NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 139

FLEXIBLE PAVEMENT DESIGN AND MANAGEMENT

SYSTEMS FORMULATION

HIGHWAY RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 139

FLEXIBLE PAVEMENT DESIGN AND MANAGEMENT
SYSTEMS FORMULATION

W. R. HUDSON AND B. F. McCULLOUGH
MATERIALS RESEARCH AND DEVELOPMENT, INC.
OAKLAND, CALIFORNIA

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- TRANSPORTATION ECONOMICS
- PAVEMENT DESIGN
- PAVEMENT PERFORMANCE
- CONSTRUCTION
- MAINTENANCE, GENERAL
- TRAFFIC MEASUREMENTS

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1973

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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 communications 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.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

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.

NCHRP Report 139

Project 1-10 FY '67 and '69
ISBN 0-309-02127-8
L. C. Catalog Card No. 73-3238

Price $4.40

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the Federal Highway Administration. Individual fiscal agreements are executed annually by the Academy-Research Council, the Federal Highway Administration, and participating state highway departments, members of the American Association of State Highway Officials.

The study reported herein was undertaken under the aegis of the National Academy of Sciences—National Research Council. The National Cooperative Highway Research Program, under which this study was made, is conducted by the Highway Research Board with the express approval of the Governing Board of the NRC. Such approval indicated that the Board considered that the problems studied in this program are of national significance; that solution of the problems requires scientific or technical competence, and that the resources of NRC are particularly suitable to the conduct of these studies. The institutional responsibilities of the NRC are discharged in the following manner: each specific problem, before it is accepted for study in the Program, is approved as appropriate for the NRC by the Program advisory committee and the Chairman of the Division of Engineering of the National Research Council.

The specific work to be performed in each problem area is defined by an advisory panel that then selects a research agency to do the work, monitors the work, and reviews the final reports. Members of the advisory panels are appointed by the Chairman of the Division of Engineering of the National Research Council. They are selected for their individual scholarly competence and judgment, with due consideration for the balance and breadth of disciplines.

Responsibility for the definition of this research project and for the publication of this report rests with the advisory panel. However, the opinions and conclusion expressed or implied are those of the research agency that performed the research, and are not necessarily those of the Highway Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway Officials, nor the individual states participating in the Program.

Although reports in this category are not submitted for approval to the Academy membership nor to the Council, each report is reviewed and processed according to procedures established and monitored by the Academy's Report Review Committee. Such reviews are intended to determine, *inter alia,* whether the major questions and relevant points of view have been addressed, and whether the reported findings, conclusions and recommendations arose from the available data and information. Distribution of the report is permitted only after satisfactory completion of this review process.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

(See last pages for list of published titles and prices)

FOREWORD

By Staff
Highway Research Board

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.

* Scrivner, F. H., McFarland, W. F., and Carey, G. R., "A Systems Approach to the Flexible Pavement Design Problem." *Res. Rep. 32-11*, Texas Transportation Institute (1968).

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 pavements 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 55F 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.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 1-10 by Materials Research & Development, Inc. B. A. Vallerga, President of MR & D, acted as principal investigator, with Dr. W. R. Hudson, Director of Research, Council for Advanced Transportation Studies, University of Texas at Austin, as co-principal investigator in systems formulation and Dr. Keshavan Nair, Vice-President of MR & D, as co-principal investigator in materials characterization. F. N. Finn, Senior Research Engineer, MR & D, served as co-principal investigator during the first phase of the work. Dr. B. F. McCullough, Associate Professor of Civil Engineering, University of Texas at Austin, assisted in the systems formulation study; Dr. C-Y. Chang, Project Research Engineer, MR & D, conducted the laboratory testing and assisted in the data analysis in the materials characterization study.

Consultants to the project who provided technical guidance in all phases of the work were Professor C. L. Monismith and Dr. K. S. Pister, both of the University of California at Berkeley, the latter being the first to point out the necessity for utilizing systems engineering concepts and techniques in the total pavement design problem. Their valuable contributions are greatly appreciated.

Special acknowledgment is made to James F. Shook, The Asphalt Institute, B. E. Colley, Portland Cement Association, and the late Bonner S. Coffman, Ohio State University, all of whom participated in the initial project planning conference.

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.

FLEXIBLE PAVEMENT DESIGN AND MANAGEMENT

SYSTEMS FORMULATION

CHAPTER ONE

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 over-all 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

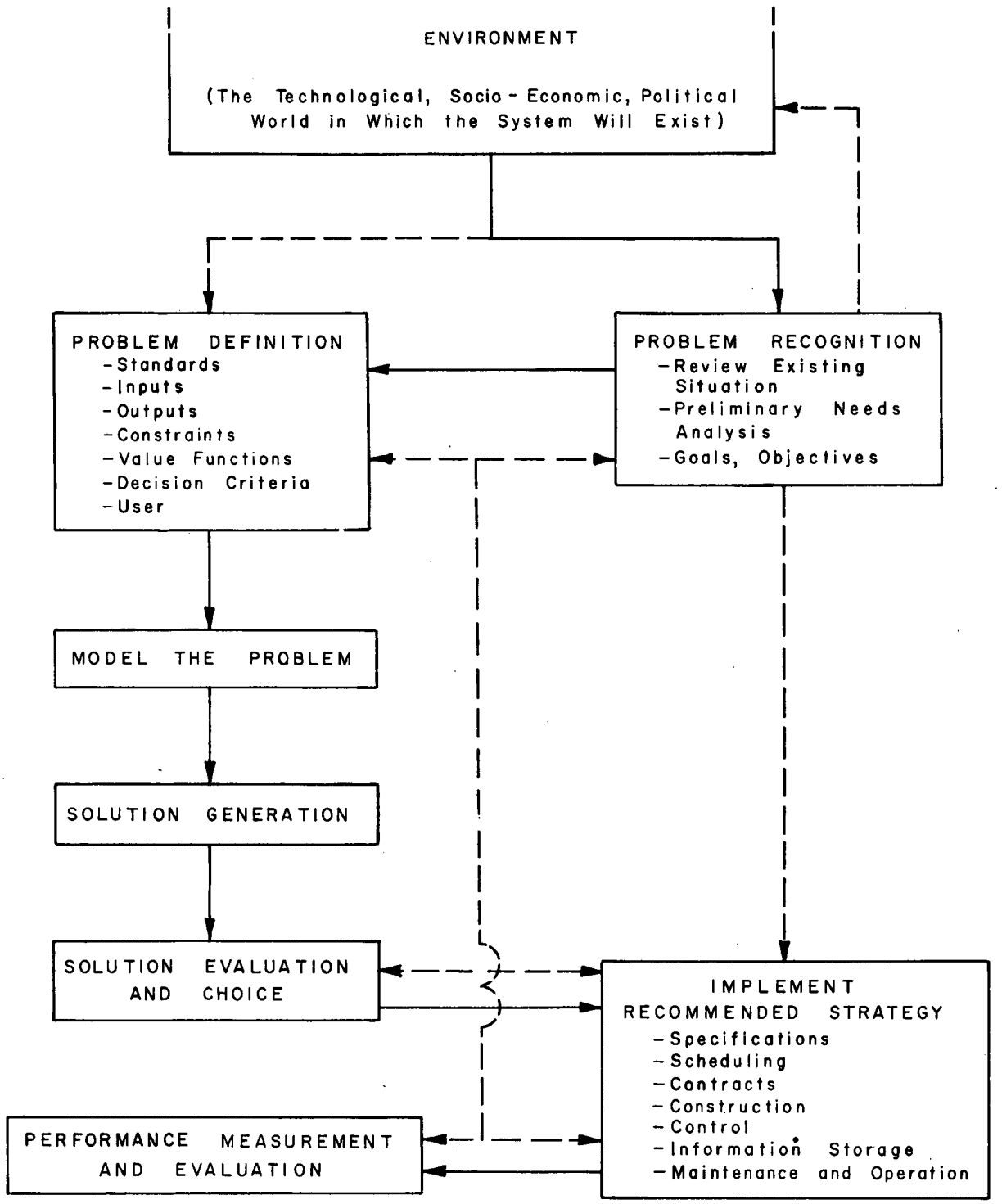


Figure 1. General representation of the systems engineering process.

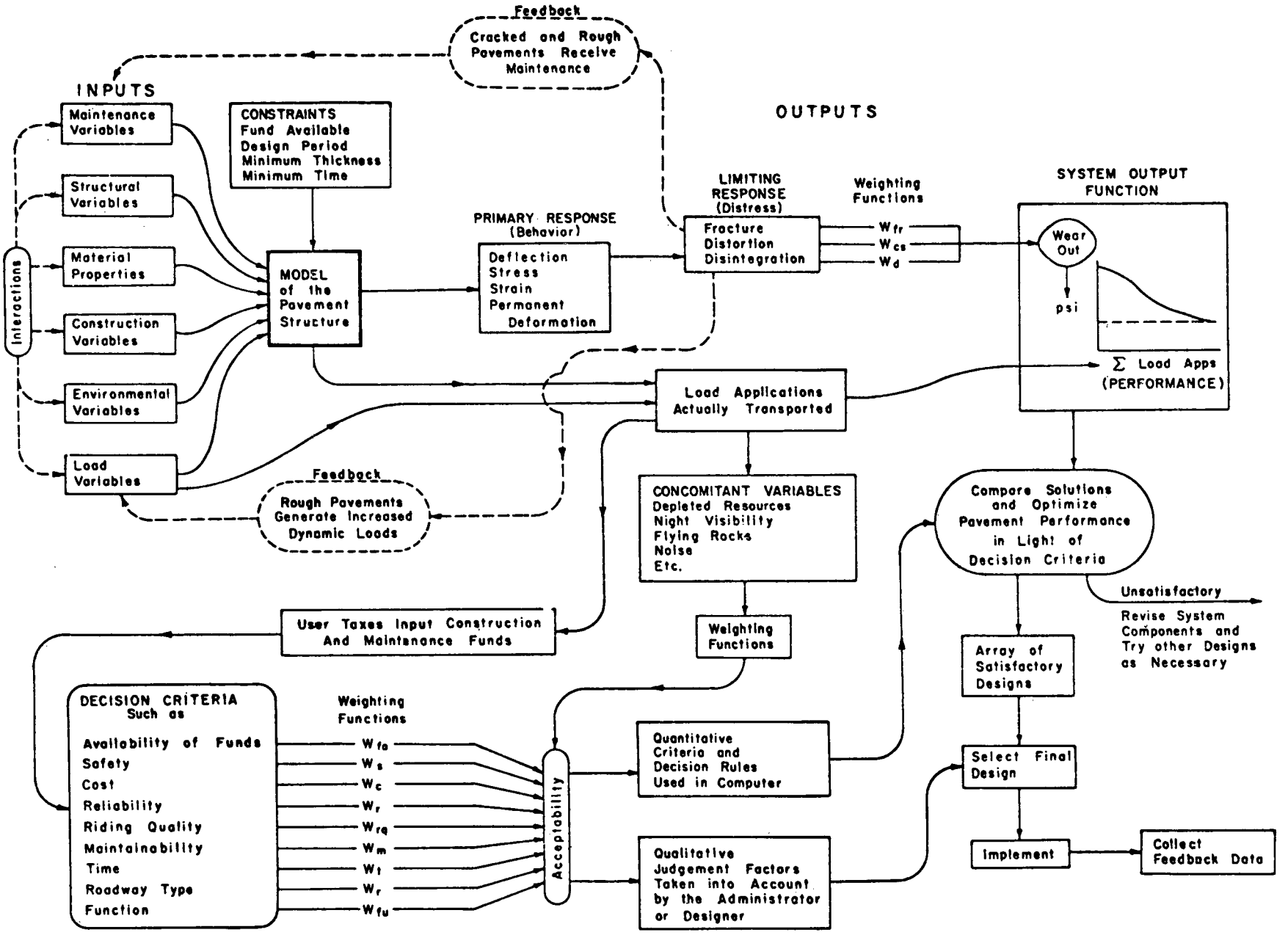


Figure 2. Block diagram of conceptual pavement system.

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 Dynaflect [after Scrivner et al. (*6*)]:

$$S = W_1 - W_2 \tag{1}$$

in which

$$W_j = \sum_{k=1}^{n+1} \Delta_{jk} \tag{2}$$

$$\Delta_{jk} = \frac{C_0}{a_k C_1}\left[\frac{1}{r_j^2 + C_2\left(\sum_{i=0}^{k-1} a_i D_i\right)^2} - \frac{1}{r_j^2 + C_2\left(\sum_{i=0}^{k} a_i D_i\right)^2}\right] \tag{3}$$

$C_0 = 0.891$;
$C_1 = 4.503$;
$C_2 = 6.25$;
$a_0 = D_0 = 0$;
$a_i =$ the strength coefficient of the ith layer of a pavement ($i = 1, 2, \ldots, n+1$);
$D_i =$ the thickness of the ith layer in inches ($D_{n+1} = \infty$);
$W_j =$ the deflection sensed by the jth sensor of the Dynaflect; and
$r_j =$ distance in inches from the point of application of either Dynaflect load to the jth sensor ($r_1^2 = 100$, $r_2^2 = 244$).

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:

$$N_k = \frac{N_c}{C(r_0 + r_c)}\left[2r_0 t_k + \left(\frac{r_c - r_0}{C}\right) t_k^2\right] \tag{4}$$

in which

t = time in years since initial construction;
N = total number of equivalent applications of an 18-kip axle that will have been applied in one direction during the time, t, in millions;
C = length in years of the analysis period;
$N_c = N$ when $t = C$;
$N_k = N$ when $t = t_k$;
r_0 = ADT (one direction) when $t = 0$;
r_c = ADT (one direction) when $t = C$; and
t_k = the value of t at the end of the kth 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':

$$Q_2 = \frac{53.6(N_k - N_{k-1})S^2}{\bar{\alpha}} + Q_2'(1 - e^{-b_k(t_k - t_{k-1})}) \qquad (5)$$

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

$$b_{k+1} = b_k e^{-b_k(t_k - t_{k-1})} \qquad (6)$$

$$Q(\text{the serviceability loss function}) = \sqrt{5 - P} - \sqrt{5 - P_1} \qquad (7)$$

$Q_2 = Q$ when $P = P_2$

$$Q_2' = \sqrt{5 - P_2'} - \sqrt{5 - P_1} \qquad (8)$$

α(a daily temperature constant) = ½ (maximum daily temperature + minimum daily temperature) −32°F.

$\bar{\alpha}$ = the effective value of α for a typical year in a given locality, defined by the formula for the harmonic mean

$$\bar{\alpha} = \frac{n}{\sum_{i=1}^{n} (1/\alpha_i)} \qquad (9)$$

in which n is the number of days in a year and α_i is the value of α for the ith day of the year.

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

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.

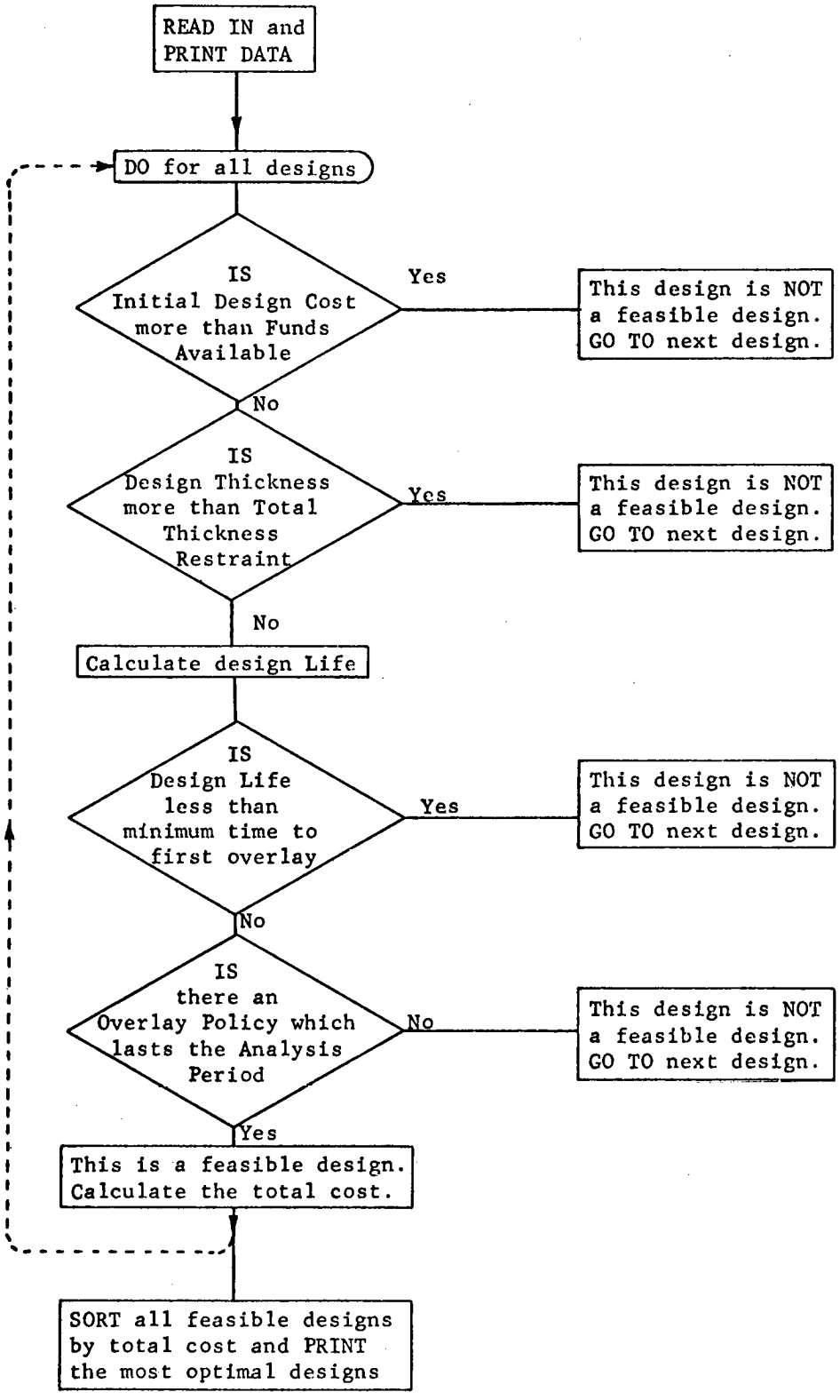


Figure 3. Summary flow chart of the Scrivner program. Source (15).

