pavements to Minimize Fatigue Distress Under
APPENDIX A

BACKGROUND OF SYSTEMS ENGINEERING APPLIED TO PAVEMENT STRUCTURAL BEHAVIOR

A pavement is a complex structure that is subjected to many diverse combinations of loading and must perform under a variety of environments. Because the subjects of material characterization and pavement performance and their interrelationships are so complicated, a coordinated framework for solution of the over-all problem of pavement design is needed. Examination of available techniques for analyzing such complex relationships revealed that the concepts of systems engineering, which have evolved in recent years in the electronics, communications, and aerospace industries, would be appropriate to the evaluation of pavement structures.

The use of systems engineering does not, per se, develop new and dramatic inputs to the solution of the pavement design problem, but it does provide a means of organizing the various segments of the total problem into an understandable framework. It proved necessary for this project, not only as an aid in the over-all definition of the problem, but also for pointing out related studies that might ultimately provide needed input for the ultimate solution. To understand the systems engineering approach, it is probably better to talk about the “concepts of systems engineering” than systems engineering itself.

Ellis and Ludwig (1) give a definition for a system that can be applied to highway and pavement structural systems:

A system is something which accomplishes an operational process; that is, something is operated on in some way to produce something. That which is operated on is usually input; that which is produced is called output, and the operating entity is called the system. The system is a device, procedure, or scheme which behaves according to some description, its function being to operate on information and/or energy and/or matter in a time reference to yield information and/or energy and/or matter and/or service.

Dommasch and Laudeman (2) use the term “systems engineering” to describe an integrated approach to the synthesis of entire systems designed to perform various tasks in what is expected to be the most efficient manner. Thus, the term “systems engineering” is used to describe an approach that views an entire system of components as an entity rather than simply as an assembly of individual parts; i.e., a system in which each component is designed to fit properly with the other components rather than to function by itself.

The systems approach emphasizes the ideas and factors that are common to the successful operation of relatively independent parts in an integrated whole. Furthermore, the successful operation of the whole is the primary objective of the system. Individual parts and equipment may not be operating most efficiently at a particular time. However, in the interest of the complete system, their action at the particular time must be compatible with over-all systems requirements for the entire period of interest.

The design of a large-scale system is overwhelming if it is attacked all at once; but if the attack is made piecemeal it is unlikely to be successful. It is necessary to subdivide the problem in a number of ways, both conceptually and organizationally; but to do this it must be possible to formulate the problem as a whole. It is also important in systems engineering to divide the problem into subsystems for analysis and to develop appropriate models, mathematical or physical, for the over-all system. Such models are inevitably simplifications of the very complex natural world, but successive iterations in the solution of the model will make it possible to increase the complexity and the acceptability of the model and its solutions.

Any system has a number of characteristics that can be related to the objectives of the individual subfunctions within the system or that may be objectives of the whole system. These characteristics may be such things as simplicity, ease of maintenance, low cost, long life, and/or good performance, all of which may be required either simultaneously or at different times (e.g., asphaltic concrete must provide long life or durability at minimum cost). Under these conditions, some compromise is often required (e.g., an increase in asphalt content to increase durability may result in lower strength and lower skid resistance).

In some systems, such as a typical city freeway, emphasis is placed on low-maintenance performance, while cost is considered less significant. Some other systems, such as farm-to-market roads, are extremely cost sensitive and are less responsive to reliability or other factors. Because of these differences in balance, each system must be considered on its own basis and the relative merits of the different objectives must be considered in order of importance. Establishing this order is the highway engineer's function.

APPLICATIONS OF THE SYSTEMS APPROACH

The system can be considered as a “black box” (Fig. A-1) equipped with a set of accessible terminals and obeying some physical law or set of laws. It is often convenient to separate the quantities that characterize the system into three categories:

1. Excitation variables—the external stimuli that influence the system behavior.
2. Response variables—those aspects of systems behavior that are of interest to the investigator.
3. Intermediate variables—those that are neither excitation nor response variables.
Rather than refer to the system as a “black box,” one can describe it as a physical object that transforms the input variables or excitation variables to the response or output variables in some still undefined manner.

If a designer could define a pavement system well enough to predict outputs from a given set of inputs with a minimum of complexity, as shown in Figure A-1, he would be satisfied from an operational point of view. Unfortunately, most of the systems problems facing civil engineers, particularly in transportation engineering, will not yield to solution without some understanding of what is going on inside the system or black box.

The scientific and engineering aspects of a systems problem usually span a broad spectrum of activities:

1. The use of physical observations to determine the laws governing its behavior.
2. The statement of mathematical models that approximate physical phenomena.
3. The design of a system for prescribed behavior using mathematical models.
4. The physical realization of a mathematical design.

Thus, systems engineers must be able to formulate the system in terms of a mathematical or physical model, or, failing this, the system must be simulated in some realistic way to observe the necessary outputs.

Another important systems engineering precept is that a number of alternate methods or designs be considered, and that the method used be one that can be shown to meet most adequately the known needs of the system.

**SYSTEMS APPLIED TO PAVEMENTS**

Having discussed the generalities of systems analysis, one may now turn to the development of a description of the pavement system. It is often convenient to regard the pavement system as the black box in Figure A-1, the contents of which are not completely discernible. The box accepts certain inputs in the form of traffic and environmental variables and responds by developing within its structure a mechanical state which, in the case of a successful design, sustains the input variables over a certain lifetime. The basic design process involves several distinct operations:

1. Appropriate input and response variables must be identified and described quantitatively.

2. Methods of selection of both construction materials and construction techniques must be adopted.

3. Response of the system to all classes of input expected to occur in service must be measured, either directly in the system itself or on some type of simulated system.

4. Quality of the response or measure of the performance of the system must be judged by an approximate criterion.

5. Modification of the system must be permitted in order to attain as near an optimum condition as possible.

To treat quantitatively the ideas described previously, it is necessary to define terms and operations more precisely. The input to the system includes traffic, environment, construction, and maintenance. The effect of traffic is to impose certain stresses on the pavement. The environmental input includes temperature and moisture in the system. In certain instances a chemical input may occur (e.g., the use of deicing salts). The response consists of the generation of a mechanical state identified by deformation and internal stress. For purposes here, the mechanical state is most readily described in terms of stress and strain.

The pavement system is characterized by properties of the individual constituents, their arrangement, and, to some extent, the method by which the system is constructed. The system function is defined as the operator which describes the manner in which the pavement accepts an input and converts it to a response. The system's function is evidently an intrinsic property of the pavement system and may be affected by aging and by the input, particularly in the case of “overloading” input; the environmental input may influence strongly the response to traffic input.

It is well to observe here that for a particular system, it is possible, although perhaps not practical, to look no further into the black box. The alternative would be to carry out a series of experiments in which expected traffic and environmental inputs are fed into the system and the response is measured. A number of alternative “boxes” could be used and their responses could be compared; and, based on evaluation of these responses, a measure of the performance of the system could be set up. Performance is in some sense a measure of the quality of the response; e.g., whether breakdown (i.e., distress) of the system results during the response, or whether excessive permanent deformation occurs, and, furthermore, whether good performance is attained for reasonable cost, both initial and maintenance. Evidently, an objective measure of performance will involve concepts of mechanical and economic life of the system. To obtain an optimum system design, it is necessary to alter the structure of the system until a maximum mechanical-economic life is achieved for a given range of inputs. It appears that some “road tests” and “satellite studies” fall into this class of black box experiment.

The principal disadvantage of the type of experiment described here is that it is not predictive; that is, changes of input variables or changes in the systems function falling outside of the range covered in the experiment must be examined by extrapolation rather than interpolation. Furthermore, the large number of variables involved in the
system (input, response, and systems function) magnifies the experimental task enormously. Consequently, it is highly desirable to place as much as possible of the system description on a rational basis so that simulation of the operation of the system can be effected, and design optimization studies can be carried out on these simulated systems prior to validation in the field. For this reason, system formulation is the next step.