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, . . . SAMP*n*) 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_2', 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_1, and the lower limit of the serviceability index or the level when overlay construction or failure occurs, P_2, 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
               MATERIALS                COST    STR.    MIN.    MAX.    SALVAGE   SOIL
    LAYER CODE        NAME            PER CY  COEFF.  DEPTH   DEPTH     PCT.   SUPPORT
      1     A   ASPHALTIC CONCRETE    10.00     .44    6.00    8.00    50.00     0.00
      2     B   CRUSHED STONE          5.00     .14    5.00    8.00    50.00     9.20
      3     C   GRAVEL                 2.00     .11    5.00   10.00    50.00     6.90
                SUBGRADE              -0.00   -0.00   -0.00   -0.00    -0.00     4.25

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
     PI - THE SERVICEABILITY INDEX OF AN OVERLAY.                                     4.2
     P2 - THE MINIMUM ALLOWED VALUE OF THE SERVICEABILITY INDEX. (POINT AT WHICH AN   2.5
          OVERLAY MUST BE APPLIED).
     P2P - THE LOWER BOUND ON THE SERVICEABILITY INDEX WHICH WOULD BE ACHIEVED IN     1.5
           INFINITE TIME WITH NO TRAFFIC
     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       5000000
           THE ANALYSIS PERIOD.
     PROP - THE PERCENT OF ADT WHICH WILL PASS THROUGH THE OVERLAY ZONE DURING          6.0
            EACH HOUR WHILE OVERLAYING IS TAKING PLACE
     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
     XLSO - THE DISTANCE IN WHICH TRAFFIC IS SLOWED IN THE OVERLAY DIRECTION            .60
     XLSN - THE DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE NON-OVERLAY DIRECTION      .60
     XLSD - 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
          THE PERCENT OF VEHICLES THAT WILL BE STOPPED BECAUSE OF THE MOVEMENT OF
          PERSONNEL OR EQUIPMENT.
     PPO2 - IN THE OVERLAY DIRECTION                                                   5.00
     PPN2 - IN THE NON-OVERLAY DIRECTION.                                              5.00
            THE AVERAGE DELAY PER VEHICLE STOPPED BECAUSE OF THE MOVEMENT OF
            PERSONNEL AND EQUIPMENT.
     DDO2 - IN THE OVERLAY DIRECTION (HOURS)                                          .150
     DDN2 - IN THE NON-OVERLAY DIRECTION (HOURS)                                      .150
     AAS - THE AVERAGE APPROACH SPEED TO THE OVERLAY AREA.                             50
           THE AVERAGE SPEED THROUGH THE OVERLAY AREA
     ASO - IN THE OVERLAY DIRECTION (MPH).                                             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, SAMP5.

PROB 000 ALL VARIABLES AT ENGINEERING AVERAGE

SUMMARY OF THE BEST DESIGN STATEGIES
IN ORDER OF INCREASING TOTAL COST

	1	2	3	4	5	6	7	8	9	10
MATERIAL ARRANGEMENT	A	A	A	A	ABC	ABC	ABC	ABC	ABC	AB
INIT. CONST. COST	2.153	2.222	2.014	2.083	2.639	2.917	2.917	2.708	2.708	2.639
OVERLAY CONST.COST	1.127	1.092	1.309	1.262	.825	.558	.570	.802	.802	.863
USER COST	.271	.252	.303	.297	.203	.130	.138	.201	.202	.208
ROUTINE MAINT.COST	.588	.633	.594	.592	.624	.710	.714	.631	.633	.627
SALVAGE VALUE	-.510	-.550	-.510	-.523	-.576	-.602	-.602	-.589	-.589	-.576
TOTAL COST	3.628	3.650	3.710	3.710	3.715	3.719	3.737	3.753	3.756	3.761
NUMBER OF LAYERS	1	1	1	1	3	3	3	3	3	2
LAYER DEPTH(INCHES)										
D(1)	7.75A	8.00A	7.25A	7.50A	6.00A	6.00A	6.25A	6.25A	6.00A	7.00A
D(2)					6.00B	5.00B	5.00B	5.00B	5.00B	5.00B
D(3)					6.00C	10.00C	8.75C	5.00C	8.25C	
NO.OF PERF.PERIODS	5	4	5	5	4	3	3	4	4	4
PERF.TIME(YEARS)										
1(1)	2.563	2.813	2.031	2.281	3.688	4.781	4.688	3.806	3.938	3.438
1(2)	5.797	7.734	5.266	5.844	8.469	11.625	11.344	9.063	9.234	7.844
1(3)	9.828	14.016	9.297	10.250	14.516	20.531	20.062	15.672	15.891	13.375
1(4)	14.750	21.750	14.219	15.594	21.875			23.641	24.047	20.031
1(5)	20.656		20.125	22.062						
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)										
0(1)	1.5	2.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5
0(2)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
0(3)	1.5	1.5	1.5	1.5	1.5			1.5	1.5	1.5
0(4)	1.5		1.5	1.5						

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_2) 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_2, 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 ½ in. starting the minimum overlay thickness constraint. All possible combinations of thicknesses (in ¼-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 SAMP5 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*):

$$SN^* = A_1D_1 + A_2D_2 + \ldots + A_nD_n \qquad (10)$$

in which

SN^* = structural number of the pavement;
A_i = AASHO strength coefficient of the ith layer;
D_i = thickness of the ith 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.

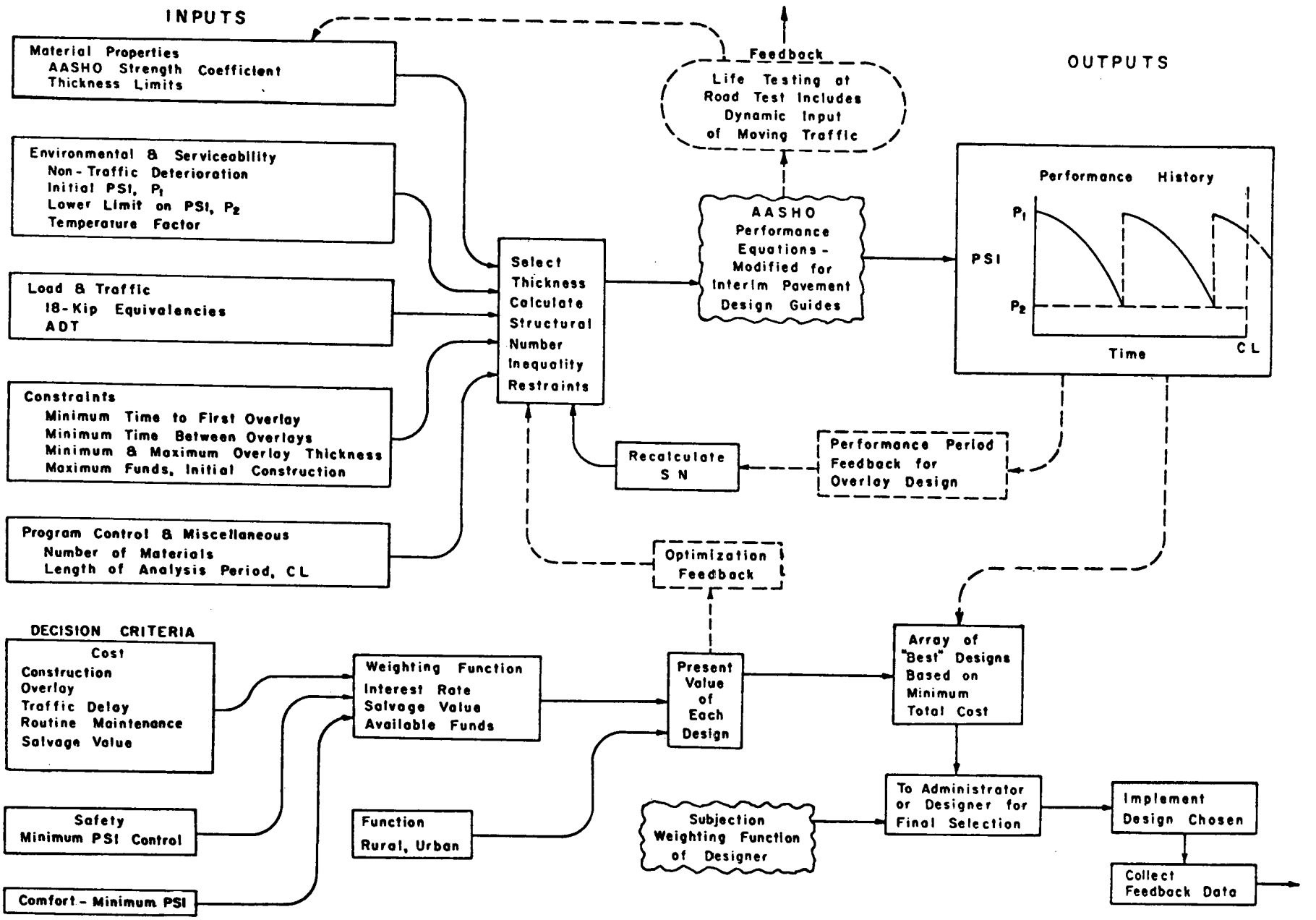


Figure 6. Block diagram of SAMP pavement system.

$$SN = \left[\frac{1.051(W_t \cdot R)^{0.106S}}{10^{0.03973(SS-3)} \cdot 10^{1/\beta_{18}} \cdot (g-g')} \right] - 1 \quad (11)$$

in which

SN = structural number required of a pavement structure;
W_t = total equivalent 18-kip single-axle loads expected during the design life of the facility;
SS = soil support term for the existing material;
R = regional factor;

$$\beta_{18} = 0.4 + \frac{0.081(19)^{3.23}}{(SN^* + 1)^{5.19}} \quad (12)$$

$$g = \frac{P_1 - P_2}{P_1 - 1.5} \quad (13)$$

$$g' = \frac{M^2 + 2M\sqrt{5 - P_1}}{P_1 - 1.5} \quad (14)$$

$$M = (\sqrt{5 - P_2'} - \sqrt{5 - P_1})(1 - e^{-b_k t_k}) \quad (15)$$

in which

P_1 = initial serviceability index;
P_2' = nontraffic deterioration lower limit;
b_k = nontraffic deterioration rate at the beginning of the kth performance period; and
t_k — length of the kth performance period.

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

$$D_1 \geq \frac{SN_2}{A_1} \quad (16)$$

$$SN_2^* = A_1 D_1 \geq SN_2 \quad (17)$$

$$D_i \geq \frac{SN_{i+1} - SN_i^*}{A_i}, \; i = 2, \ldots, n \quad (18)$$

$$SN_{i+1}^* = SN_i^* + A_i D_i \geq SN_i + 1, \; i = 2, \ldots, n \quad (19)$$

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_t, assuming that Eq. 14, the term for nontraffic deterioration, is equal to zero. The interface with the smallest W_t 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 REVISING 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.
3. Pavement performance and failure.

Thus, it is necessary to understand the interrelationship of these factors in order to establish concepts and procedures for improving components of the pavement system. 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

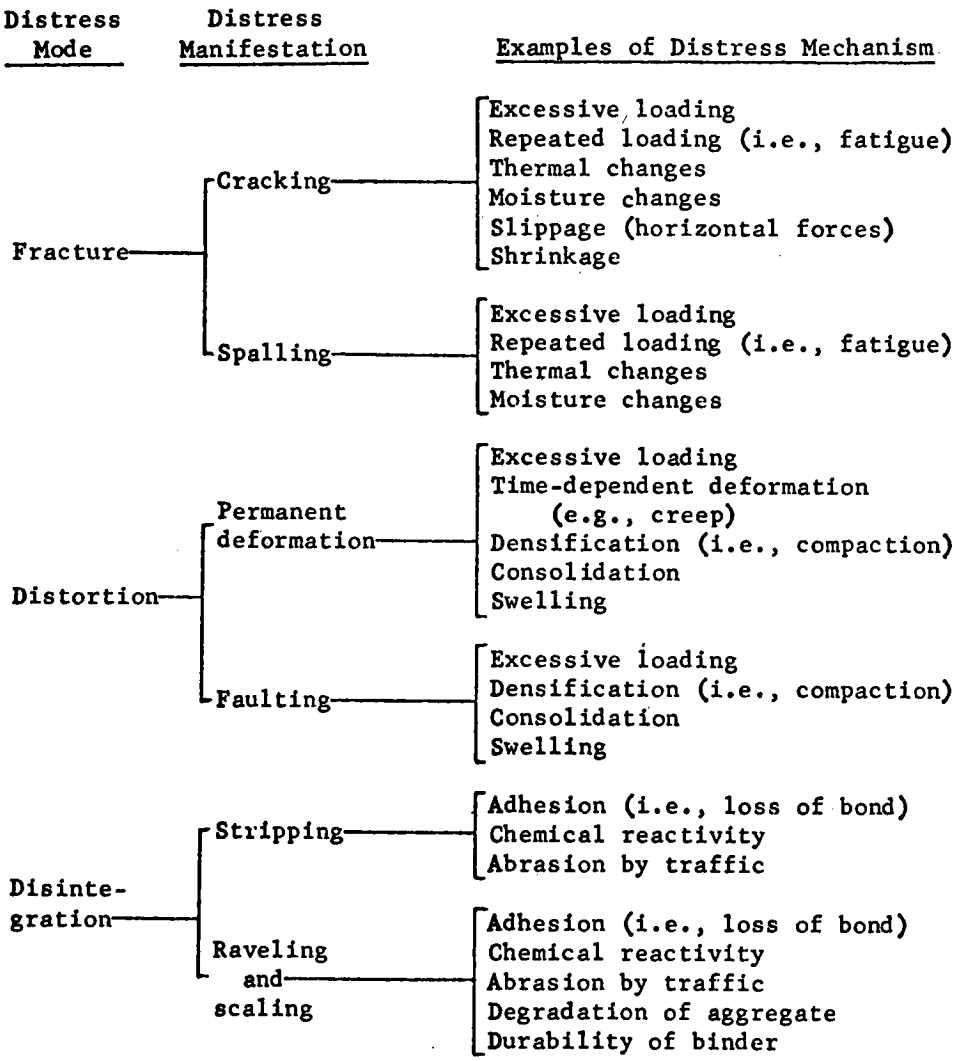


Figure 7. Categories of pavement distress.

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:

$$p = 5.03 - 1.91 \log(1 + \overline{SV}) - 0.01\sqrt{C + p} - 1.38\overline{RD}^2 \tag{20}$$

in which

$p =$ present serviceability index;

SV = mean slope variance, a summary statistic of wheel path roughness;
RD = average rut depth in the wheel path;
C = area of detrimental cracking per 1,000 sq ft; and
P = area of patching per 1,000 sq ft.

$$P(\underline{x}, t) = \overset{s=t}{\underset{s=0}{F}}[p(\underline{x}, s)] \tag{21}$$

in which

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

$$\mathrm{SN} = A_1D_1 + A_2D_2 + A_3D_3 \tag{22}$$

in which

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

$$P = p_1 - (W/\rho)^{\beta} \tag{23}$$

in which

p_1 = initial PSI;
W = number of equivalent wheel loads; and
β, ρ = parameters depending on layer thickness and strength coefficient, wheel load magnitude and configuration, etc.

The SAMP program uses a structural number value (Eq. 22) to compute the present serviceability value (Eq. 23) 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 present serviceability index at time t. Because these mathematical models are equations statistically derived from the AASHO Road Test, they may be applied successfully within the limits of material types and thicknesses and experiment at the AASHO Road Test. The use of any new materials may be an extrapolation of the equation beyond its boundary conditions; hence, the applicability is questionable and remains to be verified. Thus, one immediate improvement of the SAMP computer program would be to quantify Eqs. E-2, E-3, and E-4 for fracture distortion and disintegration and their combined value of distress index (Eq. E-1) on the basis of theory. With such a model, serviceability index could be predicted on the basis of the actual output information (i.e., fracture, disintegration, and distortion) rather than through a gross transformation between input variables and performance based on field observations. Such models would make it possible to design for any material and any conditions.

Functional Models

The complete quantification of Eqs. E-1 through E-4 to encompass all of the distress manifestations and mechanisms in Figure 7 is an extensive undertaking that is beyond the scope of this project. Therefore, the approach used here is to show a logical method for quantifying several of the distress mechanisms and demonstrate their applicability in the systems model.

The distress mechanism fatigue or repeated loading (Fig. 7) has been the subject of considerable research (*29-37*), with the result that much information is available for use; therefore, this distress mechanism has been selected for quantification. The complex interaction of the various distress mechanisms and manifestations is discussed previously. Figure 8 shows the interrelation of several distress manifestations that may be related with that caused by load repetitions. In this example, the distress mechanism of repeated loading leads to a primary manifestation of cracking, and the continued repeated load application leads to a secondary manifestation of spalling (fracture) and permanent deformation (distortion). The cracking of the pavement structure may also reduce the load-carrying capacity of the pavement structure, and for the same loads a secondary mechanism of excessive loading results and leads to a secondary distress manifestation of faulting (distortion) and spalling (fracture). In this manner, the initial distress mechanism of repeated loading has caused the distress modes of fracture and distortion to occur in the pavement structure. Thus, it is easy to envision the complex interactions that would develop when several distress mechanisms are involved.

The progressive increase of the distress index (Eq. E-1) from an initial effect of the repeated loading distress mechanism and subsequent secondary distress mechanisms is shown in Figures 9 through 12. In Figure 9, the development of the cracking index is shown in terms of traffic application. For the first period of traffic applications, little or no cracking occurs. Then at a traffic value of N_c, progressive cracking begins, and the cracking index increases rapidly. If it is assumed that only the fracture mode occurs, the cracking index is used with Eq. E-1 to compute the distress index. Its history is shown in Figure 10. There is no change in the index until cracking occurs at n_c traffic applications, at which time a progressive decay commences.

The development of the secondary manifestations of faulting and permanent deformation is shown in Figure 11, in terms of the distortion mode of distress. The distortion index might begin at a traffic value n_d, which is greater than n_c 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.

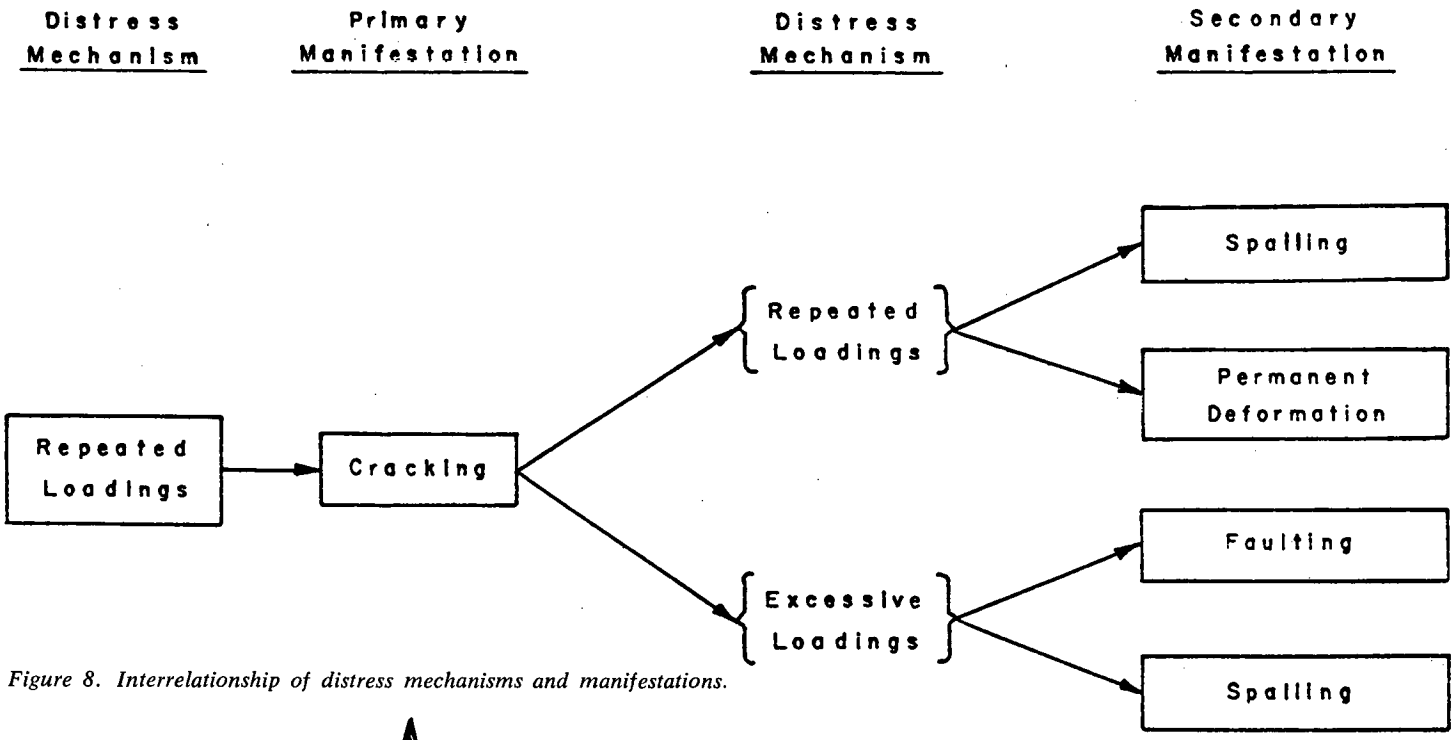


Figure 8. Interrelationship of distress mechanisms and manifestations.

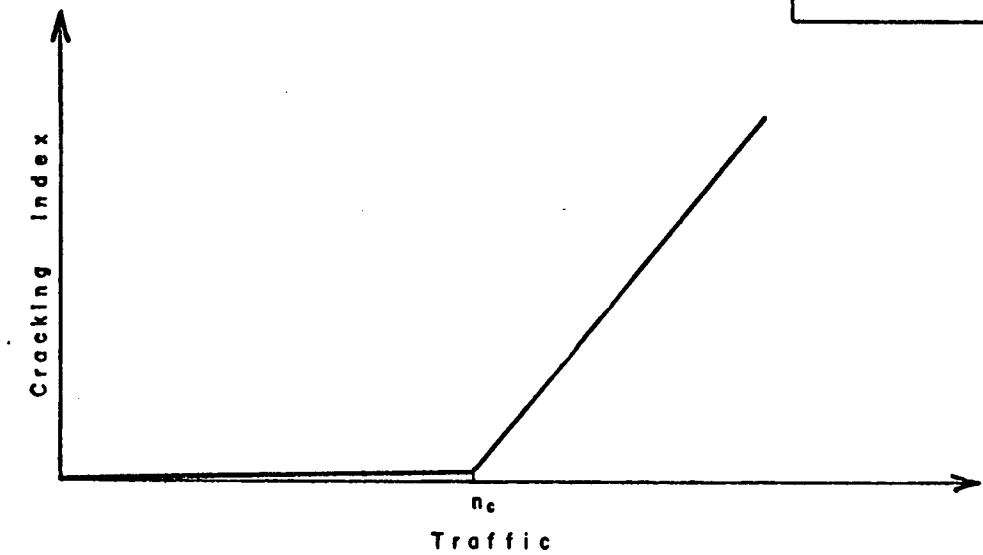


Figure 9. Progressive development of the cracking index with traffic.

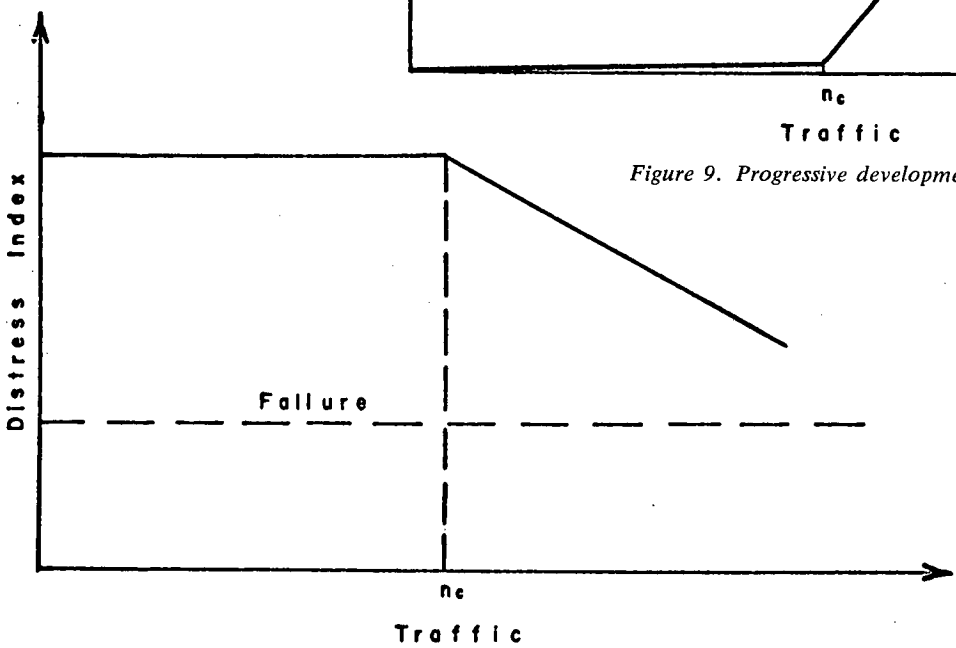


Figure 10. Progressive development of the distress index, considering only cracking.

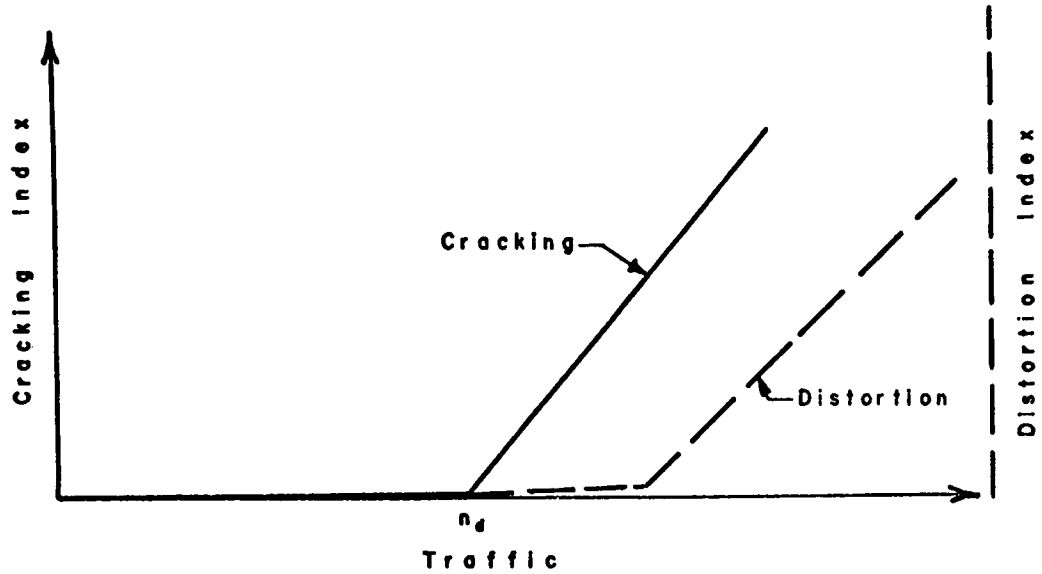


Figure 11. Progressive development of primary cracking and secondary distortion.

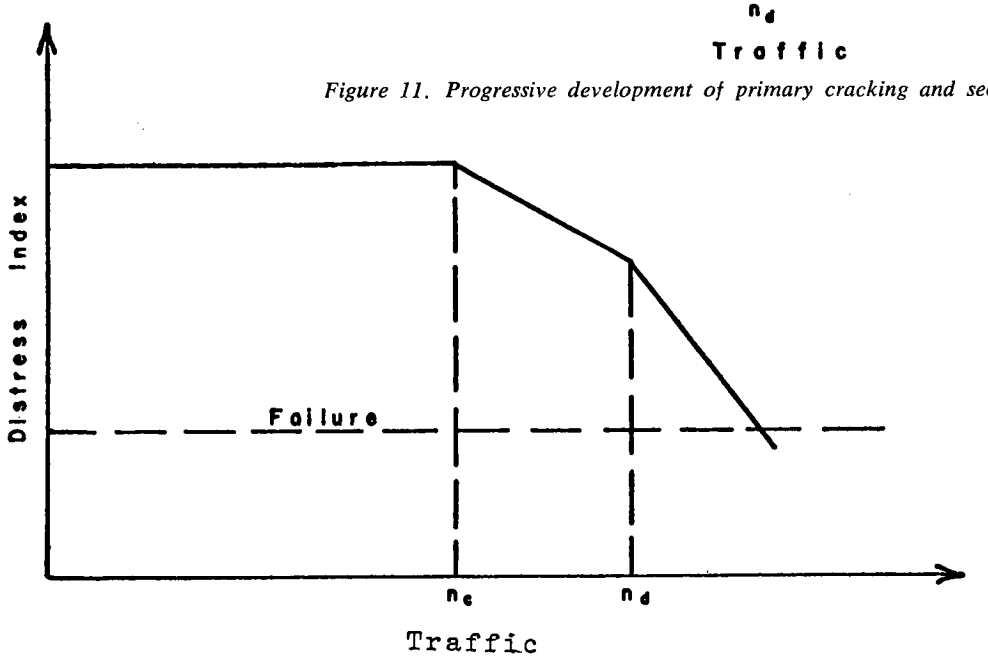


Figure 12. Progressive development of the distress index, considering both the cracking and the distortion indexes.

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:

$$P\{C\} = P\{\text{stress} > b\} + P\{\text{strength} < b\} \qquad (24)$$

in which

$P\{\ \}$ = probability of an event occurring; and
b = 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-

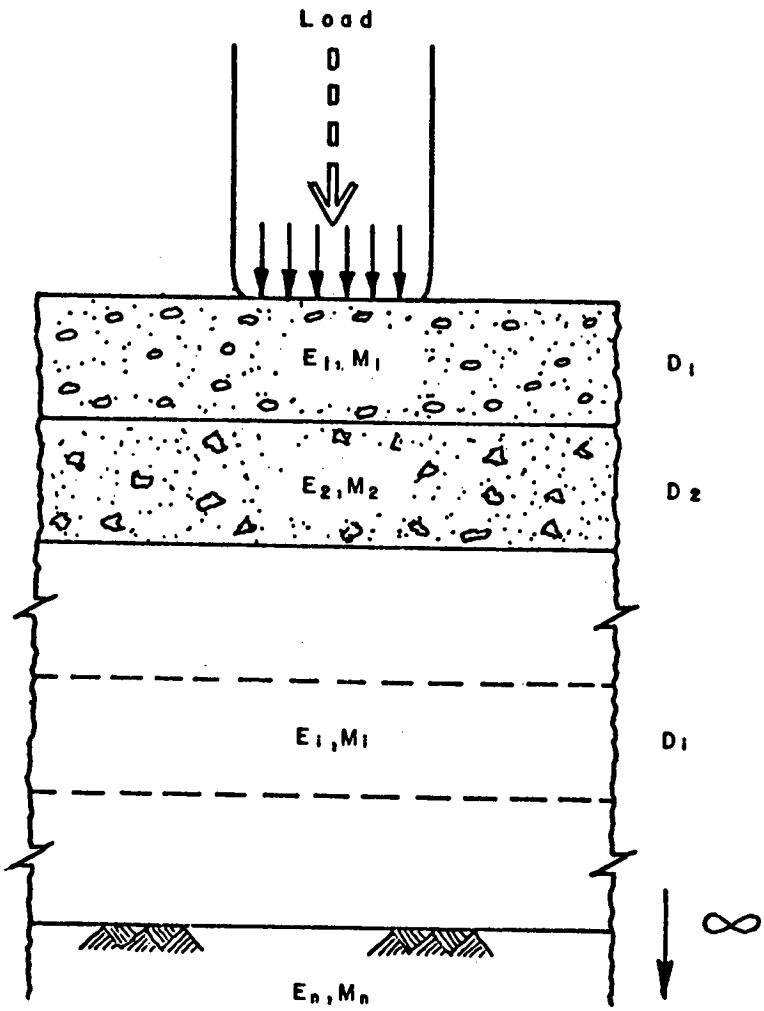


Figure 13. Typical pavement structure cross-section showing the elastic parameters.

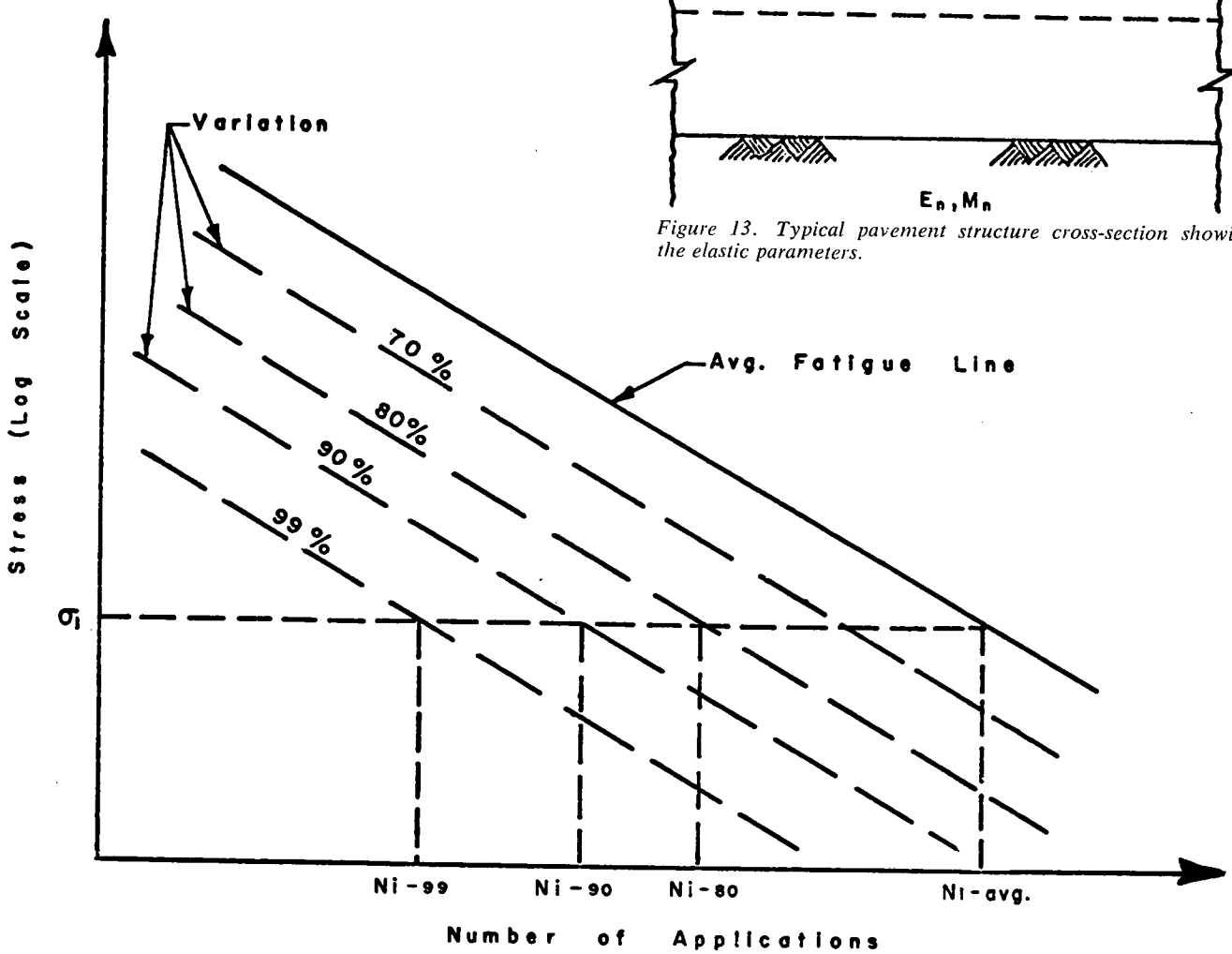


Figure 14. Typical fatigue diagram for a pavement material.

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 *i*th 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.

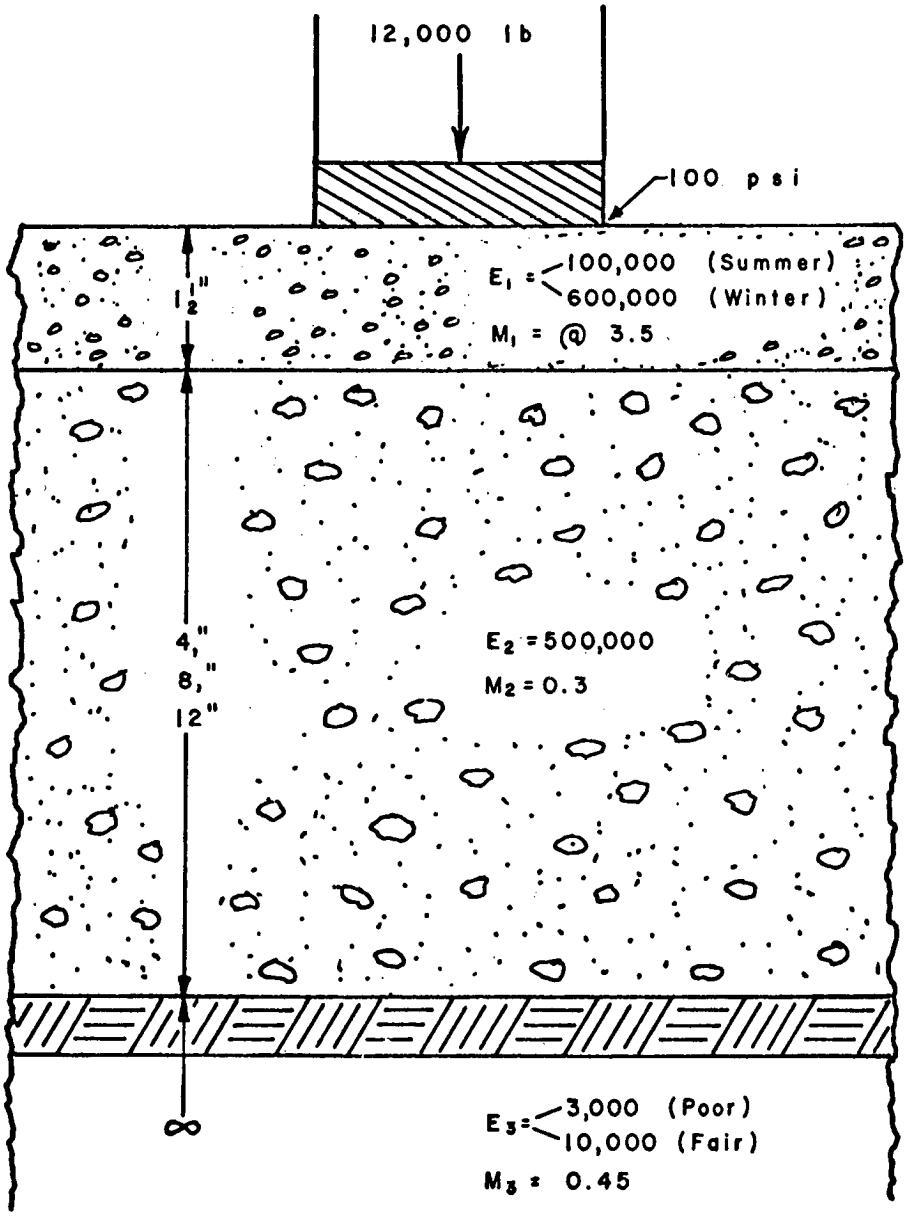


Figure 15. Geometry and material properties used in the example problem.