PHASE DEVELOPMENT IN A SYSTEM

Any system develops in a series of phases, which repeat themselves as they succeed one another. In the first trial, the general outline of the system and one significant estimate of its performance can be drawn up or developed by engineers skilled in the state of the art using rules of thumb for many of the input parameters and omitting many others. Figure A-2 shows a simple system diagram of early pavement design methods.

The pavement engineer observes the performance of these pavements and repeats the construction of those that perform well. Those designs that perform poorly are either discontinued or modified for future use. In successive phases, the design is refined in greater detail, with the evaluation of performance and the design of interconnections in the system being carried on with greater specificity. Such has certainly been the case in the development of the design of pavement structural systems.

Figure A-3 shows a block diagram of the evolution of many existing pavement design techniques. These have evolved primarily through observations of pavement behavior and their use to modify materials specifications and testing procedures, as shown in the figure. The resulting methods are primarily empirical, although the designs themselves may be expressed as equations and the materials test values are sometimes related to a mathematical theory (e.g., Young's modulus of elasticity).

FORMULATION OF THE PAVEMENT SYSTEM

Much work remains to be done before a truly realistic description of the pavement system can be formulated. More must be known about the relationships and interactions of various classes of input variables. It will be mandatory that some type of mathematical model or transfer function be developed to describe the relationships in the system, and yet it is possible through observations of pavement behavior and knowledge of theory to begin more realistic formulations of the pavement system, as shown in Figure A-4. This figure is not intended to show an exhaustive development of the details of such a system; instead, it is an attempt to interrelate many of the factors involved in the design of a pavement system.

The important aspects of the system description include its inputs, physical character, response, output, and decision criteria.

The inputs to the system include a variety of load, environmental, construction, and maintenance variables. These are not independent variables, but affect each other, as indicated by the interactions shown. These variables are stochastic in nature and are difficult to specify and predict. Physical characteristics of the system include geometric measurements such as thickness and arrangement, and the basic properties that characterize the material behavior.
Figure A-4. Block diagram of the pavement system.
Systems response involves the behavior of the physical system when subjected to inputs such as load or temperature. These are usually measurable and involve the mechanical state, such as deflection, stress, and strain. When these so-called primary responses reach some limiting value, some type of distress occurs in the form of rupture, distortion, or disintegration. The output of the system is measured by the goods and people (the load applications) actually transported.

Decision criteria are essential in systems formulation, involving a variety of factors such as funding, cost, reliability, and riding quality. These must be combined in an appropriate way to select the proper level of acceptability for a particular purpose. This level of acceptability then provides a basis for comparing and optimizing the system output or pavement performance.

Feedback and interaction are important parts of this and any system, but they are difficult to quantify and relate mathematically. Much remains to be done with these factors, but the systems approach provides the necessary framework. Figure A-4 indicates, for example, that as the pavement deteriorates, it gets rough and generates increased maintenance costs and increased dynamic loads.

It is useful to show the interrelationships of the system graphically, as in Figure A-4. If proper progress is to be made toward an adequate solution of the problem, however, it will be necessary to develop some type of mathematical model or transfer function to describe the relationships in the system. This would allow electronic computers to be used in making the decisions involved without bias. These models will be complex because they ultimately must be stochastic to provide some adequate simulation of the real pavement system. More specific decision criteria also must be developed for use in the process.

The need for these improved methods of pavement systems evaluation will be intensified as traffic demands grow, as costs increase, and as the complexity and variety of materials used in pavement construction continue to multiply.

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APPENDIX B

DEFINITIONS OF TERMS

Performance: 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 with a performance index as suggested by Carey and Irick (18). As such, it is a direct function of the present serviceability history of the pavement.

Present serviceability: ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and automobile) traffic in its existing condition. Note that the definition applies to the existing condition, the one on the day of the rating, not to the assumed condition the next day or on any other day, future or past.

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

Distress mechanisms: those responses that can 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.

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

Fracture: the state of being broken apart, a cleavage of the member or material, including all types of cracking, spalling, and slippage.

Distortion: a 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.

Disintegration: the state of being decomposed or abraded into constitutive elements; i.e., stripping, raveling, scaling, etc.

System: something that accomplishes an operational process; i.e., something is operated on in some way to produce something. That which is operated on is usually input; that which is produced is called output; the operating entity is called the system. The system is a device, procedure, or scheme that behaves according to some description, its function being to operate on information and/or energy and/or matter in a time reference to yield information and/or energy and/or matter and/or service (Ellis and Ludwig).

Systems failure: may be expressed as a condition where the distress from the system output has exceeded an acceptable level based on the decision criteria.

Hardware: in the design system, the physical equipment required, such as the computer and the Lane-Wells Dynaflect.
Software: the set of computer programs that are used for the solutions made in the design system.

Model: a system of postulates, data, and inferences presented as a mathematical description of a conceptual reality.

Feedback: reversion of the pavement distress or limiting response data to the data bank for use as new design input.

Concomitant variables: variables that are not directly considered, but that accompany variables that are directly considered.

APPENDIX C
COMPUTER PROGRAM LISTING
C **** PROGRAM SAMS ****
C
C PROGRAM SAMS IS THE FIFTH IN A SERIES OF COMPUTER
C PROGRAMS WHICH PERFORMS THE DESIGN OF OVERLAY
C MATERIALS FOR ROADWAYS IN THE DESIGN OF AN OVERLAY
C PROJECT. THE ANALYSIS OF THE BEHAVIOR OF MATERIALS
C WITHIN THE ZONE IS MADE USING THE MODEL CONCEPT
C DEVELOPED BY F H SCRIVNER. REGIONAL FACTOR, R-T,15 A
C PARAMETER THAT KEEPS TRACK OF THE DESIGN NUMBER FOR THE SAMP
C PROJECT.
C
C THE SAMS SERIES IS BASED ON A PAVEMENT SYSTEMS ANALYSIS
C MODEL CONCEPT AND COMPUTER PROGRAM DEVELOPED BY F H SCRIVNER.
C A 2 COLUMN MATHEMATICAL PROGRAM FOR PAVEMENTS.
C
C R CB CALCULATIONS ARE MADE FOR THE DESIGN OF THE OVERLAY.
C THE CROWDING CONTROL PROGRAMS ARE PART OF THE SAMS SERIES.
C
C PROGRAMS FOR THE DESIGN OF MATERIALS FOR PAVEMENTS
C ARE BASED ON AN OVERLAY SYSTEM ANALYSIS MODEL DEVELOPED BY F H SCRIVNER.

C TRANSPORTATION INSTITUTE RESEARCH REPORT 32-11, R SYSTEMS ANALYSIS
C MODEL CONCEPT AND COMPUTER PROGRAM DEVELOPED BY F H SCRIVNER.

C C PROGRAMS FOR THE DESIGN OF MATERIALS FOR PAVEMENTS
C ARE BASED ON AN OVERLAY SYSTEM ANALYSIS MODEL DEVELOPED BY F H SCRIVNER.

C COMMON INDEXES = (INDEX1, INDEX2) TYPE LAYER, MATYPE, MODEL, NM.
C READ THE LOAD AND TRAFFIC VARIABLES.
C READ IN THE MATERIAL COMBINATIONS FOR THE ALTERNATIVE DESIGNS.
C READ IN THE CONSTRUCTION MATERIALS AND THEIR PROPERTIES.
C READ IN THE ENVIRONMENTAL AND SERVICEABILITY VARIABLES.
C READ IN THE LOAD AND TRAFFIC VARIABLES.
C READ IN THE MATERIAL COMBINATIONS FOR THE ALTERNATIVE DESIGNS.
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C READ IN THE MATERIAL COMBINATIONS FOR THE ALTERNATIVE DESIGNS.
C READ IN THE CONSTRUCTION MATERIALS AND THEIR PROPERTIES.
C READ IN THE ENVIRONMENTAL AND SERVICEABILITY VARIABLES.
C NOW STORE THE TOTAL COST FOR A LATER SORT TO OBTAIN THE OVERALL OPTIMAL DESIGN.