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:

$$CI(\underline{x}, t) = \overset{s=t}{\underset{s=0}{P}}\{C(\underline{x}, s)\}1{,}000 \tag{25}$$

in which

$P\{\ \}$ = probability of an event occurring; and
$C(\underline{x}, s)$ = cracking of space and time.

The right side is defined as

$$\overset{s=t}{\underset{s=0}{P}}\{C(\underline{x}, s)\} = P\left\{\sum_{j=1}^{k} \frac{n_j}{N_j} \geq 1.0\right\} \tag{26}$$

in which

n_j = the actual number of the jth stress repetitions experienced; and
N_j = the allowable number of jth 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

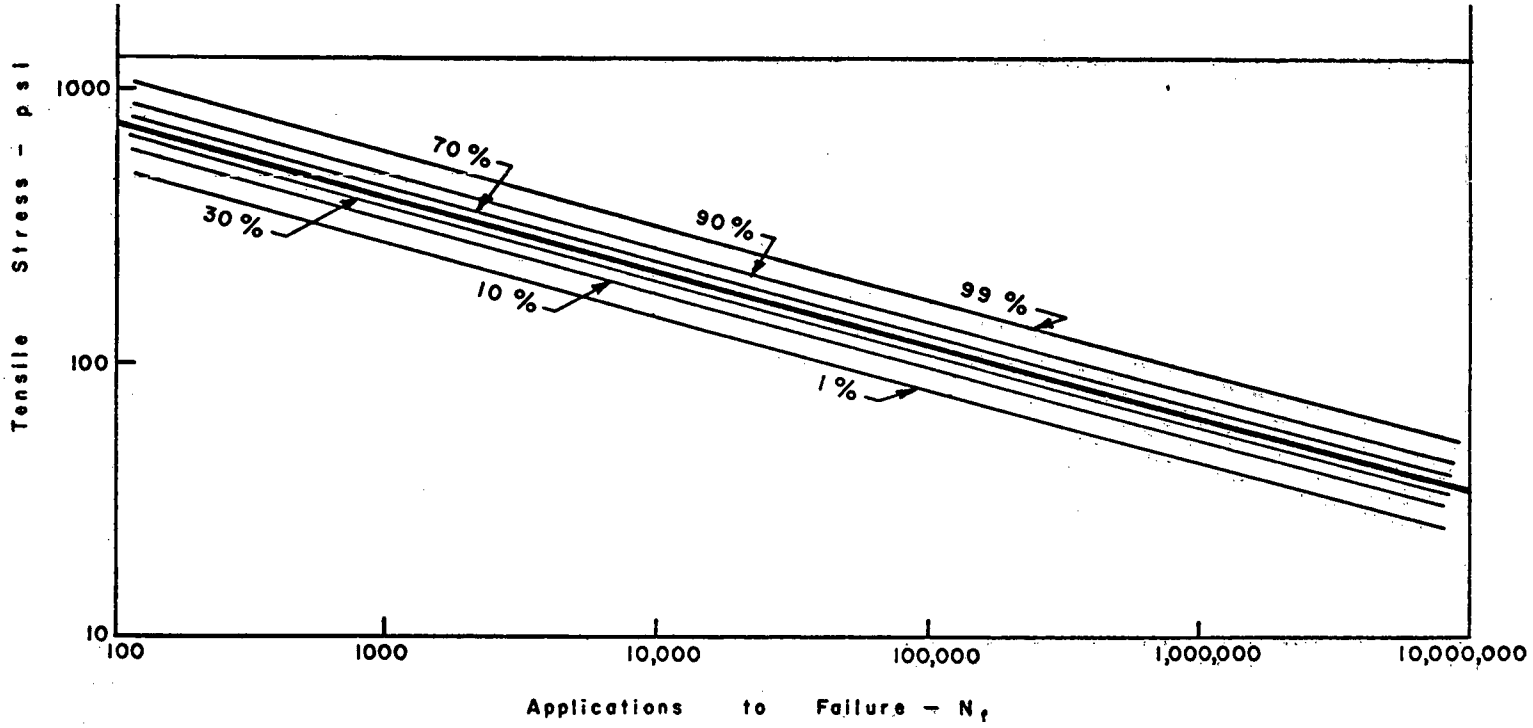


Figure 16. Fatigue diagram for an asphaltic concrete with good quality control.

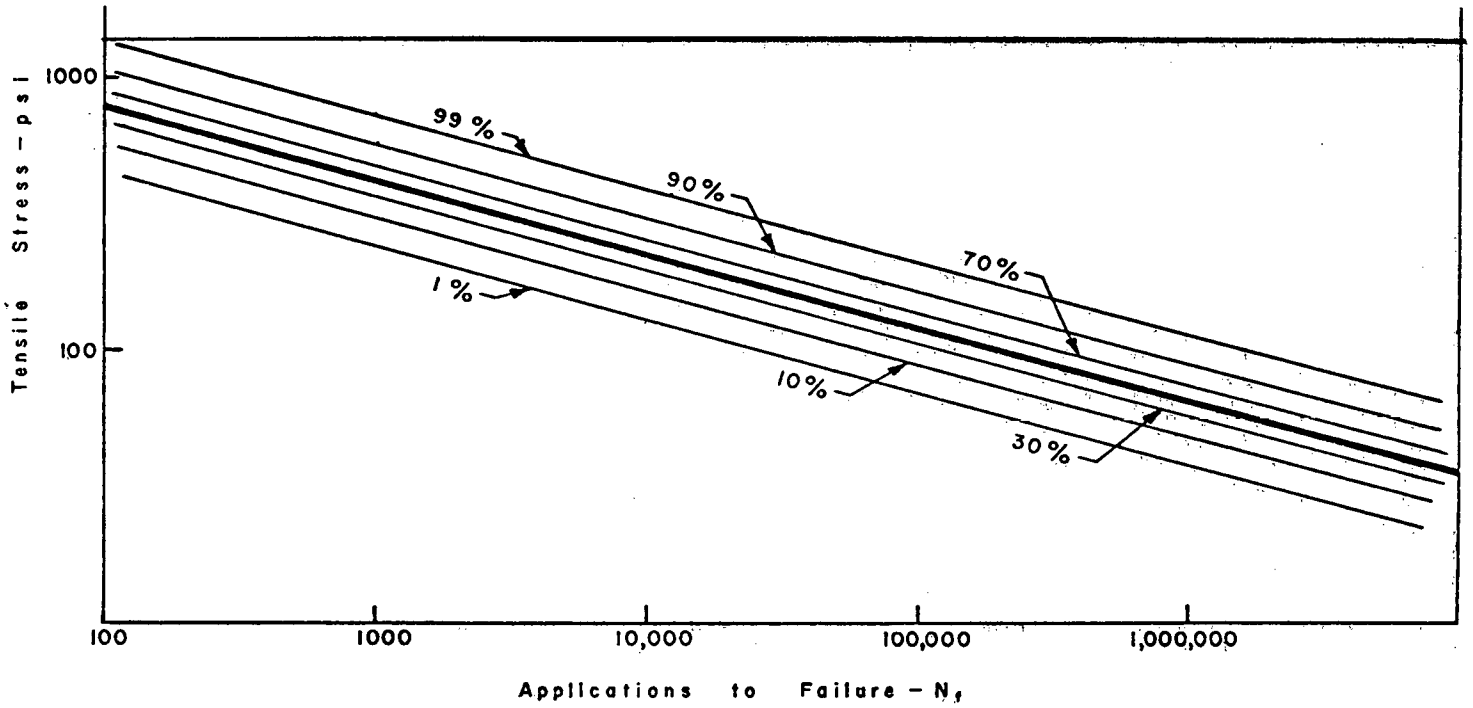


Figure 17. Fatigue diagram for an asphaltic concrete with poor quality control.

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.

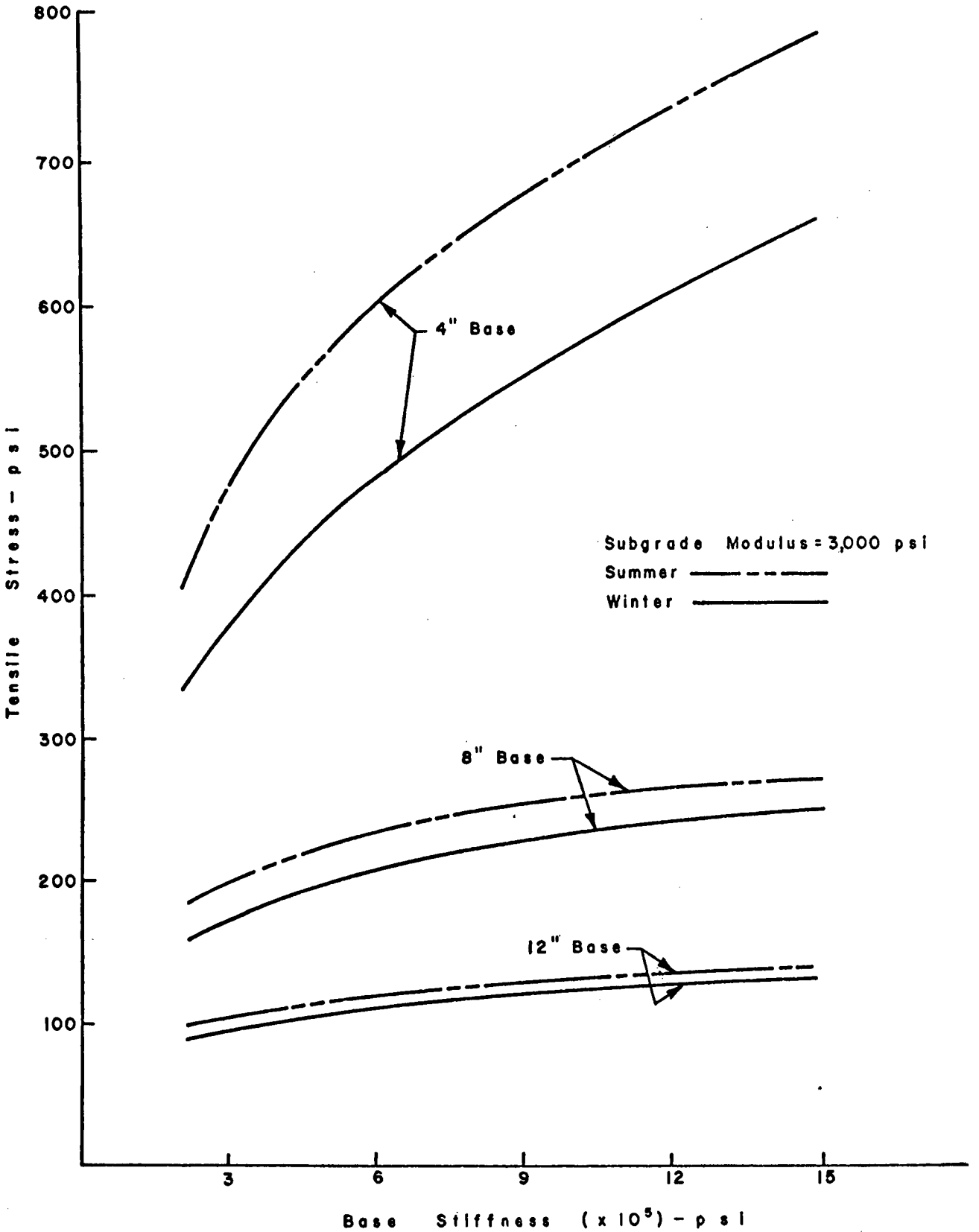


Figure 18. Tensile stresses at soil-base interface with poor soil support for varying conditions of base thickness, base modulus, and seasons.

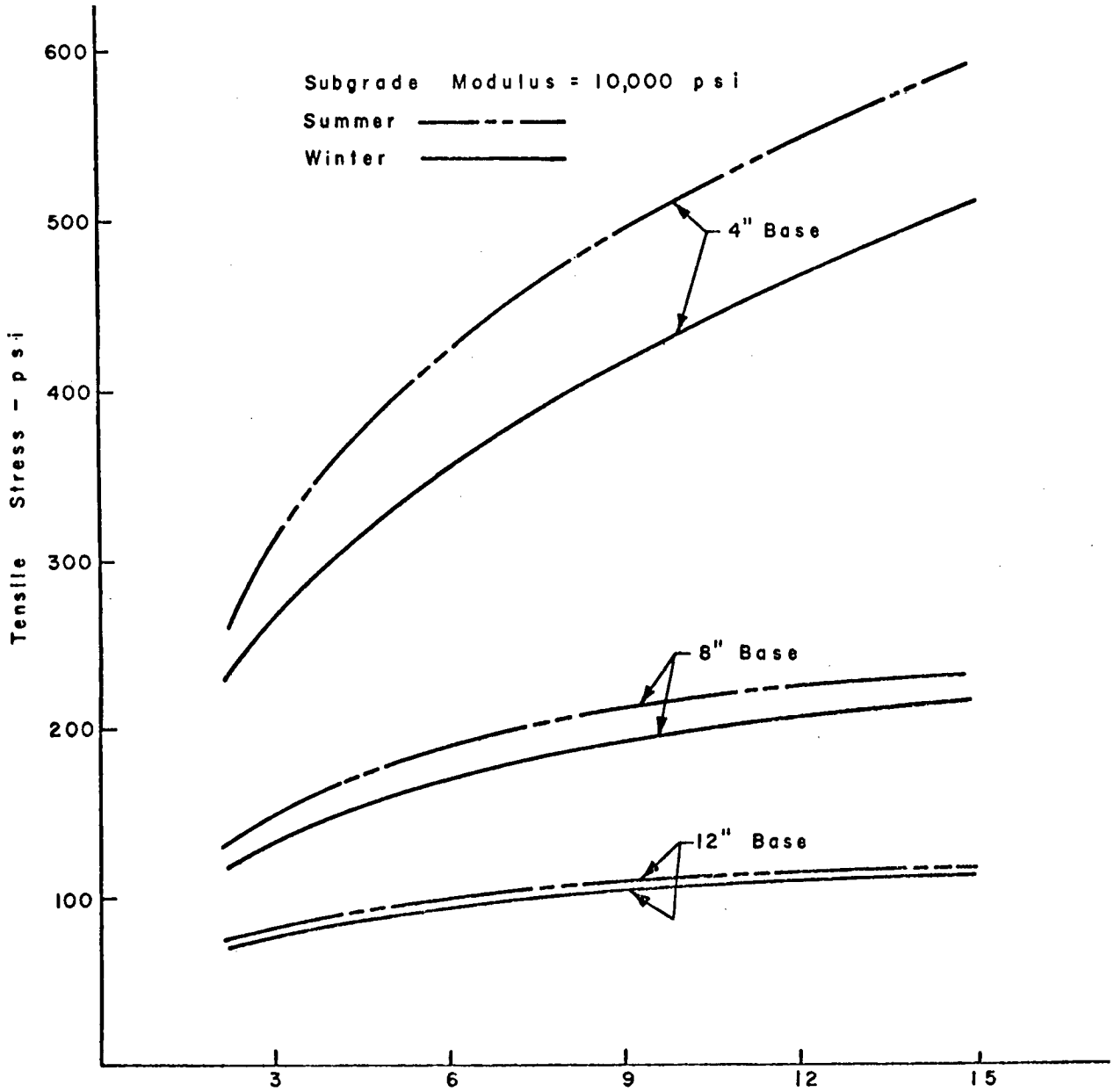


Figure 19. Tensile stresses at soil-base interface with fair soil support and varying conditions of base thickness, base modulus, and seasons.

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

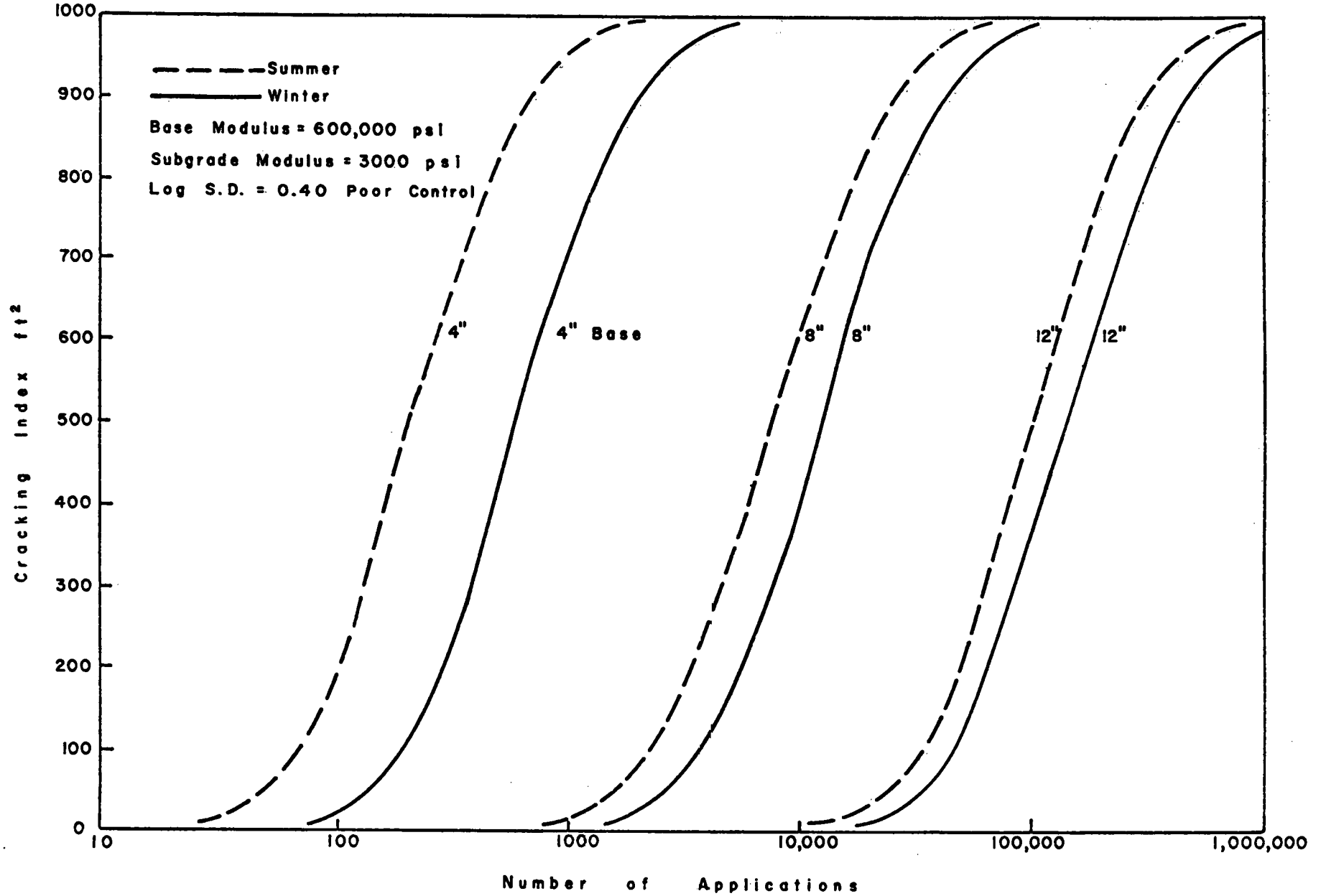


Figure 20. Effect of base thickness and season on cracking index.

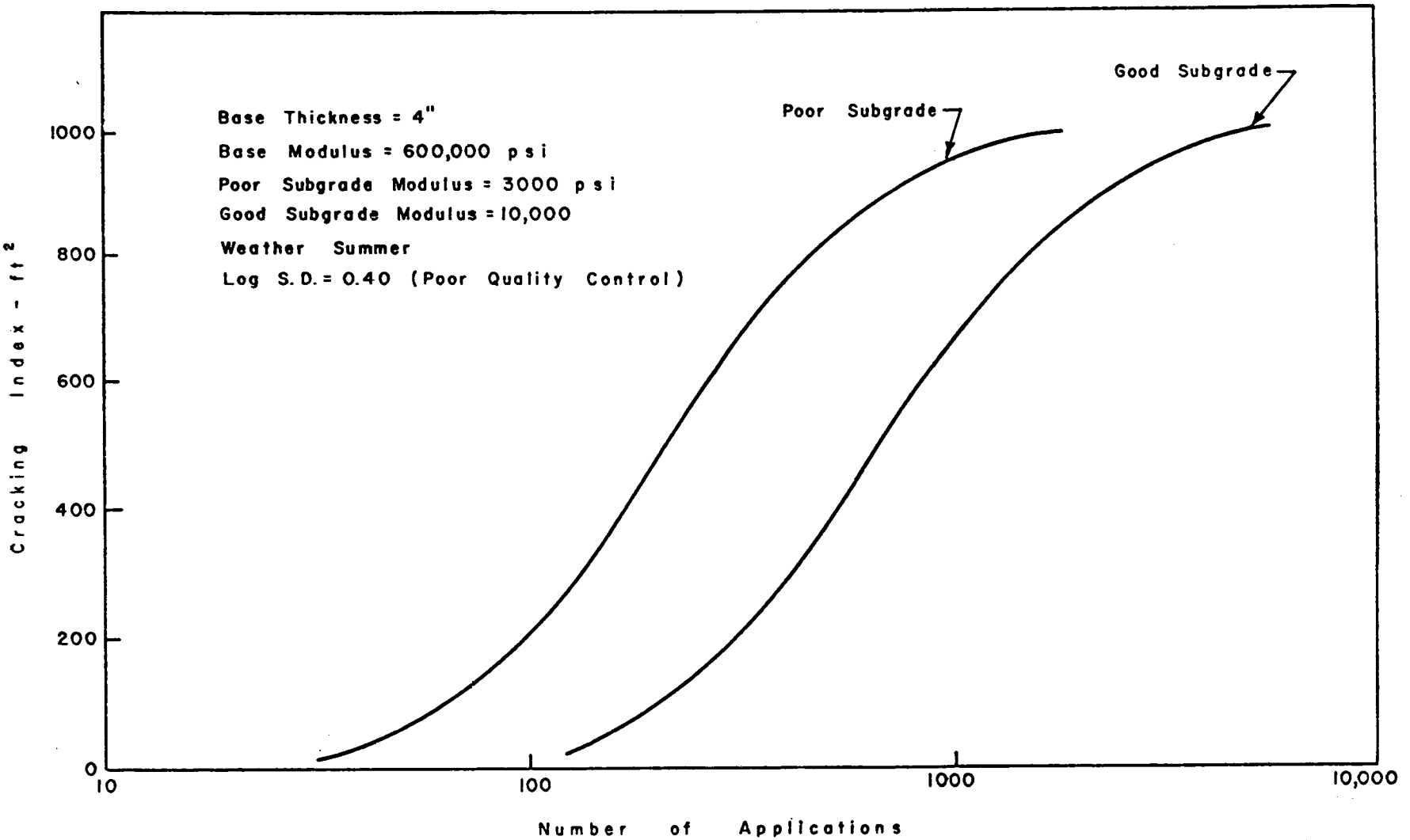


Figure 21. Effect of subgrade support on computed cracking index.

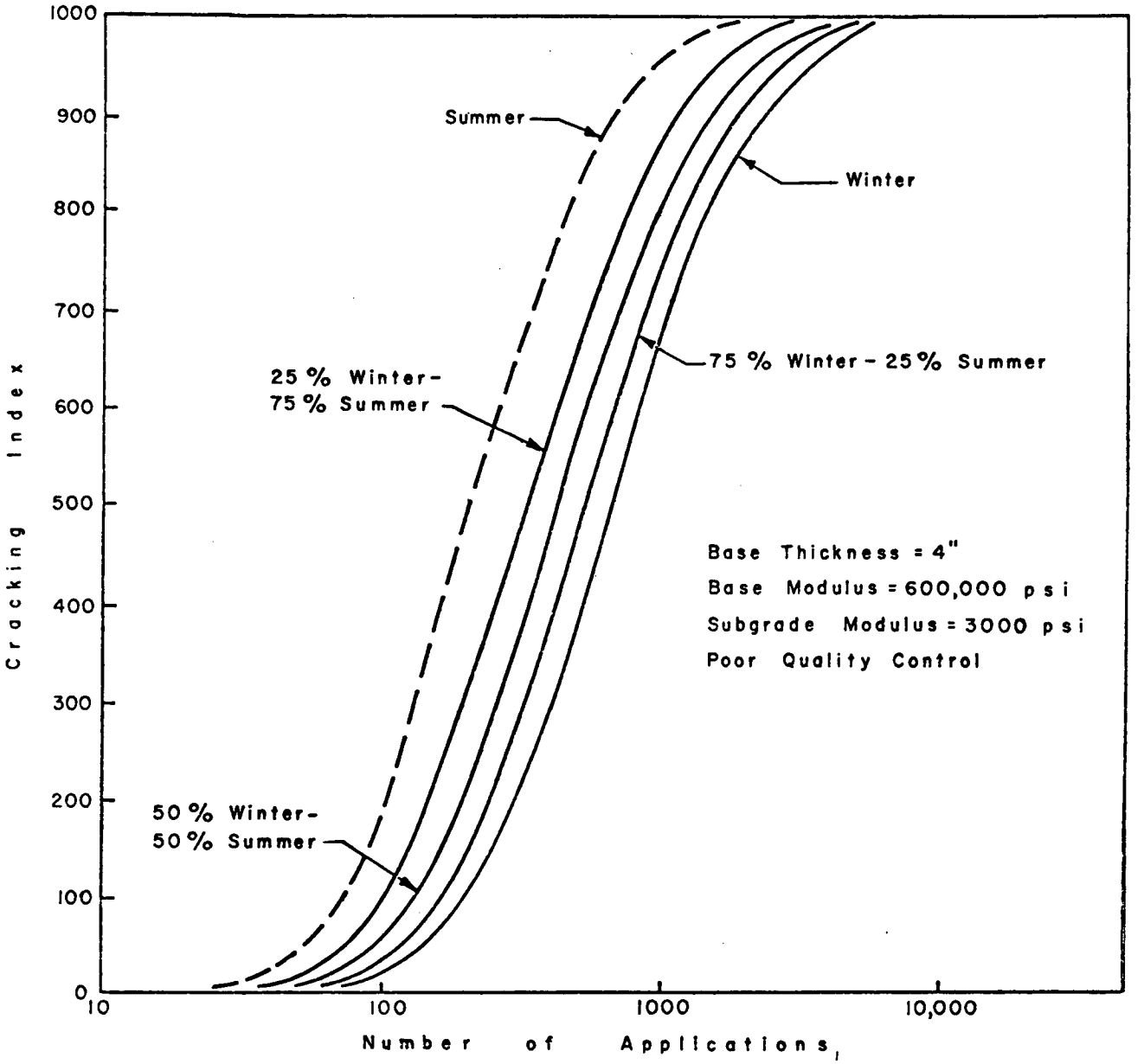


Figure 22. Effect of seasonal distribution of wheel loads on cracking index history.

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:

$$DI(\underline{x}, t) = 1.0 - 0.0002\, P\left\{ \sum_{j=1}^{k} \frac{n_j}{N_j} \geq 1.0 \right\} 1{,}000 \qquad (27)$$

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.

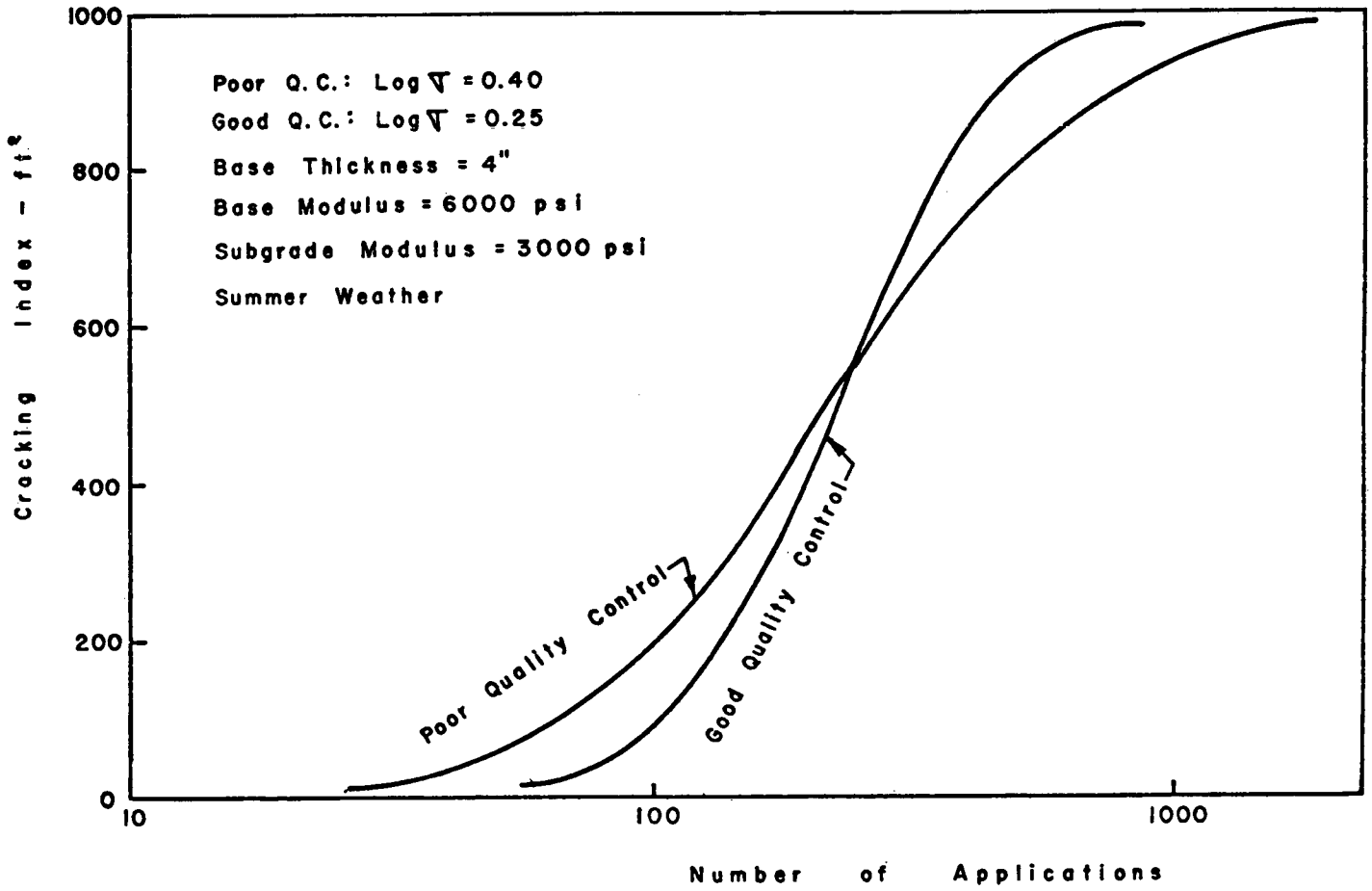


Figure 23. Effect of construction quality control on cracking index history.

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-

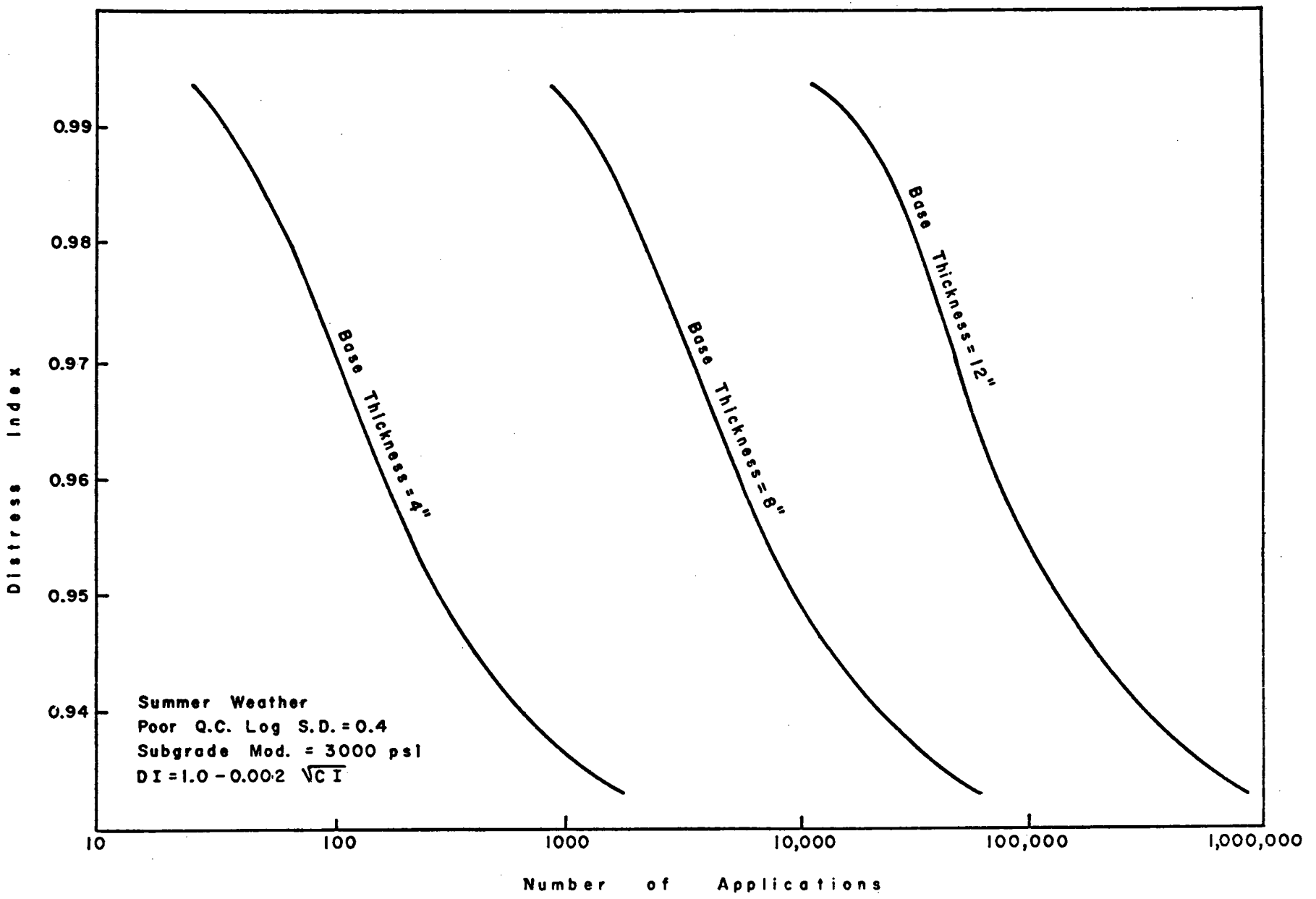


Figure 24. Effect of base thickness on distress index and N_t.

ects 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.