C THE FOLLOWING DESIGNS ARE POSSIBLE. 

NOW THE SORT ROUTINE TO OBTAIN THE OVERALL OPTIMAL DESIGN.

C ARE NOT POSSIBLE DESIGNS TO SELECT FROM.

C THE FOLLOWING DESIGNS ARE IMPOSSIBLE UNDER THE CRITERION.

C THE FOLLOWING DESIGNS ARE IMPOSSIBLE UNDER THE CRITERION.

C ARE NOT POSSIBLE DESIGNS TO SELECT FROM.

C CONTINUE

C NOW STORE THE TOTAL COST FOR A LATER SORT TO OBTAIN THE OVERALL OPTIMAL DESIGN. 

C ARE NOT POSSIBLE DESIGNS TO SELECT FROM.

C THE FOLLOWING DESIGNS ARE POSSIBLE. 

NOW THE SORT ROUTINE TO OBTAIN THE OVERALL OPTIMAL DESIGN.

C ARE NOT POSSIBLE DESIGNS TO SELECT FROM.

C THE FOLLOWING DESIGNS ARE IMPOSSIBLE UNDER THE CRITERION.

C ARE NOT POSSIBLE DESIGNS TO SELECT FROM.

C CONTINUE

C THE FOLLOWING DESIGNS ARE IMPOSSIBLE UNDER THE CRITERION.

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C THE FOLLOWING DESIGNS ARE IMPOSSIBLE UNDER THE CRITERION.
C THE REMAINDER OF THE OVERLAY OPTIMIZATION RESEMBLES A **TREE***. IT
C IS NECESSARY TO SELECT THE OVERLAY POLICY WITH THE LEAST COST.
C ABO = 0.0
C ABO IS THE ACCUMULATED DEPTH OF ALL PREVIOUS OVERLAYS.
C DSAY = DOVER(1)
C
104 DO DEL = OVPRM
C THE DEPTH OF LAYER 1 IS (ORIGINAL D1) + SUM OF PREVIOUS OVERLAYS +
C CURRENT OVERLAY DEPTH.
C DOVER(1) + DSAY=ABDDEL.
C IF (ABDDEL) GT. OVMAX) GO TO 194.
C DSAY = 0.0
C DO 109 J=1, LAYER
C SNPRIM = XN
C BI = BIP
C SN = (SNPRIM .+ BIP)/2.
C
119 SN = 1
C TIME = DOVER(J)
C IF (TIME .LT. LAYER) GO TO 120.
C
120 DEL = DEL+DEL0.5
C TIME = TIME + DEL
C GO TO 114
C
134 DEXT(J) = DEL0
C AD = TPRIM-RD/CL=CM.
C DETERMINE THE PRESENT WORTH OF USER COST DURING THE 1 TH PERFORMANCE
C PERIOD IF T .GE. CL. GO TO 144.
C TPRIM = T + TIME DEL0.
C
144 DEXT(J) = DEL0
C CALL MAX(1.0, TPRIM, 0.0)
C ABDD = ABDD+DELY.*TIME
C GO BACK TO STATEMENT 114 TO DETERMINE THE OVERLAY COSTS.
C
158 = TIME + 1.0
C THE FOLLOWING ARE TABLES CONTAINING THE USER COSTS, USEF
C
158 = TIME + 1.0
C DATA CCSU/G.849, 11,769, 19.5, 00.00, 49,01.2, 67.868, 6. • USER 120
C
210 XH = 0.5
C IF (DEL 'LT. TIME) GO TO 165.
C XH = 0.5
C
215 IF (GETL .LT. LST) GO TO 165.
C IF (GETL .GT. LST) GO TO 165.
C
220 RETURN
C E N
C SUBROUTINE TIME (1 = SN, XNPRIM, PRIM, XN, ISW, BIP, BIP)
C
1 G0, DXY, BI
C COMMON INDEX00, INDEX, ITEST, ITPY, LAYER, MATYPE, MODEL, NM,
C
1 NAPE, NPROB, NPB
C COMMON ANGLE1, ANGLE2, ANGLE, ANGLE, ANGLE1, ANGLE2, ANGLE
C 1 MINI, DOVER(1), DSAY, LAYER, SNX, TPRIM, PRIM, XNPRIM
C 1 TPROM, XNPRIM = XNPRIM = 0.0
C 1 CNEX, TL, CL = TIME + CL0, RC = TPRIM
C 1 SNPRIM = XNPRIM
C 1 TIME = TIME + CL0
C C AN ITERATIVE PROCEDURE TO DETERMINE HOW LONG THE OVERLAY
C PERFORMANCE PERIOD WILL END AT TIME TIME + CL0. PERFORM.
C C PERIOD IS SHORTER THAN THE MINIMUM TIME BETWEEN OVERLAYS.
C IF (CNEX .LT. 1) RETURN
C
1 TEST05 = 0
C BIP = TPRIM
C DELT = XTO)
C GO TO 116
C 044 RETURN
C E N
C SUBROUTINE TIME (1 = SN, XNPRIM, PRIM, XN, ISW, BIP, BIP)
C
1 G0, DXY, BI
C COMMON INDEX00, INDEX, ITEST, ITPY, LAYER, MATYPE, MODEL, NM,
C
1 NAPE, NPROB, NPB
C COMMON ANGLE1, ANGLE2, ANGLE, ANGLE, ANGLE1, ANGLE2, ANGLE
C 1 MINI, DOVER(1), DSAY, LAYER, SNX, TPRIM, PRIM, XNPRIM
C 1 TPROM, XNPRIM = XNPRIM = 0.0
C 1 CNEX, TL, CL = TIME + CL0, RC = TPRIM
C 1 SNPRIM = XNPRIM
C 1 TIME = TIME + CL0
C C AN ITERATIVE PROCEDURE TO DETERMINE HOW LONG THE OVERLAY
C PERFORMANCE PERIOD WILL END AT TIME TIME + CL0. PERFORM.
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C BIP = TPRIM
C DELT = XTO)
C GO TO 116
C 044 RETURN
C E N
C SUBROUTINE TIME (1 = SN, XNPRIM, PRIM, XN, ISW, BIP, BIP)
C
1 G0, DXY, BI
C COMMON INDEX00, INDEX, ITEST, ITPY, LAYER, MATYPE, MODEL, NM,
C
1 NAPE, NPROB, NPB
C COMMON ANGLE1, ANGLE2, ANGLE, ANGLE, ANGLE1, ANGLE2, ANGLE
C 1 MINI, DOVER(1), DSAY, LAYER, SNX, TPRIM, PRIM, XNPRIM
C 1 TPROM, XNPRIM = XNPRIM = 0.0
C 1 CNEX, TL, CL = TIME + CL0, RC = TPRIM
C 1 SNPRIM = XNPRIM
C 1 TIME = TIME + CL0
C C AN ITERATIVE PROCEDURE TO DETERMINE HOW LONG THE OVERLAY
C PERFORMANCE PERIOD WILL END AT TIME TIME + CL0. PERFORM.
C C PERIOD IS SHORTER THAN THE MINIMUM TIME BETWEEN OVERLAYS.
C IF (CNEX .LT. 1) RETURN
C
1 TEST05 = 0
C BIP = TPRIM
C DELT = XTO)
C GO TO 116
C 044 RETURN
C
C MODEL 2
106 OUTRAT = TRAFIO(I*ITYPE-1, NLRU)
RECUV = TRAFIO(I*ITYPE-1, NLROI)
IF (TYPF .LE. OUTRAT) GO TO 156
PO1 = (1.-(EXP(AO1-EXP(AQ(,1.)))/EXP(AQ(,1.)))*EXP(AO1)
PO1 = PO1
1 CONTINUE
GO TO 156
C MODEL 3
116 OUTRAT = TRAFIO(I*ITYPE-1, NLRU)
RECUV = TRAFIO(I*ITYPE-1, NLROI)
IF (TYPF .LE. OUTRAT) GO TO 156
PO1 = (1.-(EXP(AO1-EXP(AQ(,1.)))/EXP(AQ(,1.)))*EXP(AO1)
PO1 = PO1
1 CONTINUE
GO TO 156
C MODEL 4
126 OUTRAT = TRAFIO(I*ITYPE-1, NLRU)
RECUV = TRAFIO(I*ITYPE-1, NLROI)
IF (TYPF .LE. OUTRAT) GO TO 156
PO1 = (1.-(EXP(AO1-EXP(AQ(,1.)))/EXP(AQ(,1.)))*EXP(AO1)
PO1 = PO1
1 CONTINUE
GO TO 156
C MODEL 5
136 OUTRAT = TRAFIO(I*ITYPE-1, NLRU)
RECUV = TRAFIO(I*ITYPE-1, NLROI)
IF (TYPF .LE. OUTRAT) GO TO 156
PO1 = (1.-(EXP(AO1-EXP(AQ(,1.)))/EXP(AQ(,1.)))*EXP(AO1)
PO1 = PO1
1 CONTINUE
GO TO 156
C MODEL 6
146 OUTRAT = TRAFIO(I*ITYPE-1, NLRU)
RECUV = TRAFIO(I*ITYPE-1, NLROI)
IF (TYPF .LE. OUTRAT) GO TO 156
PO1 = (1.-(EXP(AO1-EXP(AQ(,1.)))/EXP(AQ(,1.)))*EXP(AO1)
PO1 = PO1
1 CONTINUE
GO TO 156
C MODEL 7
156 CONTINUE
C NOW COLLECT ALL PENDIENT INFORMATION SO THAT THE USER COST
C FOR THE OVERLAY CAN BE COMPUTED.
C
C DATA ARRAY FOR PERCENTAGE OF MAINTENANCE REQUIREMENTS
DATA PLW,PERR,PMA1,0.6,0.19,0.21/
DATA DLW,DERP,MAT,0.75,0.23,0.35/
DATA DLW,DERP,MMAT,0.79,0.37,0.04/
DATA PLW,PERR,PMA1,0.6,0.19,0.21/
DATA DLW,DERP,MMAT,0.79,0.37,0.04/
DATA PLW,PERR,PMA1,0.6,0.19,0.21/
DATA DLW,DERP,MMAT,0.79,0.37,0.04/