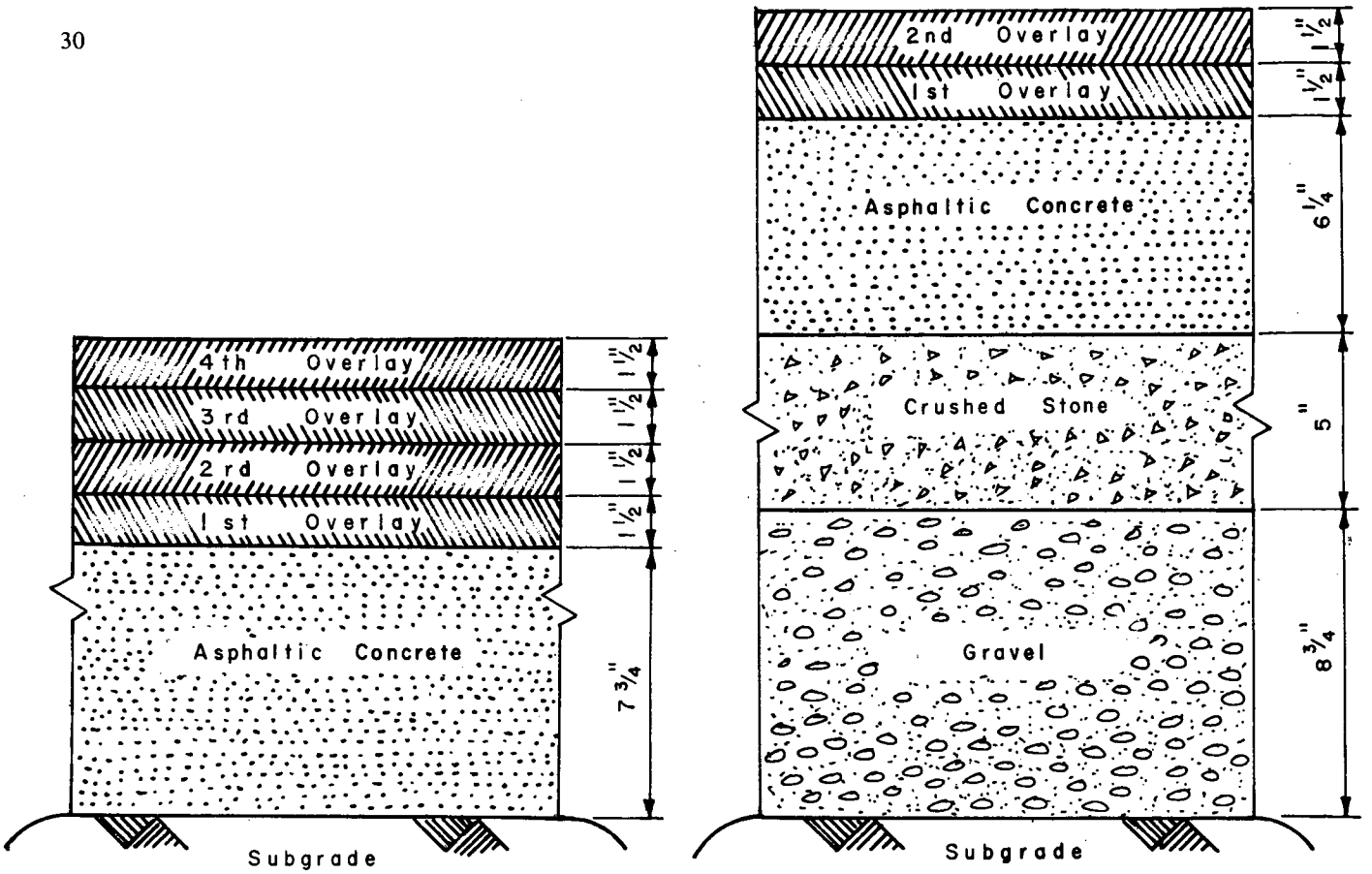
SUBSEQUENT PROGRAM USE

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



a. Design 1

b. Design 7

Figure 25. Pavement cross-section for Design Strategies 1 and 7.

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.

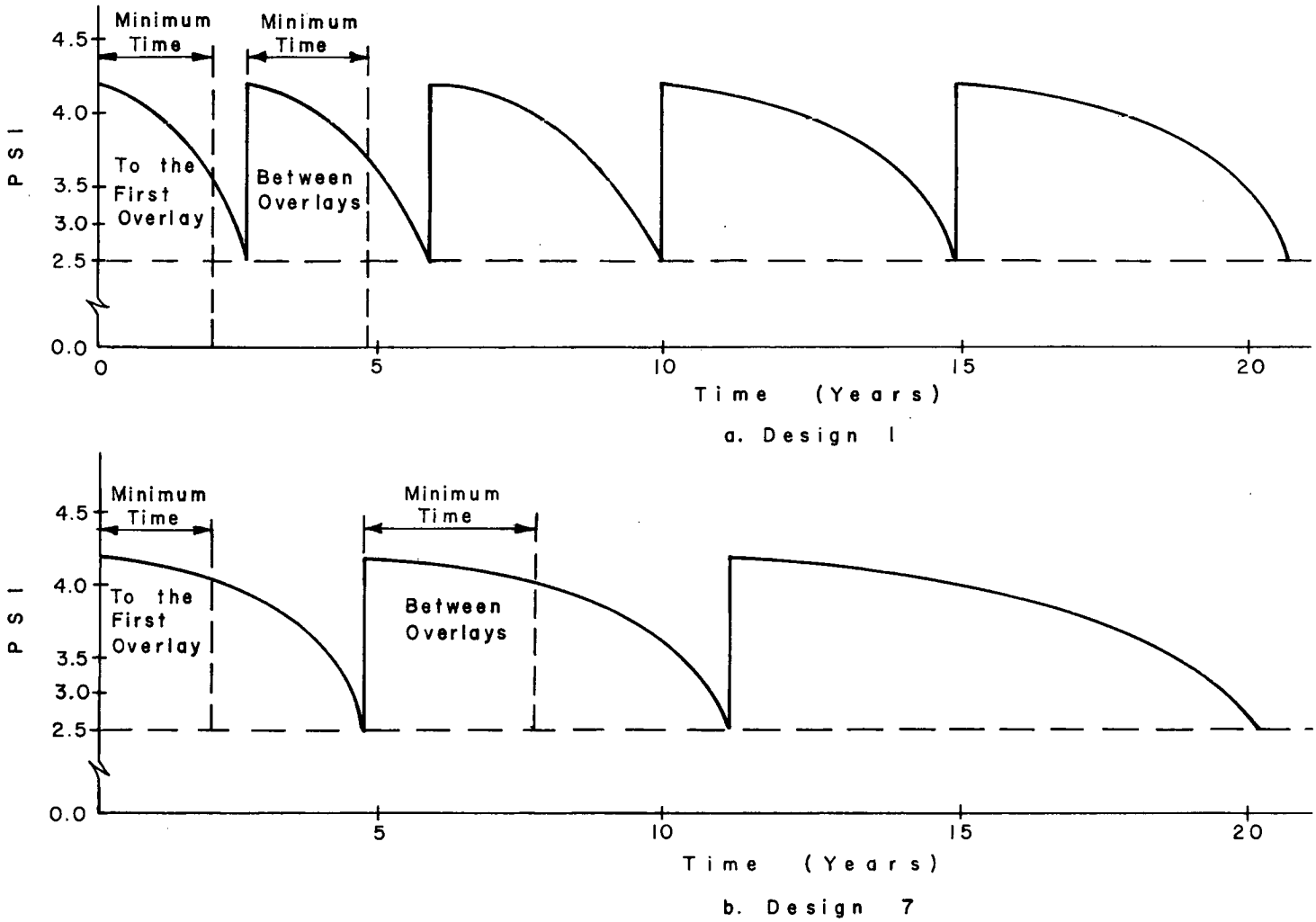


Figure 26. Predicted performance histories of Design Strategies 1 and 7.

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 SAMP5 program, the time subroutine must be called from 5,000

TABLE 1

VALUES OF VARIABLES USED IN SENSITIVITY STUDY

VARIABLE	VALUE LOW	AVERAGE	HIGH
1. Nontraffic deterioration parameter	0.0	0.12	0.24
2. Accumulated number of equivalent 18-kip axles	2×10^6	5×10^6	8×10^6
3. Number of days the temperature remains below 32°F	0	60	120
4. Strength coefficient of the asphaltic concrete layer	0.33	0.44	0.77
5. Soil support value of the subgrade	2.00	4.25	6.50

to 10,000 times; thus, the computer time required to get 1,000 solutions of the subroutine would be fairly small. These solutions can be analyzed by any of a number of statistical computer programs available to determine the significance of each variable and the interactions between them. Ultimately, some type of statistical analysis would be helpful here.

There are many other types of objective analysis that can be run involving evaluation of one or more of the output variables, including performance, initial thickness requirements, number of overlays, and number of layers.

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

VARIABLE	LOW: INITIAL CONST. THICKNESS [a]	LOW: NO. OF OVERLAYS	LOW: TOTAL COST/SQ YD ($)	HIGH: INITIAL CONST. THICKNESS [a]	HIGH: NO. OF OVERLAYS	HIGH: TOTAL COST/SQ YD ($)
1. Nontraffic deterioration parameter	8.00A	2	3.266	5.25A 5.00B 10.00C	3	3.842
2. Accumulated number of equivalent 18-kip axles	7.25A	3	3.220	6.00A 5.00B 7.50C	3	3.860
3. Number of days the temperature remains below 32°F	7.75A	4	3.049	7.75A	4	4.307
4. Strength coefficient of the asphaltic concrete layer	6.00A	2	2.703	6.00A 7.00B 10.00C	2	3.965
5. Soil support value of the subgrade	6.75A	2	2.857	8.00A 5.00B 10.00C	3	4.438

	INITIAL CONST. THICKNESS	NO. OF OVERLAYS	TOTAL COST/SQ YD ($)
Average value solution	7.75A	4	3.628

[a] A, B, and C refer to material type in example problem.

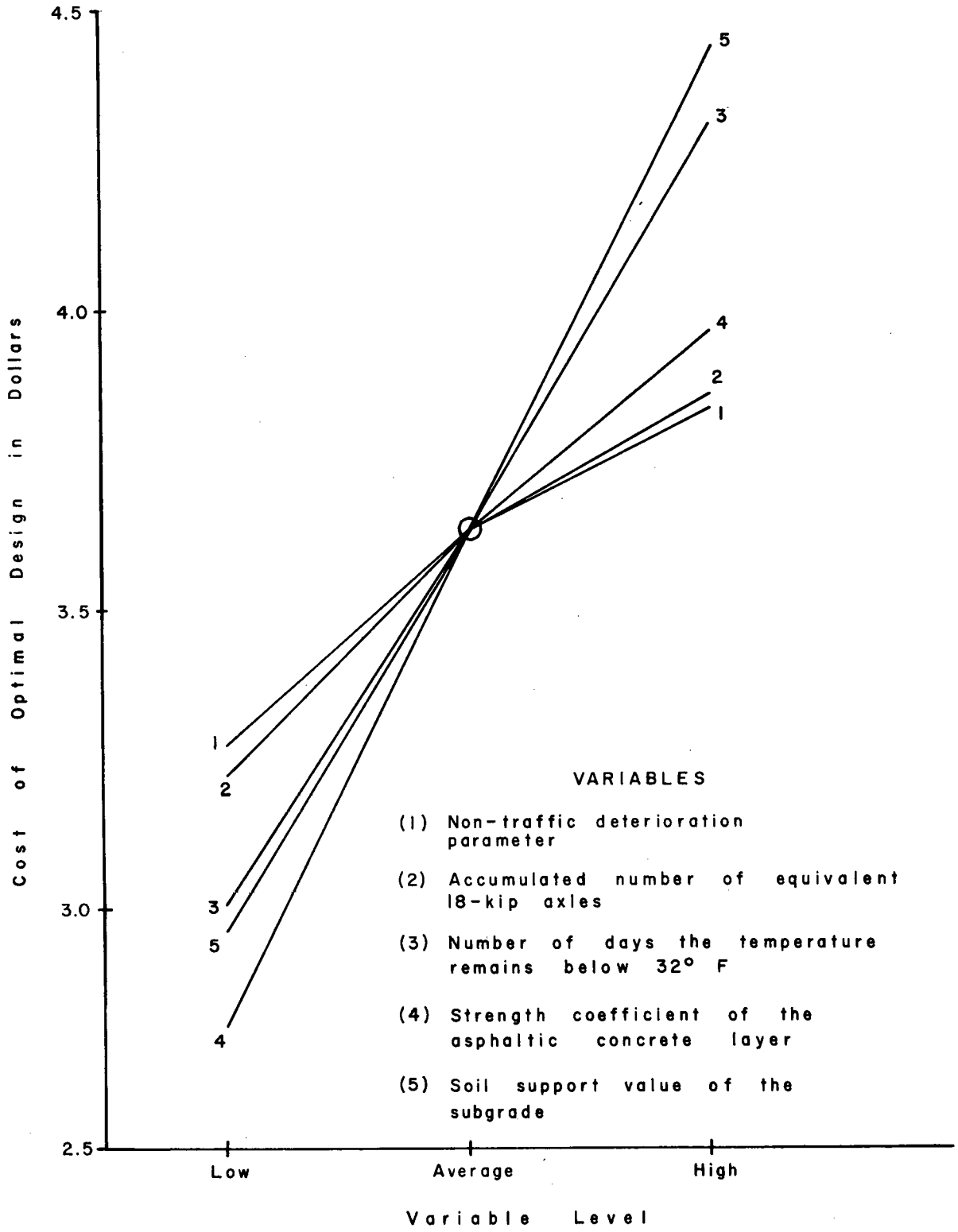


Figure 27. Cost of optimal design vs variable level for solutions in sensitivity study.

TABLE 3

NUMERICAL RATING OF VARIABLES

VARIABLE	LOW TO AVERAGE		AVERAGE TO HIGH		LOW TO HIGH	
	CENTS/ 10% CHANGE	PERCENTILE RATING [a]	CENTS/ 10% CHANGE	PERCENTILE RATING [a]	CENTS/ 10% CHANGE	PERCENTILE RATING [a]
1. Nontraffic deterioration parameter	8.04	43.5	4.28	23.1	6.16	33.3
2. One-direction accumulated number of equivalent 18-kip axles	8.16	44.1	4.64	25.1	6.40	34.6
3. Number of days the temperature remains below 32°F	11.58	62.6	13.58	73.4	12.58	68.0
4. Strength coefficient of the first material (asphaltic concrete)	18.50	100.0	6.74	36.4	12.62	68.2
5. Soil support value of the subgrade	15.42	83.3	16.2	87.6	15.82	85.5

[a] 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

1. Ellis, D. O., and Ludwig, F. J., *Systems Philosophy.* Prentice-Hall (1962).
2. Dommasch, D. O., and Laudeman, C. W., *Principles Underlying Systems Engineering.* Pitman (1962).
3. "Compendium of Support Documentation for Research Project 123." Center for Highway Research, Univ. of Texas at Austin (Dec. 1968-69).
4. Hudson, W. R., McCullough, B. F., and Finn, F. N., "Factors Affecting Performance of Pavement Systems." *Trans. Eng. Jour.,* Vol. 95, No. TE3, ASCE (Aug. 1969).
5. Nair, K., and Chang, C-Y, "Flexible Pavement Design and Management—Materials Characterization." *NCHRP Report 140* (1973).
6. Scrivner, F. H., McFarland, W. F., and Carey, G. R., "A Systems Approach to the Flexible Pavement Design Problem." *Res. Rep. 32-11,* Texas Trans. Inst. (1968).
7. Hutchinson, B. G., and Haas, R. C. G., "A Systems Analysis of the Highway Pavement Design Process." *Hwy. Res. Record No. 239* (1968) pp. 1-24.
8. Lemer, A. C., and Moavenzadeh, F., "The Analysis of Highway Pavement Systems." *Prof. Paper P69-12,* MIT (Sept. 1969).
9. Haas, R. C. G., and Hutchinson, B. G., "A Management System for Highway Pavements." Prepared for Australian Road Res. Board (Sept. 1970).
10. AASHO, "AASHO Interim Guide for the Design of Flexible Pavement Structures." Committee on Design (1961).
11. Scrivner, F. H., and Michalak, C. H., "Flexible Pavement Performance Related to Deflections, Axle Applications, Temperature and Foundation Movements." *Res. Rept. 32-13,* Texas Trans. Inst. (1969).
12. Scrivner, F. H., and Moore, W. M., "Some Recent Findings in Flexible Pavement Research." *Res. Rept. 32-9,* Texas Trans. Inst. (1967).
13. Scrivner, F. H., and Moore, W. M., "Standard Measurements for Satellite Road Test Program." *NCHRP Report 59* (1968).
14. Scrivner, F. H., and Moore, W. M., "An Empirical Equation for Predicting Pavement Deflections." *Res. Rept. 32-12,* Texas Trans. Inst. (1968).
15. Hudson, W. R., McCullough, B. F., Scrivner, F. H., and Brown, J. L., "A Systems Approach Applied to Pavement Design and Research." *Res. Rept. 123-1,* publ. jointly by Texas Highway Dept.; Texas Trans. Inst., Texas A&M Univ.; and Center for Highway Res., Univ. of Texas at Austin (Apr. 1970).
16. Van Til, C. J., McCullough, B. F., Vallerga, B. A., and Hicks, R. G., "Evaluation of AASHO Interim Guides for Design of Pavement Structures." *NCHRP Report 128* (1972).
17. Bertram D. Tallamy Associates, "Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index." *NCHRP Report 42* (1967).
18. Carey, W. N., Jr., and Irick, P. E., "The Pavement Serviceability-Performance Concept." *HRB Bull. 250* (1960) pp. 40-58.
19. Mellinger, F. M., "Evaluation of Rigid Pavement Performance." *HRB Bull. 187* (1958) pp. 58-66.
20. Monismith, C. L., "Asphalt Paving Mixtures—Properties, Design, and Performance." Inst. of Trans. and Traffic Eng., Univ. of Calif. (1961).
21. Vallerga, B. A., "On Asphalt Pavement Performance." *Proc. AAPT,* Vol. 24 (1955).
22. Irick, P. E., and Hudson, W. R., "Guidelines for Satellite Studies of Pavement Performance." *NCHRP Report 2A* (1964).
23. Harr, M. E., and Head, W. J., "Extension of AASHO Road Test Performance Concepts." *NCHRP Report 30* (1966).
24. Hveem, F. N., "Types and Causes of Failure in Highway Pavements." *HRB Bull. 187* (1958) pp. 1-52.
25. Yoder, E., *Principles of Pavement Design.* Wiley (1959).
26. Monismith, C. L., "Design Considerations for Asphalt Pavements to Minimize Fatigue Distress Under

Repeated Loading." Presented at Fourth Ann. Pavement Conf., Univ. of New Mexico (Dec. 1966).

27. "The AASHO Road Test: Report 5—Pavement Research." *HRB Spec. Rept. 61E* (1962) 352 pp.
28. AASHO, "AASHO Interim Guide for the Design of Rigid Pavement Structures." Committee on Design (Oct. 1962).
29. MONISMITH, C. L., KASIANCHUK, D. A., and EPPS, J. A., "Asphalt Mixture Behavior in Repeated Flexure: A Study of an In-Service Pavement Near Morro Bay, California. *Rept. No. TE 67-4,* Univ. of Calif., Berkeley (Dec. 1967).
30. DEACON, J. A., "Fatigue of Asphalt Concrete." Ph.D. dissertation, Univ. of Calif., Berkeley (1965).
31. EPPS, J. A., "Influence of Mixture Variables on the Flexural Fatigue and Tensile Properties of Asphalt Concrete." Ph.D. dissertation, Univ. of Calif., Berkeley (Sept. 1968).
32. MONISMITH, C. L., *Fatigue of Asphalt Paving Mixtures.* Presented at First Ann. Street and Highway Conf., Univ. of Nev. (Mar. 1966).
33. PELL, P. S., "Fatigue Characteristics of Bitumen and Bituminous Mixes." *Proc. Internat. Conf., Structural Design of Asphalt Pavements,* Univ. of Mich. (1963).
34. NORDBY, G. M., "Fatigue of Concrete—A Review of Research." *Jour. ACI,* Vol. 30, No. 2 (Aug. 1958).
35. HILSDORF, H. K., and KESLER, C. E., "Fatigue Strength of Concrete Under Varying Flexural Stresses." *J. ACI,* Vol. 63, No. 10 (Oct. 10, 1966) pp. 1059-1076.
36. MCCALL, J. T., "Probability of Fatigue Failure of Plain Concrete." *Jour. ACI,* Vol. 30, No. 2 (Aug. 1958).
37. NORDBY, G. M., "Fatigue of Concrete—A Review of Research." Presented at ACI 54th Ann. Conv., ACI Committee 215, Chicago (Feb. 26, 1958).
38. TIMOSHENKO, S., *Theory of Elasticity.* McGraw-Hill (1934).
39. BURMISTER, D. M., "The General Theory of Stresses and Displacements in Layered Systems." *J. Appl. Phys.,* Vol. 16, No. 2, pp. 89-96; No. 3, pp. 126-127; No. 5, pp. 296-302 (1945).
40. PEUTZ, M. G. F., VAN KEMPEN, H. P. M., and JONES, A., "Layered Systems Under Normal Surface Loads." *Hwy. Res. Record No. 228* (1968) pp. 34-45.
41. KASIANCHUK, D. A., "Fatigue Considerations in the Design of Asphalt Concrete Pavements." Ph.D. Dissertation, Univ. of Calif., Berkeley (1968).
42. MCCULLOUGH, B. F., "A Pavement Overlay Design System Considering Wheel Loads, Temperature Changes, and Performance." Ph.D. dissertation, Univ. of Calif., Berkeley (July 1969).
43. FINN, F. N., "Factors Involved in the Design of Asphaltic Pavement Surfaces." *NCHRP Report 39* (1967).
44. SEED, H. B., MITRY, F. G., MONISMITH, C. L., and CHAN, C. K., "Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests." *NCHRP Report 35* (1967).
45. YODER, E. J., and MILHOUS, R. T., "Comparison of Different Methods of Measuring Pavement Condition." *NCHRP Report 7* (1964).
46. KONDNER, R. L., and KRIZEK, R. J., "Factors Influencing Flexible Pavement Performance." *NCHRP Report 22* (1966).
47. "Road Test One-MD, Final Report: "Effect of Controlled Axle Loadings on Concrete Pavement." *HRB Spec. Rept. 4* (1952).
48. "The WASHO Road Test—Part 2." *HRB Spec. Rept. 22* (1955).
49. "The AASHO Road Test: Report 5—Pavement Research." *HRB Spec. Rept. 61E* (1962).
50. RAO, C. R., *Linear Statistical Inference and Its Application.* Wiley (1965).
51. "The AASHO Road Test: Report 2—Materials and Construction." *HRB Spec. Rept. 61B* (1962).
52. BINGHAM, J. M., and WHITE, J. R., JR., "An Evaluation of the Moisture and Density Road Logger Unit." *Res. Rept. No. 37-1,* Texas Highway Dept. (1965).
53. TELLER, W., *An Introduction to Probability Theory and its Applications.* Wiley (1961).
54. ALDEN, H. L., and ROESSLER, E. B., *Introduction to Probability and Statistics.* Freeman & Sons (1964).
55. THOMASIAN, A. J., *The Structure of Probability Theory with Application.* McGraw-Hill (1967).
56. BUSCHING, H. W., GOETZ, W. H., and HARR, M. E., "Stress Deformation Behavior of Anisotropic Bituminous Mixtures." *Proc. AAPT,* Vol. 36 (1967).
57. VESIĆ, A. S., and DOMASCHUK, L., "Theoretical Analysis of Structural Behavior of Road Test Flexible Pavements." *NCHRP Report 10* (1964).

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.

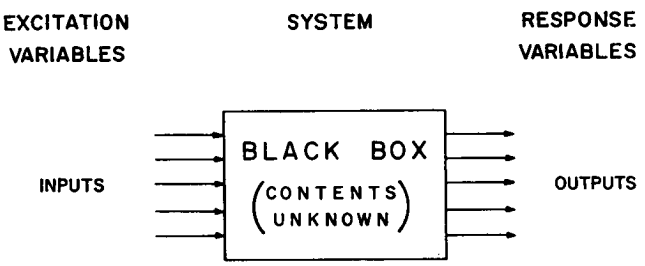


Figure A-1. Black box system.

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).

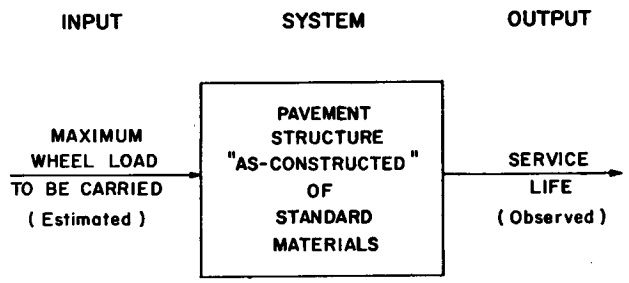


Figure A-2. System diagram of early pavement design methods.

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.

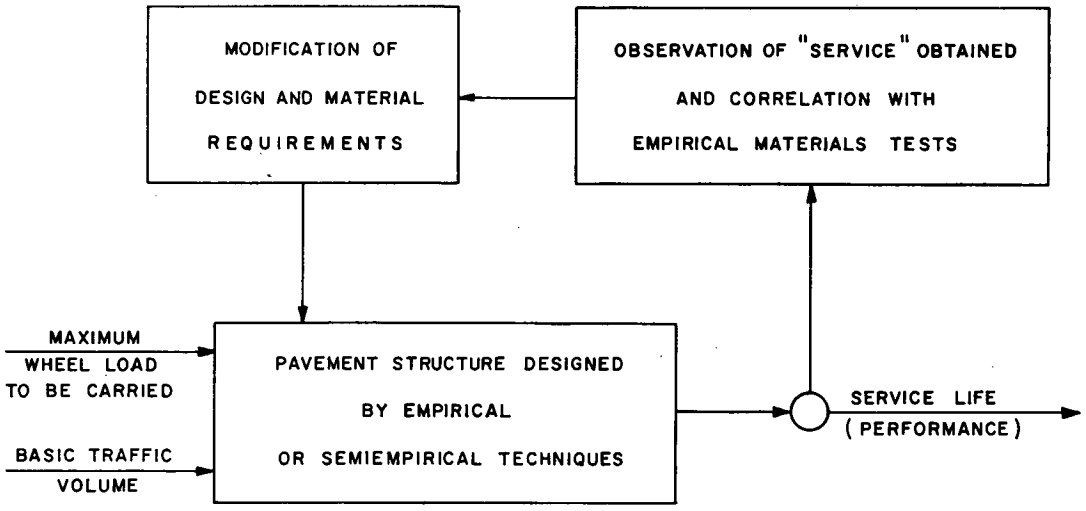


Figure A-3. Block diagram of pavement design techniques.

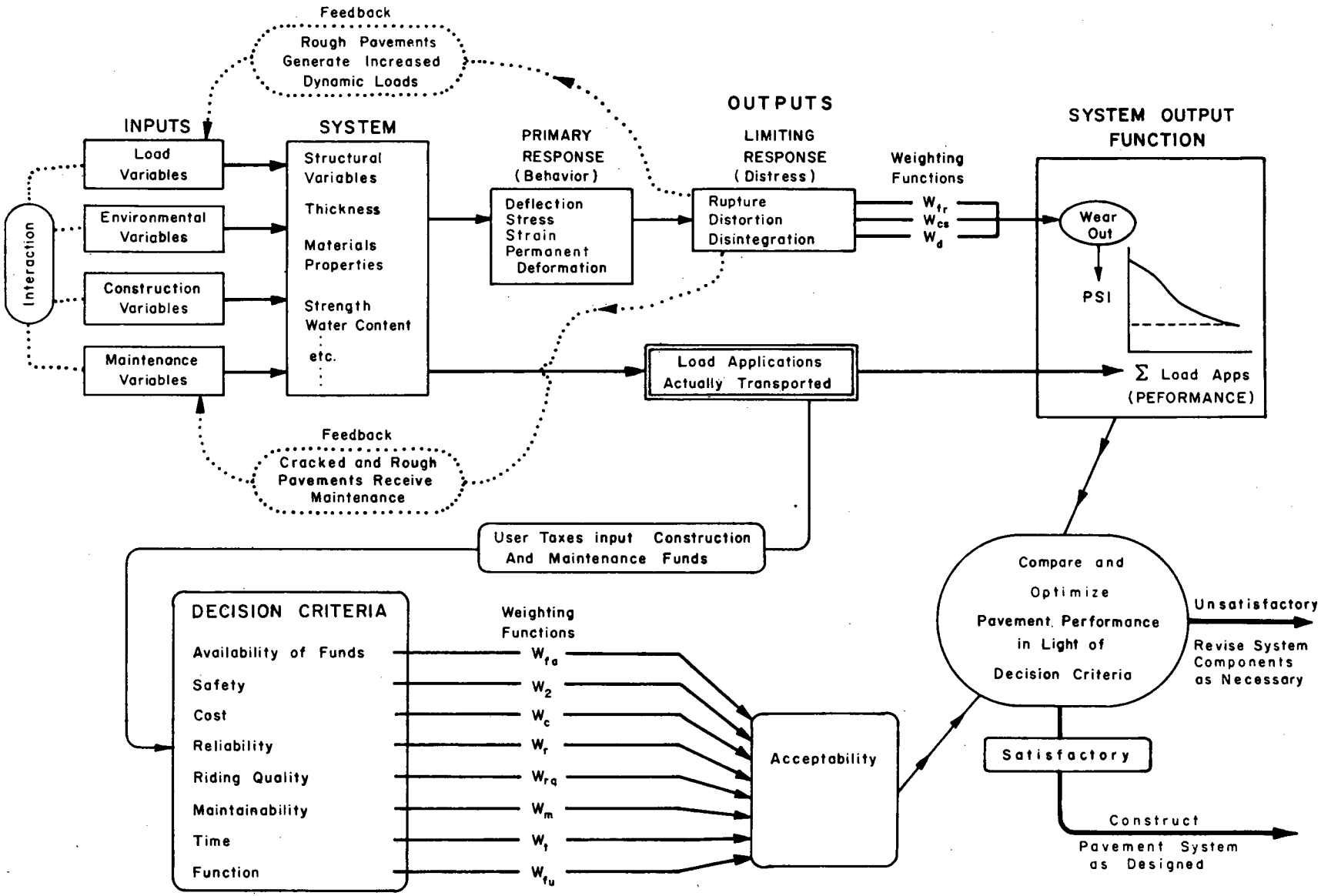


Figure A-4. Block diagram of the pavement system.

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.

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
C     ****          P R O G R A M   S A M P 5          ****      C
C                         REVISED 21MAY70                        C
C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C
C                                                                C
C          PROGRAM SAMP5 IS THE FIFTH IN A SERIES OF COMPUTER     C
C     PROGRAMS CALLED SYSTEMS ANALYSIS MODEL FOR PAVEMENTS.       C
C          THE SAMP SERIES IS BASED ON A PAVEMENT SYSTEMS ANALYSIS C
C     MODEL CONCEPT AND COMPUTER PROGRAM DEVELOPED BY F H SCRIVNER, C
C     G R CAREY, W F MCFARLAND, AND W M MOORE AS REPORTED IN TEXAS C
C     TRANSPORTATION INSTITUTE RESEARCH REPORT 32-11, *A SYSTEMS  C
C     APPROACH TO THE FLEXIBLE PAVEMENT DESIGN PROBLEM.*          C
C                                                                C
C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C C
C                                                                C
C     ****          P R O G R A M   S A M P 5          ****      C
C                                                                C
C                                                                C
      COMMON INDEX(10), ITEST, ITYPE, LAYER, MATYPE, MODEL, NM,
     1      NPAGE, NPROB, NMB
      COMMON A(11), AN1(20), AN2(19), COST(11), DATA(11, 14), DMAX(11),D
     1     MIN(11), DOVER(20), PSVGE(11), STNUM(10), TT(20), XINC(11),
     2      XJ(11), Z(1000, 6), AAS, ACCD, ACPR, ASN, ASO, BONE,
     3      CERR, CL, CLW, CMAT, CMAX, DDN2, DDO2, HPD, OVMAX, OVMIN,
     4      PPN2, PPO2, PROP, PSI, P1, P2, P2P, R, RATE, RC, RO,
     5      TCKMAX, XLSD, XLSN, XLSO, XLW, XNC, XTBO, XTTO, X2
      DIMENSION UCOST(100), IPOSS(100), NPOSS(100), POLICY(50,30)
      DIMENSION IDUMMY(30), NMBMAT(6), NN(6)
      DIMENSION XNDKP(5,50), ILAYER(11), XXJ(11)
      DIMENSION X8(10), F821(5), F851(4), F871(4)
      DATA BLANK/1H /
      DATA STAR/4H****/
      DATA X8(1)/4H,21X/,X8(2)/4H,29X/,X8(3)/4H,37X/,X8(4)/4H,45X
     1     /, X8(5)/4H,53X/,X8(6)/4H,61X/,X8(7)/4H,69X/,X8(8)/4H,77X
     2     /, X8(9)/4H,85X/,X8(10)/4H,93X/,F821(1)/4H(1H+/,F821(3)
     3     /4H,F7./, F821(4)/4H2,A1/,F821(5)/1H)/,F851(1)/4H(1H+
     4     /,F851(3)/4H,F8./, F851(4)/2H3)/,F871(1)/4H(1H+/,F871(3)
     5     /4H,F8./,F871(4)/2H1)/
C**********************************************************************
C  READ IN RUN AND PROBLEM IDENTIFICATIONS.
      READ (5,571) AN1
            NPAGE = 0
 101  READ (5,571) NPROB, AN2
          IF (EOF, 5) 561,111
 111      CONTINUE
C**********************************************************************
C READ IN THE PROGRAM CONTROL AND MISCELLANEOUS VARIABLES.
      READ (5,581) NMB, NM, CL, XLW, RATE
C  NMB-THE NUMBER OF OUTPUT PAGES FOR THE SUMMARY TABLE(10 DESIGNS/PAGE)
C  NM-THE TOTAL NUMBER OF MATERIALS AVAILABLE,EXCLUDING SUBGRADE.
C  CL-THE LENGTH OF THE ANALYSIS PERIOD IN YEARS.
C  XLW-THE WIDTH OF EACH LANE(FEET).
C  RATE-THE INTEREST RATE OR TIME VALUE OF MONEY(PERCENT).
C**********************************************************************
C READ IN THE ENVIRONMENTAL AND SERVICEABILITY VARIABLES.
      READ (5,591) R, PSI, P1, P2, P2P, BONE
C  R-THE REGIONAL FACTOR.
C  PSI-THE SERVICEABILITY INDEX OF THE INITIAL STRUCTURE.
C  P1-THE BEGINNING SERVICEABILITY INDEX OF THE PAVEMENT
C     AFTER AN OVERLAY.
C  P2-THE MINIMUM ALLOWED VALUE OF THE SERVICEABILITY INDEX
C     (POINT AT WHICH AN OVERLAY MUST BE APPLIED).
C  P2P-NON-TRAFFIC DETERIORATION PARAMETER-THE LOWER BOUND ON THE
C       SERVICEABILITY INDEX WHICH WOULD BE ACHIEVED IN INFINITE
C       TIME WITH NO TRAFFIC.
C  BONE-NON-TRAFFIC DETERIORATION PARAMETER-THE CONSTANT WHICH
C  IS DETERMINED BY THE RATE AT WHICH A PAVEMENT DETERIORATES DUE
C  TO NON-TRAFFIC FORCES
C**********************************************************************
C READ IN THE LOAD AND TRAFFIC VARIABLES.
      READ (5,601) RO, RC, XNC, PROP, ITYPE
C  RO-THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE BEGINNING OF THE
C     ANALYSIS PERIOD.
C  RC-THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE END OF THE
C     ANALYSIS PERIOD.
C  XNC-THE ONE-DIRECTION ACCUMULATED NUMBER OF EQUIVALENT 18-KIP AXLES
C      DURING THE ANALYSIS PERIOD.
C  PROP-THE PERCENT OF ADT WHICH WILL PASS THROUGH THE OVERLAY ZONE
C        DURING EACH HOUR WHILE OVERLAYING TAKES PLACE(NORMALLY ABOUT
C        6 PERCENT FOR RURAL AREAS AND 5.5 PERCENT FOR URBAN AREAS).
C  ITYPE-IS A CODE FOR THE TYPE OF ROAD UNDER CONSIDERATION.
C          ITYPE=1 DESIGNATES A RURAL ROAD AND ITYPE=2 DESIGNATES AN
C          URBAN ROAD.
C**********************************************************************
C READ IN THE CONSTRAINTS.
      READ (5,611) XTTO, XTBO, CMAX, TCKMAX, OVMIN, OVMAX
C  XTTO-THE MINIMUM ALLOWED TIME TO THE FIRST OVERLAY.
C  XTBO-THE MINIMUM ALLOWED TIME BETWEEN OVERLAYS PERMITTED.
C  CMAX-MAXIMUM FUNDS AVAILABLE FOR INITIAL CONSTRUCTION.
C  TCKMAX-THE MAXIMUM ALLOWABLE TOTAL THICKNESS OF INITIAL CONSTRUCTION.
C  OVMIN-THE MINIMUM THICKNESS OF AN INDIVIDUAL OVERLAY.
C  OVMAX-THE ACCUMULATED MAXIMUM THICKNESS OF ALL OVERLAYS.
C**********************************************************************
C READ IN THE TRAFFIC DELAY VARIABLES.
      READ (5,621) ACPR, ACCD, XLSO, XLSN, XLSD, HPD
C  ACPR-ASPHALTIC CONCRETE PRODUCTION RATE(TONS PER HOUR)
C  ACCD-ASPHALTIC CONCRETE COMPACTED DENSITY(TONS/COMPACTED CY)
C  XLSO-THE DISTANCE,MEASURED ALONG THE C.L.,OVER WHICH TRAFFIC IS
C        SLOWED IN THE OVERLAY DIRECTION.
C  XLSN-THE DISTANCE,MEASURED ALONG THE C.L.,OVER WHICH TRAFFIC IS
C        SLOWED IN THE NON-OVERLAY DIRECTION.
C  XLSD-THE DISTANCE ,MEASURED ALONG THE DETOUR,AROUND THE OVERLAY ZONE.
C  HPD-THE NUMBER OF HOURS PER DAY THAT OVERLAY CONSTRUCTION TAKES PLACE
C  THE PRODUCT OF PROP*HPD SHOULD NOT BE GREATER THAN 1.  IF THE STRIP
C  IS UNDER CONSTRUCTION FOR 24 HOURS EACH DAY, PROP*HPD = 1.
          IF ((PROP*HPD) .GT. 100.) WRITE (6,631)
      READ (5,641) PPO2, PPN2, DDO2, DDN2, AAS, ASO, ASN, MODEL
C  PPO2-THE PERCENT OF VEHICLES THAT WILL BE STOPPED IN THE OVERLAY
C      DIRECTION BECAUSE OF MOVEMENT OF PERSONNEL OR EQUIPMENT.
C  PPN2-THE PERCENT OF VEHICLES THAT WILL BE STOPPED IN THE
C      NON-OVERLAY DIRECTION BECAUSE OF PERSONNEL OR EQUIPMENT.
C  DDO2-THE AVERAGE DELAY PER VEHICLE STOPPED IN THE OVERLAY DIRECTION
C      BECAUSE OF MOVEMENT OF OVERLAY PERSONNEL AND EQUIPMENT IN THE
C      RESTRICTED ZONE.
C  DDN2-THE AVERAGE DELAY PER VEHICLE STOPPED IN THE NON-OVERLAY
C      DIRECTION BECAUSE OF MOVEMENT OF PERSONNEL OR EQUIPMENT.
C  AAS-THE AVERAGE APPROACH SPEED TO THE OVERLAY AREA,ASSUMED TO BE
C      THE SAME FOR BOTH DIRECTIONS.
C  ASO-THE AVERAGE SPEED THROUGH THE OVERLAY AREA,IN THE OVERLAY
C      DIRECTION.
C  ASN-THE AVERAGE SPEED THROUGH THE OVERLAY AREA,IN THE
C      NON-OVERLAY DIRECTION.
C  MODEL-THE MODEL NUMBER WHICH DESCRIBES THE TRAFFIC SITUATION.
C**********************************************************************
C READ IN THE MAINTENANCE VARIABLES.
      READ (5,621) X2, CLW, CERR, CMAT
C  X2-THE NUMBER OF DAYS PER YEAR THAT THE TEMPERATURE REMAINS BELOW 32F
C  CLW-THE COMPOSITE LABOR WAGE.
C  CERR-THE COMPOSITE EQUIPMENT RENTAL RATE.
C  CMAT-THE RELATIVE MATERIAL COST BASED ON A VALUE OF 1.00 FOR A ROAD
C       OF THE INTERSTATE TYPE.
C  ***FOR INFORMATION ON THESE VARIABLES SEE NCHRP REPORT 42.***
C
                  NK = 0
                  NPOS = 0
                  LAYER = 1
                  LP1 = 2
                  NMP = NM+1
C**********************************************************************
C  READ IN THE CONSTRUCTION MATERIALS AND THEIR PROPERTIES.
           DO 121 J = 1, NMP
 121  READ (5,651) ILAYER(J), (DATA(J, K), K = 2, 14)
C  THE COLUMN DESCRIPTIONS ARE AS FOLLOWS--
C    FIRST FIELD--1 COLUMN-LAYER ID (THE LAYER NUMBER IN WHICH
C                          THE MATERIAL MAY BE USED.)
C    SECOND FIELD-1 COLUMN-CODE LETTER OF THE MATERIAL.
C    THIRD FIELD-18 COLUMNS-THE NAME OF THE TYPE OF MATERIAL.
C    FOURTH FIELD-10COLUMNS-THE IN-PLACE COST PER COMPACTED CUBIC YARD.
C    FIFTH FIELD-10 COLUMNS-THE STRENGTH COEFICIENT OF THE MATERIAL.
C    SIXTH FIELD-10 COLUMNS-THE MINIMUM LAYER THICKNESS ALLOWED.
C    SEVENTH FIELD-10COLUMNS-THE MAXIMUM LAYER THICKNESS ALLOWED.
C    EIGHT FIELD-10 COLUMNS-SALVAGE VALUE PERCENTAGE OF THE MATERIAL.
C    NINETH FIELD-10 COLUMNS-THE SOIL SUPPORT VALUE OF THE MATERIAL.
C**********************************************************************
C**********************************************************************
C
C  NMBMAT(J)-CONTAINS THE NUMBER OF MATERIALS OF TYPE.J THAT ARE
C  AVAILABLE. ONLY 1 OF EACH TYPE MAY BE USED AT A TIME TO GENERATE
C  THE MATERIAL COMBINATIONS FOR THE ALTERNATIVE DESIGNS.
C
           DO 131 I = 1, 6
                NN(I) = 0
 131            NMBMAT(I) = 0
           DO 141 J = 1, NM
                K = ILAYER(J)
 141            NMBMAT(K) = NMBMAT(K)+1
                MATYPE = K
C  NMDGN IS A COUNTER THAT KEEPS TRACK OF THE DESIGN NUMBER FOR THE
C        MATERIALS UNDER CONSIDERATION.
C  KNTOL IS A COUNTER THAT KEEPS TRACK OF THE TOTAL NUMBER OF FEASIBLE
C        DESIGNS INCLUDED IN ALL COMBINATIONS OF MATERIALS.
                NMDGN = 0
                KNTOL = 0
           DO 161 J = 1, NMP
           IF (DATA(J, 14) .NE. 0.0) GO TO 151
                XXJ(J) = 0.0
           GO TO 161
 151            XXJ(J) = 10.**(0.03973*(DATA(J, 14)-3.))
 161       CONTINUE
C
C  THE NEXT PORTION OF THIS SUBROUTINE(DOWN TO STATEMENT 231) IS
C  A LAYER INDEXING SCHEME. THE SUBGRADE OF THE SITE IS THE ONLY
C  CONSTANT. THERE ARE MATYPE GROUPS OF MATERIALS AVAILABLE. FOR
C  J LAYER DESIGNS,ALL COMBINATIONS OF MATERIALS IN GROUPS 1
C  THROUGH J ARE USED(ONLY 1 PER GROUP). GROUPS MAY NOT BE SKIPPED
C  WITHIN THIS HIERARCHY. THE ARRAY INDEX KEEPS TRACK OF THE
C  MATERIAL TYPES UNDER CONSIDERATION.
C
 171            NN(LAYER) = NN(LAYER)+1
           DO 201 J = 1, MATYPE
           IF (NN(J) .EQ. 0) GO TO 211
                INDEX(J) = NN(J)
           IF (J .EQ. 1) GO TO 191
           DO 181 I = 2, J
 181            INDEX(J) = INDEX(J)+NMBMAT(I-1)
 191            IDX = INDEX(J)
                COST(J) = DATA(IDX, 9)/36.
                A(J) = DATA(IDX, 10)
                DMIN(J) = DATA(IDX, 11)
                DMAX(J) = DATA(IDX, 12)
                PSVGE(J) = DATA(IDX, 13)
                XJ(J) = XXJ(IDX)
 201       CONTINUE
 211            A(LP1) = DATA(NMP, 10)
                COST(LP1) = DATA(NMP, 9)/36.
                DMIN(LP1) = DATA(NMP, 11)
                DMAX(LP1) = DATA(NMP, 12)
                PSVGE(LP1) = DATA(NMP, 13)
                XJ(LP1) = XXJ(NMP)
                INDEX(LP1) = NMP
                XINC(1) = 0.25
           IF (LAYER .EQ. 1) GO TO 241
           DO 231 J = 2, LAYER
           IF (COST(J) .GT. 0.) GO TO 221
                XINC(J) = 1.0
           GO TO 231
 221            IND = (COST(1)/COST(J))+0.5
                XINC(J) = XINC(1)*IND
 231       CONTINUE
 241  CALL SOLVE2 (ISKIP, ICOST, NUMBER, SCOST)
                NMBEST = NMB*10
                NMDGN = NMDGN+1
      CALL OUTPUT (BCOST, NMDGN, KNTOL, KOUNT, POLICY, NMBEST, ISKIP,
     1      ICOST, NUMBER, SCOST, XNDKP, ILAYER)
```