? YEARS OF MAINTENANCE
C IF (TYPE .EQ. 2) GO TO 107
XLLX = PLLX
ZERX = PERR
MAT = PHAI
TLM = DLXW
YERX = DERR
MAT = DMMX
GO TO 117
107 XLLX = PLLX
ZERX = PERR
MAT = PHAI
TLM = DLXW
YERX = DERR
MAT = DMMX
GO TO 117
C CONTINUE

C MTO = 0.0
TF = T-TPRIM+1.0
IF (T .GE. TPRIM+1.0) NT = TF
GO 127 I = 1, NT
C
TUT = Q0
R = I-I
Y = 19.72*X1**2+15.72*X1**2-183
IF (Y .LE. D2) GO TO 127
LAB = P0+Q0*CLW
EQUIP = P*Y+K*Y*CERR
MAT = Y+K*MAT+CERR
LAB = (LAB+EQP)/MAT+1.0RAT)**(X1-TPRIM)
GO 117 IF (EQ, NT) GO TO 137
C
127 CONTINUE
C T = NT
TF = TOT-T-TF+1.0
TOT = TOT-TF-TOT
MTOT = MTOT+TOT
GO 137
C MTO IS THE TOTAL MAINTENANCE COST FOR (T-TPRIM) YEARS.
C
C RETURN
C
APPENDIX D

COMPLETE OUTPUT LIST OF EXAMPLE PROBLEM

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**PROGRAM SAMS (SYSTEMS ANALYSIS MODEL FOR PAVEMENTS; REVISED 21 MAY 71)**

*A RUN TO SOLVE THE AVERAGE VALUE PROBLEM.*

**PROB 4000**

**ALL VARIABLES AT ENGINEERING AVERAGE**

<table>
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<tr>
<th>Layer</th>
<th>Name</th>
<th>Unit</th>
<th>Means</th>
<th>Str.</th>
<th>Min.</th>
<th>Max.</th>
<th>Salvage</th>
<th>Soil</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Asphaltic Concrete</td>
<td>1000</td>
<td>4.00</td>
<td>5.00</td>
<td>8.00</td>
<td>50.00</td>
<td>0.00</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>Crushed Stone</td>
<td>5.00</td>
<td>1.00</td>
<td>5.00</td>
<td>8.00</td>
<td>50.00</td>
<td>0.20</td>
<td>6.00</td>
</tr>
<tr>
<td>3</td>
<td>Gravel</td>
<td>2.00</td>
<td>0.11</td>
<td>5.00</td>
<td>10.00</td>
<td>50.00</td>
<td>6.90</td>
<td>0.20</td>
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**SALVAGE SOIL**

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<th>Max.</th>
<th>Salvage</th>
<th>Soil</th>
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<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.20</td>
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<td>0.20</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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**LOAD AND TRAFFIC VARIABLES**

**NO** = THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE BEGINNING OF THE ANALYSIS PERIOD.

**NC** = THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE END OF ANALYSIS PERIOD.

**AC** = THE ONE-DIRECTION ACCUMULATED NUMBER OF EQUIVALENT 10-KIP AXLES DURING THE ANALYSIS PERIOD.

**PROP** = THE PERCENT OF NOU WHICH WILL PASS THROUGH THE OVERLAY ZONE DURING EACH HOUR WHILE OVERLAYING IS TAKING PLACE.

**TYPE** = THE TYPE OF ROAD UNDER CONSTRUCTION: 1 = RURAL; 2 = URBAN.
30
50
3

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Co,ST01.1

IIdkJ1.jL 	 rJ .LLtu TIMF HLPAEEN 0VEIAYS.

rA-1 l 	 l.MX1.4IIt'

JI) 	 AVldL4L

TRAFFIC DELAY VARIABLES ASSOCIATED WITH OVERLAY AND ROAD GEOMETRICS.
ACPA-ASPHALTIC CONCRETE PRODUCTION RATE (TON/HOUR),
ACCP-ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/COMPACTED CY),
ALSU-THE DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE OVERLAY DIRECTION,
ALSN-THE DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE NON-OVERLAY DIRECTION,
ALSU-THE DISTANCE AROUND THE OVERLAY ZONE (MILES),
MPD-THE NUMBER OF MOUNDS/DAY OVERLAY CONSTRUCTION TAKES PLACE,

TRAFFIC DELAY VARIABLES ASSOCIATED WITH TRAFFIC SPEEDS AND DELAYS.
THE PERCENT OF VEHICLES THAT WILL BE STOPPED BECAUSE OF THE MOVEMENT OF
PERSONNEL OR EQUIPMENT,

MAINTENANCE VARIABLES
THE NUMBER OF YEARS PER YEAR THAT THE TRAFFIC WILL AVERAGE 32 FT.
CLAI-THE COMPOSITE EQUIPMENT INITIAL COST,
CMAI-THE RELATIVE MATERIAL COST (LDO IS AVERAGE).

1. THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--
   FOR INITIAL CONSTRUCTION, THE DEPTHS SHOULD BE
   ASPHALTIC CONCRETE 7.75 INCHES
   THE LIFE OF THE INITIAL STRUCTURE = 2.56 YEARS
   THE OVERLAY SCHEDULE IS
   1.50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 2.56 YEARS,
   1.50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 5.00 YEARS,
   1.50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 9.03 YEARS,
   1.50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 14.75 YEARS
   THE TOTAL LIFE = 22.00 YEARS

   THE TOTAL COSTS PER SQ. FT. FOR THESE CONSIDERATIONS ARE
   INITIAL CONSTRUCTION COST 2.157
   TOTAL ROUTINE MAINTENANCE COST 4.88
   TOTAL OVERLAY CONSTRUCTION COST 1.127
   TOTAL USE COST DURING
   OVERLAY CONSTRUCTION 271
   SALVAGE VALUE 210
   TOTAL OVERALL COST 3.68
PROB 4500  ALL VARIABLES AT ENGINEERING AVERAGE

FOR THE 2 LAYER DESIGN WITH THE FOLLOWING MATERIALS.

<table>
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<tr>
<th>MATERIALS</th>
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<th>MAX.</th>
<th>SALVAGE</th>
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<td>DEPTH</td>
<td>PCT.</td>
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2 THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE

ASPHALTIC CONCRETE 12.00 INCHES
CRUSHED STONE 5.00 INCHES

THE LIFE OF THE INITIAL STRUCTURE = 3.44 YEARS

THE OVERLAY SCHEDULE IS

1-50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 3.44 YEARS.
1-50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 7.84 YEARS.
1-50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 13.77 YEARS.

THE TOTAL LIFE = 20.04 YEARS

THE TOTAL COSTS PER SW. YD. FOR THESE CONSIDERATIONS ARE

INITIAL CONSTRUCTION COST $2.670
TOTAL ROUTINE MAINTENANCE COST $627
TOTAL OVERLAY CONSTRUCTION COST $841
TOTAL USER COST DURING OVERLAY CONSTRUCTION $200
SALVAGE VALUE $576
TOTAL OVERALL COST $3.715

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SFT -- 63

PROB 4500  ALL VARIABLES AT ENGINEERING AVERAGE

FOR THE 3 LAYER DESIGN WITH THE FOLLOWING MATERIALS.

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<tr>
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<td>PCT.</td>
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3 THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE

ASPHALTIC CONCRETE 6.00 INCHES
CRUSHED STONE 3.00 INCHES
GRAVEL 5.00 INCHES

THE LIFE OF THE INITIAL STRUCTURE = 3.67 YEARS

THE OVERLAY SCHEDULE IS

1-50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 3.67 YEARS.
1-50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 6.47 YEARS.
1-50 INCHES (INCLUDING 1 INCH LEVEL-UP) AFTER 14.52 YEARS.

THE TOTAL LIFE = 21.68 YEARS.

THE TOTAL COSTS PER SW. YD. FOR THESE CONSIDERATIONS ARE

INITIAL CONSTRUCTION COST $2.670
TOTAL ROUTINE MAINTENANCE COST $627
TOTAL OVERLAY CONSTRUCTION COST $841
TOTAL USER COST DURING OVERLAY CONSTRUCTION $200
SALVAGE VALUE $576
TOTAL OVERALL COST $3.715

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SFT -- 315
### SUMMARY OF THE BEST DESIGN STRATEGIES

**In Order of Increasing Total Cost**

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**Summary of the Best Design for Each Combination of Materials, in Order of Increasing Total Cost**

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**All Material Combinations Have Feasible Designs.**

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**ALL VARIABLES AT ENGINEERING AVERAGE**

**Summary of the Best Design Strategies**

**In Order of Increasing Total Cost**

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**NUMBER OF LAYERS**

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**NUMBER OF LAYERS**

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**PERF. TIME (YEARS)**

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**TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED WAS**

300
APPENDIX E

PAVEMENT BEHAVIOR AND PERFORMANCE

The pavement system in Figure 2 shows the complex interrelationships that necessarily exist between (1) materials comprising the system, (2) manifestations of pavement behavior, and (3) pavement performance.

This appendix defines terms and establishes procedures and concepts for relating these factors for use in the evaluation and design of pavement systems.

Pavement behavior is first considered in terms of pavement performance and failure. Failure is discussed in detail to conceptually quantify the factors included in the block diagram of the pavement system of Figure 2. The top part of the figure is quantified in terms of a “distress index,” and the lower part is quantified by a “decision criteria index.”

Because the output function is defined in terms of performance (and performance, as well as distress mechanisms associated with it, has a variety of connotations), the definitions in Appendix B should be reviewed to ensure a uniform basis for the ensuing discussion. The definitions were selected for clarity in this presentation and generally are based on concepts developed by Carey and Irick (18) for evaluating the performance of the various pavements in the AASHO Road Test. Inherent in the definitions and the development of the equations for the system is the purpose of the highway designer to provide a safe, comfortable, and economical method of transporting goods and people.

PAVEMENT BEHAVIOR

It would be desirable to define or list the various manifestations of pavement distress that typically occur and to relate these manifestations through behavior to material properties. The rationale to such an approach would be, for instance, to relate specific values of measurable material properties to the specific distress symptoms observed in such a way as to be able to predict the potential for distress occurring. By design and specification, therefore, the distress can be minimized.

In Chapter Two, factors affecting pavement structure behavior are discussed. Figure 7 shows three different distress modes (fracture, distortion, and disintegration); these are divided into distress manifestations and distress mechanisms. Early in the project, a preliminary study was made to provide background information and orientation. The review concentrated primarily on previous NCHRP pavement studies. Each study was evaluated and considered in an attempt to correlate and relate the previous work. Studies from other areas of NCHRP and other publications were included in this review.

A standard form was developed for all reviewers; the reviews were compiled to serve as background material for each of the investigators. The format for the literature review codification form is related to the outline on pavement distress shown in Figure 7. The material in the next sections follows this general format, and is considered in terms of the three distress modes: fracture, distortion, and disintegration. A particular study is categorized into one or more of the distress modes and then discussed in terms of five classes of variables related to pavement performance: (1) load, (2) environment, (3) structure, (4) construction, and (5) maintenance variables, which were listed by Irick and Hudson (22).

Fracture

Of the three distress modes, the fracture mode has been examined in more detail in the NCHRP pavement studies than any of the other factors; the majority of the reports issued thus far are in this area.

Several of the studies use static wheel loads or wheel loads at creep speed to predict maximum deflection and the deflection basin (23, 44, 56). Each approach assumes the pavement material may be characterized as a linear elastic material. The Burmister and Boussinesq equations are used to solve for deflections and stresses. In these analyses, it was found that, generally, the Boussinesq solution gives a better prediction of the measured deflections. This observation is of limited application because most of these analyses consider only the pavement sections using granular materials. If the sections using stabilized materials were considered in the analyses, then layered theories probably would give a much better prediction of stresses and deflection.

A number of reports consider the fatigue effect of repetitive loadings (29-37). Seed et al. (44) consider repeated triaxial load tests applied at 20 repetitions per minute. In this study, a resilient modulus obtained from the repeated loading of a triaxial specimen is used to determine a modulus of resilient deformation which is then used as a modulus of elasticity value in the Burmister solution. The modulus of resilient deformation is a measure of the recoverable deformation in repeated loading; it is not instantaneous, nor is it invariant with repetitions. The repeated load apparatus was also applied to test sections constructed of granular materials on a cohesive subgrade. These test sections involved the structural variable, thickness (8 in. and 12 in. of gravel base), and the environmental variable, moisture. The test pits were tested in a dry condition and after saturation of the base and subbase. The measured properties obtained with triaxial tests were then used to predict the deflections of the pit. Only deflections were considered, and no attempt was made to predict distress or rupture.

Deacon and Monismith (30) used repetitive flexural tests in uniaxial loading to predict the fatigue life of an
asphaltic concrete. In these studies, the environmental factor temperature also is considered. Results indicate that the fatigue life decreases as the applied stress increases. Equations are presented that can be used to predict the mean fracture life of the asphaltic concrete for mixed discrete loadings.

Scrivner and Moore (12) use elastic principles to predict deflection obtained with vibratory loads. In the analyses, a point load is assumed to simulate the loading conditions of the Lane-Wells Dynaffect. In this study, 27 test sections are used to obtain a variation in the structural variables. There are three levels of surface, base, and subbase thicknesses. The subgrade ranges from a plastic clay to a sandy gravel. In this analysis a modified Boussinesq equation is used, which introduces a value for the modulus of elasticity. The modulus of elasticity is obtained by triaxial compressive tests at 5-psi lateral pressure. With this method, full shear transfer is assumed between layers because the analysis assumes a Boussinesq distribution. The technique is an excellent tool for evaluating the in-place properties of an in-service pavement, but not for predicting the rupture of the pavement due to the loads.

Harr and Head (23) used AASHO Road Test data to develop a method for predicting the performance of the flexible sections based on the theoretical stresses obtained from Boussinesq's equation. Three-layered theory was considered also, but it did not give any significant improvement over the Boussinesq equation. A static wheel load is used for predicting the stresses. A fair correlation was found between the stress due to a wheel load and the number of weighted applications to reduce the present serviceability index to a level of 3.5 and 1.5. By the nature of the equation, this method predicts the integrated effect of the various distress modes as reflected in the present serviceability index. The scatter in the analysis indicates that other distress mechanisms in addition to excessive load-strain should be considered. This observation emphasizes the importance of considering all three distress modes in an integrated framework prediction of pavement performance. A limiting factor in this analysis is that the stabilized base sections were not considered. The absence of a modulus of elasticity term for different layers is a weakness of the Boussinesq stress distribution that limits its use in future design techniques, considering the present trend toward treated materials.

Finn et al. (43) considered the parameters affecting the tensile strength of asphaltic concrete. The environmental variable of temperature is examined in terms of its effect on the elastic properties and the viscous nature of the asphaltic concrete. With regard to the structural variables, the effects of modulus of elasticity, tensile strength, fatigue, and durability on performance of asphaltic concrete are examined.

Busching et al. (56) characterized the stress deformation response of asphaltic concrete using elastic principles. The environmental variable of temperature is considered. It was found that the stiffness of asphaltic concrete decreased with time, stress, and temperature. The laboratory data presented in the report also indicate the importance of the construction variables. The tests indicate that asphaltic concrete is not truly isotropic and may be more appropriately described by an isotropic characterization.

**Distortion**

The Vesic and Domaschuk study (57) is the only one that considers specifically the distortion mode of distress. In this analysis the Boussinesq stress distribution is used to predict the level of rutting in the pavement. The analysis indicates that the higher the level of stress the greater the rutting reflected in the pavement surface. The study included only the nontreated sections of flexible pavement at the AASHO Road Test. Therefore, the analysis also is limited with regard to the application to present methods of design where treated materials are used in flexible pavements.

Finn et al. (43) considered the viscous effects of asphaltic concrete under load and temperature. The data presented in this study could be used in the prediction of rutting and plastic deformation in the asphaltic concrete layer.

The foregoing studies are the only efforts specifically directed to the distortion mode of distress. In essence, only two mechanisms of the 11 possible distress mechanisms listed in Figure 7 have been considered by NCHRP studies. Considerable additional work is required in this field.

**Disintegration**

Finn et al. considered, among other factors, the durability properties of asphaltic concrete that may be related to the disintegration mode of distress (43). The study indicates that the environmental variables of temperature and moisture have a pronounced influence on durability. The report indicated that the void content of the mix is the variable that most influences durability of asphaltic concrete surfacing. The void content may be considered as a construction variable. The studies reported indicated that the smaller the void content, the longer the performance of the pavement from a durability standpoint.

**Combination of Distress Modes**

Two of the NCHRP studies consider the combined effect of the three distress modes (45, 46). The Yoder and Milhouse study (45) was a relative evaluation of the various parameters considered in the PSI equations and the methods of measuring these terms. The study indicated that the slope variance term has the greatest influence on the present serviceability index equation. It also indicated that a number of devices could be used successfully to obtain the measurements required for predicting the PSI of a pavement.

Kondner and Krizek (46) developed equations for predicting the performance of pavements using design parameters. The analysis was based on the flexible pavement sections from the AASHO Road Test. The loading variables considered in that analysis are the equivalent wheel loads and the number of repetitions. The environmental variable of spring thaw also is considered in the equation for predicting performance. The structural variable of layer thickness also is considered in the equation. The limiting
factor here is that no material values are used; hence, the equation is limited to materials that are similar to the ones used at the AASHO Road Test. With regard to construction variables, the analysis indicates that the specifications and construction procedures are reflected in the original value for PSI and would be considered accordingly.

Summary

The studies reported thus far in the NCHRP indicate that considerable effort has been expended in (1) predicting the rupture mode of distress, with a bulk of this work confined to predicting cracking due to excessive load strain; and (2) developing the fatigue distress mode. Work with the distortion and disintegration modes of distress has been lacking. Considerable effort needs to be expended in a systems framework to develop models to predict distortion and disintegration. Studies considering the parameters affecting these two modes that have been considered in material studies are useful in this analysis but do not provide the mechanistic solutions required in a systems analysis.

FAILURE CONCEPT

Generalized Models

To permit designs of the pavement system to be accomplished, what constitutes failure must be fully specified. “Failure” here refers to a failure of the pavement system shown in Figure 2. A key point to this discussion is that failure of a pavement system generally is not a catastrophic occurrence, as is the case of a steel rod rupturing in tension. Instead, it is 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 that has been 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 pavement system block diagram (Fig. 2) provides the framework for development of a general model of pavement failure. This figure 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 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. Referring to Figures 2 and 7, the limiting response is known as distress (i.e., fracture, distortion, disintegration) and may be expressed conceptually as follows:

$$\text{DI}(x, t) = \frac{s}{t} \left\{ C(x, s), S(x, s), D(x, s) \right\}$$

in which

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

Distress is spatial in nature and is best considered on a unit area basis. The notation in Eq. E-1 indicates that the distress index is a function of the history of the variables shown from time zero to current time $t$. Because the arguments in the foregoing equations are functions, such equations are referred to as functionals.

Each parameter in Eq. E-1 must be quantitatively predicted from the input parameters into the system. Considering the systems framework, fracture, distortion, and disintegration may be expressed as a function of five classes of variables, as follows:

For fracture:

$$C(x, t) = F' \quad \text{(load, environment, construction, maintenance, and structural variables; space and time)} \quad \text{(E-2)}$$

For distortion:

$$S(x, t) = F' \quad \text{(load, environment, construction, maintenance, and structural variables; space and time)} \quad \text{(E-3)}$$

For disintegration:

$$D(x, t) = F' \quad \text{(load, environment, construction, maintenance, and structural variables; space and time)} \quad \text{(E-4)}$$

These equations predict the three modes of distress in terms of five classes of variables. All the variables are 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. Therefore, only the spatial function is considered.

The next development step is to substitute Eqs. E-2, E-3, and E-4 into Eq. E-1, which conceptually describes the upper region of Figure 2. If the proper weighting functions are used, Eq. E-1 would represent the system output function. This output function may then be evaluated in terms of the decision criteria.

Decision Criteria Index

Basically, an engineer's criterion for judging a pavement structure is, "How well is it accomplishing its purpose?" The "decision criteria" should include riding quality, economics, and safety. These "decision criteria" may be expressed as a Decision Criteria Index, or
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 E-1. Failure concept.
\[
DCI(x, t) = F \quad \text{(riding quality, economics, safety, maintainability, and other factors; space and time)} \quad (E-5)
\]

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. This level is time-invariant in that the acceptable level is constant regardless of the age. 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 a definite need for consideration of time in an economics term.

Each of the parameters in Eq. E-5 must be quantified. Thus far, there has been no attempt in the highway field to do this. Generally, these factors are considered subjectively, either directly or indirectly, by highway administrators, but not in a broad systems framework.

Systems 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 E-1 shows the principles of this failure definition. Through a mechanistic model as shown in Eq. E-1, fracture, distortion, and disintegration may be combined into an output curve shown by the solid line in the graph. This level of output generally decreases with time, depending on the variables of load, pavement structure, environment, construction, and maintenance.

Acceptable levels for each of the decision criteria are shown in Figure E-1. The decision criteria are represented by the combined effect of the weighted function expressed by the dashed line in the center figure. The point at which these two curves intersect would represent failure for the system. Other functions, such as the area between the curves in the center of Figure E-1, may ultimately become appropriate measures of the performance.

The Interstate System, for instance, would require high levels of riding quality and safety; hence, the acceptable numerical value of distress level of the pavement structure (on a 0.0 to 1.0 scale, with 1.0 representing no distress) would be relatively high. Therefore, it would take a small reduction of the distress index to reach the minimum desirable level of serviceability set for pavement structures on the Interstate System. This has been defined here as failure. A farm-to-market road might represent the other extreme, allowing a much lower level of riding quality.

It is not in the scope of this report to fully define Eq. E-1, but rather to develop generalized models that illustrate its use in a systems framework and to use it in the definition of basic properties and significant basic properties (1).

The theories used to predict the failure manifestations in Eq. E-1 might be referred to as deterministic solutions; i.e., exact values are computed for specific input values. In some cases, materials experience wide variations, even though they are placed under controlled conditions.

All inputs into the system experience uncontrolled variations; therefore, deterministic concepts ultimately must be replaced by a concept in which every cause of variability is termed a "chance cause." Every material property (i.e., modulus of elasticity, Poisson's ratio) has a statistical distribution, with a mean value and a variation around this mean. Stochastic techniques required to handle these variations are discussed in Appendix F.

**APPENDIX F**

**STOCHASTIC FAILURE**

Engineers working with materials recognize that the properties of the materials vary considerably from point to point in a specimen, whether it is a steel bar or an asphalt surface. Figure F-1, a continuous density profile for a crushed limestone base course, shows a typical dispersion of material properties in a pavement structure. Note that the density ranges in a random fashion from a low of 138 pcf to a high of 147 pcf. The dispersion would be present for other material properties such as strength and modulus of elasticity. Although these variations are recognized from a practical standpoint, current design procedures do not take this variation into account directly. Generally, design procedures assume a homogeneous material.

This type of approach assumes distress is a catastrophic occurrence such that when the stress exceeds a limiting value, a distress manifestation occurs. For example, the design premise for a static wheel load on a pavement is based on the assumption that if a limiting stress value is exceeded, the entire pavement cracks. Experience and data from test roads indicate this concept is contrary to that observed in the field (47, 48, 49). Generally, pavement distress is experienced only over some percentage of the
area, and seldom does pavement distress appear throughout its length.

The purpose of this section is to develop a general format for illustrating the stochastic nature of distress in a pavement structure. The example developed herein is for the excessive load-strain distress mechanism that produces a distress manifestation of cracking. Although not considered directly, the concepts developed in the following sections are also applicable to the other distress mechanisms shown in Figure 7. The stochastic variation of material properties is introduced into a deterministic equation presently used. Examples of deterministic equations are Westergaard's and Burmister's solutions for the state of stress in rigid and flexible pavements, respectively. The insertion of the stochastic concepts into deterministic models requires no conceptual change of the equations used to describe a material. It should be recognized that the equations are simplified versions that were selected to illustrate how probability may be used. In a complete development, more sophisticated multivariate techniques would be required (50).

CONCEPTUAL EQUATIONS

Studies of the nonhomogeneous characteristics of most materials indicate that the strength (compressive, flexural, etc.) varies about a mean value (51, 52). An examination of these variations indicates that they may be approximated by a continuous normal distribution. Although less work has been performed with the other material properties such as modulus of elasticity and Poisson's ratio, it is reasonable to expect that the variation of these properties also could be approximated by a normal distribution.

Design of a pavement structure for the rupture mode of distress usually is based on the premise that if a stress value exceeds a given strength value, cracking occurs. This same concept is used here, except that mean values of stress and strength with a measure of the variation (standard deviation) around it will be used. Figure F-2 shows generally what might be expected if the stress and strength variations in the pavement are characterized by normal distributions. Figure F-2 shows the probability concept of distress. If the dispersion of the stress and strength are clearly separated, as is the case shown by position (1) for the stress density function, the material will perform satisfactorily without distress. (The fatigue concept is not considered in this analysis.) The probability of distress in position (1) is zero. If the load, temperature, or moisture conditions change, a shift of the stress density function to position (2) might be experienced; thus, the probability of a failure assumes a finite value between 0 and 100 percent. Although the mean stress would still be less than the mean strength, a safe condition from a purely deterministic standpoint, the diagrams show that some distress would occur. Conceptually, the probability of distress may be expressed as the area beneath the intersection of curves A

* Deterministic as used herein refers to an exact solution of a stress state which assumes the material properties have no variance.

† The standard deviation is a measure of the dispersion around a mean and is expressed in the same units as the mean. The greater the magnitude of the standard deviation, the greater the dispersion.
and $B$ and is represented by the shaded area in Figure F-2. This may be stated as follows:

$$P(D) = A \Omega B$$  \hspace{1cm} (F-1)$$

in which

$P(D) =$ probability of distress being experienced; and

$\Omega =$ functional representation of the intersection area.

In Figure F-2, the intersection of the two density functions may be designated as $b$ on the psi axis. If the stress in a material is assumed to be independent of the strength, the probability of distress may be restated as follows:

$$P(D) = P\{\text{stress} > b\} + P\{\text{strength} < b\}$$  \hspace{1cm} (F-2)$$

By quantifying the foregoing expression, the percentage of area experiencing distress in a roadway may be predicted for certain stress and strength variations around mean values.

**DERIVATION OF EQUATIONS**

In deriving an expression to characterize Eq. F-2, (1) the characteristics of a normal distribution curve are discussed from a general standpoint; (2) an equation is derived for predicting the point of intersection for the two density functions, given the means and standard deviations; (3) an expression for the probability of distress is derived.

**General Equations**

A number of references discuss the continuous normal distribution equations; these may be consulted for further details (53, 54, 55). The density function to predict the ordinate in terms of the absissa for a normal curve is

$$f(x) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$  \hspace{1cm} (F-3)$$

in which

$x =$ distance from a zero value on the abscissa; and

$e =$ Napierian base of natural logarithm.

The normal distribution function for area under the curve between any two vertical lines through the curve is

$$F(x) = \int_a^b f(x) dx$$  \hspace{1cm} (F-4)$$

in which $a$ and $b$ are any two points on abscissa beneath the curve.

A characteristic of the normal distribution curve is that the area beneath the curve between $\pm \infty =$ 1:

$$F(x) = \int_{-\infty}^{\infty} f(x) dx = 1$$  \hspace{1cm} (F-5)$$

These equations represent the general form of the normal curves; they are used further to develop distress probability.

Eq. F-3 is in a general form where the dispersion is around a zero value. Because actual materials properties (i.e., strength and stress) are dispersed around a mean value other than zero, this equation has to be revised to account for this:

For curve $A$, the density function is

$$f(x_A) = \frac{1}{\sigma_A \sqrt{2\pi}} e^{-\frac{(x-\mu_A)^2}{2\sigma_A^2}}$$  \hspace{1cm} (F-6)$$

For curve $B$, the density function is

$$f(x_B) = \frac{1}{\sigma_B \sqrt{2\pi}} e^{-\frac{(x-\mu_B)^2}{2\sigma_B^2}}$$  \hspace{1cm} (F-7)$$

in which

$\mu =$ mean value of quantities being considered;

$\sigma =$ standard deviation of quantities being considered;
$x$ = any value along the abscissa; and
$A$ and $B$ = subscripts referring to the respective curves.

The foregoing expressions are apropos, whether one is working with stress or strength, as long as the units are constant. Eqs. F-6 and F-7 place the data in a form so that the intersection point of the two curves can be determined.

Point of Intersection

The exact value of magnitude of the intersection along the abscissa may be obtained by equating Eqs. F-6 and F-7, and solving for the $x$ value:

$$F(x_A) = F(x_B)$$ (F-8)

By the proper algebraic manipulations, the point of intersection designated as $b$ may be obtained as follows:

**General case ($\sigma_A \neq \sigma_B$)**

$$b = \frac{\sqrt{\left(\mu_A - \mu_B\right)^2 - (1-\beta) \left[2\sigma_A^2 \log e^{\frac{\sigma_A}{\sigma_B}} + \mu_A^2 - \beta \mu_B^2\right]}}{\beta - 1}$$

in which

$$\beta = \frac{\sigma_A^2}{\sigma_B^2}$$ (F-10)

**Special case ($\sigma_A = \sigma_B$)**

$$b = \frac{\mu_B + \mu_A}{2}$$ (F-11)

The solution of Eq. F-9 will provide two answers, but only the one meeting the criterion $\mu_A < b$ is applicable.

Probability Equations

Using the density functions expressed in Eqs. F-6 and F-7, and the distribution functions in Eq. F-4, the area of intersection of the two curves in Figure F-2 that was conceptually expressed in Eq. F-2 may be quantified. Figure F-3 is an enlargement of the intersection area.

In Figure F-3, for $x=b$, the area under curve $B$ between $-\infty$ and $x=b$ portrayed by the vertical hatching may be represented by

$$F(x_B) = \int_{-\infty}^{b} f(x_B) \, dx$$ (F-12)

The area under curve $A$ between $x=b$ and $+\infty$ shown by the vertical hatching may be represented by

$$F(x_A) = \int_{-\infty}^{b} f(x_A) \, dx$$ (F-13)

Eq. F-2 functionally states that if the stress is greater than or the strength less than the value of psi at the point of intersection, cracking will occur. The component parts of Eq. F-2 may be equated to Eqs. F-12 and F-13 as follows:

$$P\{\text{stress} > b\} = F(x_B)$$ (F-14)

$$P\{\text{strength} < b\} = F(x_A)$$ (F-15)

The area of the intersection beneath the two density functions as conceptionally expressed in Eq. F-2 is obtained by the addition of the two previous expressions. By appropriately combining Eqs. F-6 and F-7 with Eqs. F-12, F-13, F-14, and F-15, the following is obtained:

$$P\{D\} = \int_{-\infty}^{+\infty} \frac{1}{\sigma_A \sqrt{2\pi}} e^{-\frac{(x-\mu_A)^2}{2\sigma_A^2}} \, dx + \int_{\mu_A}^{b} \frac{1}{\sigma_B \sqrt{2\pi}} e^{-\frac{(x-\mu_B)^2}{2\sigma_B^2}} \, dx$$ (F-16)

The integrals here have been solved and tabulated in probability tables in numerous references (53, 54, 55). Because the solution of these integrals would require considerable effort, it is recommended that the probability tables be used. To use the probability tables, the following format is required:

$$P\{D\} = F\left(\frac{b-\mu_A}{\sigma_A}\right) + F\left(\frac{b-\mu_B}{\sigma_B}\right)$$ (F-17)

Eq. F-17 is applicable only when the mean value of $B$ is greater than the mean value of $A$. If this condition is reversed, then technically the material is experiencing distress everywhere. The foregoing terms involve negative signs that must be taken into account when using the tables.

![Figure F-3. Enlargement of the intersection area of Figure F-2.](image-url)
Readjusting to account for signs, the following expression is obtained that may be used directly with the probability tables:

\[
P(D) = 2 - F\left( \frac{b - \mu_a}{\sigma_a} \right) - F\left( \frac{\mu_b - b}{\sigma_b} \right) \quad (F-18)
\]

**Summary**

To use stochastic principles, the mean value and the standard deviation for the stress and strength in a material would have to be determined. The next step would be to locate the intersection point as expressed in Eq. F-9. This value would be inserted into Eq. F-18 to obtain the probability of failure. For example, if a value of 0.10 is obtained from Eq. F-17, then, for the specific conditions, there is a 10 percent probability of distress. In a large number of trials matching a stress and a strength, there is a probability of 10 percent that the specimen will fail due to overstress. Thus, in a very large number of trials approximately 10 percent of the specimens would fail. Relating this to a given area of roadway that could be considered as a large number of specimens, it may be hypothesized that approximately 10 percent of the roadway area would experience distress if it were subjected to this stress pattern.

The assumptions made in this analysis are:

1. The materials are nonhomogeneous, and the variation of properties in a material may be represented by a normal distribution function.
2. The stress in a specimen also experiences a normal distribution due to the variation in material properties in the pavement.
3. Cracking occurs where the stress exceeds the strength and occurs in localized areas.
4. The stress in a material is independent of the strength.
5. Only the excessive load-strain distress mechanism is considered in this analysis.

**APPLICATION**

The previous expressions may be injected into a concrete pavement design problem, to illustrate the stochastic concepts of distress. The design premise is to keep the working stress in the pavement less than the strength of the concrete. Cracking occurs when the stress exceeds the strength. The design equations assume homogeneous materials properties that do not account for the variation in properties within the slab. To revise Eq. F-18 to correspond with the concrete design problem, let

\[
\begin{align*}
\mu_a &= \text{mean value of the flexural strength of the concrete;} \\
\sigma_a &= \text{standard deviation of the concrete flexural strength;} \\
f &= \text{mean working stress in the concrete;} \quad \text{and} \\
\sigma_f &= \text{standard deviation of the working stress in the concrete.}
\end{align*}
\]

The first two terms would be obtained from strength tests of the concrete taken during construction. The flexural tests used for control purposes could be averaged and the standard deviation computed. The last two terms would have to be derived through the deterministic model used to predict stress.

Substituting these terms into Eq. F-18 gives:

\[
P(D) = 2 - F\left( \frac{b - \mu_a}{\sigma_a} \right) - F\left( \frac{\mu_b - b}{\sigma_b} \right) \quad (F-19)
\]

Values are assumed for each parameter to illustrate example problems. Two example problems are presented; the only difference between them is that the standard deviation for flexural strength of the concrete is 20 psi for Case One and 40 psi for Case Two.

<table>
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<th>CASE ONE</th>
<th>CASE TWO</th>
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<tr>
<td>(\bar{f}=500 \text{ psi})</td>
<td>(\bar{f}=500 \text{ psi})</td>
</tr>
<tr>
<td>(\sigma_f=20 \text{ psi})</td>
<td>(\sigma_f=20 \text{ psi})</td>
</tr>
<tr>
<td>(S=600 \text{ psi})</td>
<td>(S=600 \text{ psi})</td>
</tr>
<tr>
<td>(\sigma_s=20 \text{ psi})</td>
<td>(\sigma_s=40 \text{ psi})</td>
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Using these values in Eqs. F-7 and F-18, the following values are obtained:

- **Case One**
  - \(P(D)=1.24 \text{ percent}\)

- **Case Two**
  - \(P(D)=8.95 \text{ percent}\)

These data are shown in Figure F-4. The shaded area represents the probability of distress.

From a purely deterministic standpoint, both designs are safe because stress is less than strength; but, from a stochastic standpoint, there is a 1.2 percent chance of cracking for Case One and a 9 percent chance of cracking for Case Two. The increase in chance of cracking in Case Two could be due to poor quality control of the flexural strength. The larger the standard deviation the poorer the quality control. These results illustrate not only that distress may be experienced even though not predicted by deterministic analysis, but also that quality control affects the amount of distress.

The effect of quality control may be illustrated further by taking the case of a roadway that is designed with a safety factor of two using a working stress of 300 psi and a flexural strength of 600 psi. Assume that a wheel load heavier than the design value or a loss of subgrade support value results in the stress increasing to 400 psi, which is a realistic assumption. Figure F-5 shows what might happen with this condition in terms of the standard deviation stress and strength. To simplify computations, equal standard deviations were used for both stress and strength for a given case. If good quality control had been observed on the project (a standard deviation of less than 25 psi) no failure would probably be experienced. At a ±40-psi standard deviation, approximately 1.2 percent of the pavement would experience failure, even though, from a deterministic standpoint, a safety factor of 1.5 is still retained. By increasing the standard deviation to ±60 psi, one can see that approximately 10 percent of the area would experience failure. This graph shows that the variability of the concrete properties should be taken into account in the design procedures.

This example is for concrete pavements, but the concept would be applicable to any particular layer of the pavement structure system.
Figure F-4. Failure for two conditions.
Figure F-5. Effect of standard deviation of stress and strength on failure for a given condition.

\[ \sigma_f = \sigma_s \]
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