```
C NOW STORE THE TOTAL COST FOR A LATER SORT TO OBTAIN THE OVERALL
C OPTIMAL DESIGN.
          IF (KOUNT .EQ. 0) GO TO 251
C THE FOLLOWING DESIGNS ARE POSSIBLE.
               NK = NK+1
               IPOSS(NK) = NMDGN
               OCOST(NK) = BCOST
          GO TO 261
C THE FOLLOWING DESIGNS ARE IMPOSSIBLE UNDER THE CRITERION.
 251           NPOS = NPOS+1
               NPOSS(NPOS) = NMDGN
 261      IF (LAYER .EQ. MATYPE) GO TO 271
               LAYER = LAYER+1
               LP1 = LAYER+1
          GO TO 171
 271      IF (NN(LAYER) .NE. NMBMAT(LAYER)) GO TO 171
          IF (LAYER .EQ. 1) GO TO 281
               NN(LAYER) = 0
               LAYER = LAYER-1
               LP1 = LAYER+1
          GO TO 271
 281      CONTINUE
C NOW THE SORT ROUTINE TO OBTAIN THE OVERALL OPTIMAL DESIGN.  THERE
C ARE NK POSSIBLE DESIGNS TO SELECT FROM.
          IF (NK-1) 551,321,291
 291           NKM = NK-1
          DO 311 II = 1, NKM
               IIP = II+1
          DO 301 JJ = IIP, NK
          IF (OCOST(II) .LT. OCOST(JJ)) GO TO 301
               STORE = OCOST(II)
               OCOST(II) = OCOST(JJ)
               OCOST(JJ) = STORE
               IS = IPOSS(II)
               IPOSS(II) = IPOSS(JJ)
               IPOSS(JJ) = IS
 301      CONTINUE
 311      CONTINUE
 321           NPAGE = NPAGE+1
      WRITE (6,661) NPROB, AN2, NPAGE
      WRITE (6,671)
      WRITE (6,681) (IPOSS(KK), OCOST(KK), KK = 1, NK)
          IF (NPOS .EQ. 0) GO TO 331
      WRITE (6,691) (NPOSS(I), I = 1, NPOS)
          GO TO 341
 331  WRITE (6,701)
C
C  THE REMAINDER OF THIS SUBROUTINE WRITES OUT THE SUMMARY TABLE.
C
 341           L = 1
               LL = 10
C
          DO 541 JJ = 1, NMB
          IF (L .GT. KNTOL) GO TO 541
          IF (LL .GT. KNTOL) LL = KNTOL
               NMBT = 5 + 2*(LL-L+1)
```

```
               NPAGE = NPAGE+1
      WRITE (6,661) NPROB, AN2, NPAGE
      WRITE (6,711) (I, I = L, LL)
          DO 351 I = L, LL
 351           IDUMMY(I) = POLICY(9, I)
          DO 381 I = 1, 5
               NKOUNT = 0
          DO 371 K = L, LL
          IF (IDUMMY(K) .GE. 1) GO TO 361
               POLICY(I+9, K) = 0.0
               XNDKP(I, K) = BLANK
          GO TO 371
 361           NKOUNT = NKOUNT+1
 371      CONTINUE
          IF (NKOUNT .EQ. 0) GO TO 391
               NLINE = I
 381      CONTINUE
 391  WRITE (6,721) (STAR, I = 1, NMBT)
          IF (NLINE .GE. 4) GO TO 421
               NLP = NLINE+2
          DO 411 I = NLP, 5
          DO 401 K = L, LL
 401           XNDKP(I, K) = BLANK
 411      CONTINUE
 421  WRITE (6,731) ((XNDKP(I, II), I = 1, 5), II = L, LL)
      WRITE (6,741) (POLICY(2, I), I = L, LL)
      WRITE (6,751) (POLICY(3, I), I = L, LL)
      WRITE (6,761) (POLICY(4, I), I = L, LL)
      WRITE (6,771) (POLICY(6, I), I = L, LL)
      WRITE (6,781) (POLICY(7, I), I = L, LL)
      WRITE (6,721) BLANK
      WRITE (6,791) (POLICY(8, I), I = L, LL)
      WRITE (6,721) BLANK
      WRITE (6,721) BLANK
      WRITE (6,801) (IDUMMY(I), I = L, LL)
      WRITE (6,721) BLANK
      WRITE (6,811)
          DO 431 I = 1, NLINE
      WRITE (6,821)I
               K=0
          DO 436 J=L,LL
               K=K+1
               IF(POLICY(I+9,J).EQ.0.)GO TO 436
               F821(2)=X8(K)
      WRITE (6,F821)POLICY(I+9,J),XNDKP(I,J)
 436      CONTINUE
 431      CONTINUE
          DO 441 I = L, LL
 441           IDUMMY(I) = POLICY(20, I)
      WRITE (6,721) BLANK
      WRITE (6,721) BLANK
      WRITE (6,831) (IDUMMY(I), I = L, LL)
      WRITE (6,721) BLANK
      WRITE (6,841)
          DO 471 I = 1, 10
               NKOUNT = 0
```

```
          DO 461 K = L, LL
          IF (IDUMMY(K) .GE. 1) GO TO 451
               POLICY(I+20, K) = 0.0
          GO TO 461
 451           NKOUNT = NKOUNT+1
 461      CONTINUE
          IF (NKOUNT .EQ. 0) GO TO 481
      WRITE (6,851)I
               K=0
          DO 466 J=L,LL
               K=K+1
               IF(POLICY(I+20,J).EQ.0.)GO TO 466
               F851(2)=X8(K)
      WRITE (6,F851)POLICY(I+20,J)
 466      CONTINUE
 471      CONTINUE
 481  WRITE (6,721) BLANK
      WRITE (6,861)
          DO 511 I = 1, 9
               NKOUNT = 0
          DO 501 K = L, LL
          IF (IDUMMY(K) .GE. I+1) GO TO 491
               POLICY(I+30, K) = 0.0
          GO TO 501
 491           NKOUNT = NKOUNT+1
               POLICY(I+30,K)=POLICY(I+30,K)+1.0
 501      CONTINUE
          IF (NKOUNT .EQ. 0) GO TO 521
      WRITE (6,871)I
               K=0
          DO 506 J=L,LL
               K=K+1
               IF(POLICY(I+30,J).EQ.0.)GO TO 506
               F871(2)=X8(K)
      WRITE (6,F871)POLICY(I+30,J)
 506      CONTINUE
 511      CONTINUE
 521      DO 531 I = L, LL
 531           IDUMMY(I) = POLICY(40, I)
      WRITE (6,721) (STAR, I = 1, NMBT)
               L = L+10
               LL = LL+10
 541      CONTINUE
      WRITE (6,881) KNTOL
          GO TO 101
 551           NPAGE = NPAGE + 1
      WRITE (6,661) NPROB, AN2, NPAGE
      WRITE (6,891)
          GO TO 101
 561      STOP
C
 571  FORMAT (20A4)
 581  FORMAT (2I10,3F10.0)
 591  FORMAT (5F10.2,F10.4)
 601  FORMAT (3F10.0,F10.2,I10)
 611  FORMAT (4F10.1,4F10.2)
```

```
 621  FORMAT (8F10.0)
 631  FORMAT (1H1,5X,13H***WARNING***/10X,47HAS INPUT,THE PRODUCT OF HPD
     1 AND PROP IS GREATER/10X,39HTHAN 100.0 PERCENT -- PROGRAM CONTINUE
     2S)
 641  FORMAT (2F10.2,2F10.4,3F10.2,I10)
 651  FORMAT (I1,A1,6A3,6F10.0)
 661  FORMAT (1H1,5X,5HPROB ,20A4,5H PAGE,I5)
 671  FORMAT (/////,24X,38HA SUMMARY OF THE BEST DESIGN FOR EACH ,
     1  11HCOMBINATION,/,24X,33HOF MATERIALS, IN ORDER OF INCREAS,
     2  15HING TOTAL COST.,//,31X,13HDESIGN NUMBER,4X,10HTOTAL COST)
 681  FORMAT (36X,I2,11X,F7.3)
 691  FORMAT (//,25X,42HTHE MATERIALS ASSOCIATED WITH EACH OF THE ,
     1  10HFOLLOWING ,/,25X,31HDESIGN NUMBERS DO NOT HAVE ANY ,
     2  17HFEASIBLE DESIGNS.,//,(40X,I5))
 701  FORMAT (//,25X,48HALL MATERIAL COMBINATIONS HAVE FEASIBLE DESIGNS.
     1)
 711  FORMAT (/,35X,37HSUMMARY OF THE BEST DESIGN STATEGIES,/,37X,
     1  33HIN ORDER OF INCREASING TOTAL COST,//,20X,10I8)
 721  FORMAT (2X,25A4)
 731  FORMAT (2X,20HMATERIAL ARRANGEMENT,4X,10(5A1,3X))
 741  FORMAT (2X,17HINIT. CONST. COST,3X,10F8.3)
 751  FORMAT (2X,19HOVERLAY CONST. COST,1X,10F8.3)
 761  FORMAT (2X,9HUSER COST,11X,10F8.3)
 771  FORMAT (2X,19HROUTINE MAINT. COST,1X,10F8.3)
 781  FORMAT (2X,13HSALVAGE VALUE,7X,10F8.3)
 791  FORMAT (2X,10HTOTAL COST,10X,10F8.3)
 801  FORMAT (2X,16HNUMBER OF LAYERS,2X,10I8)
 811  FORMAT ( 2X,20HLAYER DEPTH (INCHES) )
 821  FORMAT (7X,2HD(,I1,2H) )
 831  FORMAT (2X,18HNO.OF PERF.PERIODS,10I8)
 841  FORMAT ( 2X,18HPERF. TIME (YEARS) )
 851  FORMAT (7X,2HI(,I1,2H) )
 861  FORMAT ( 2X,20HOVERLAY POLICY(INCH)/2X, 20H(INCLUDING LEVEL-UP) )
 871  FORMAT (7X,2HO(,I1,2H) )
 881  FORMAT (//10X,51HTHE TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED W
     1AS, I10////)
 891  FORMAT (////10X,60HTHERE WERE NO FEASIBLE DESIGNS FOR THE CONDITIO
     1NS SPECIFIED.////)
      END
C
      SUBROUTINE SOLVE2 (ISKIP, ICOST, NUMBER, SCOST)                   SOLV  10
      COMMON INDEX(10), ITEST, ITYPE, LAYER, MATYPE, MODEL, NM,         SOLV  20
     1       NPAGE, NPROB, NMB                                          SOLV  30
      COMMON A(11), AN1(20), AN2(19), COST(11), DATA(11, 14), DMAX(11),D SOLV  40
     1      MIN(11), DOVER(20), PSVGE(11), STNUM(10), TT(20), XINC(11),  SOLV  50
     2      XJ(11), Z(1000, 6), AAS, ACCD, ACPR, ASN, ASO, BONE,        SOLV  60
     3      CERR, CL, CLW, CMAT, CMAX, DDN2, DDO2, HPD, OVMAX, OVMIN,   SOLV  70
     4      PPN2, PPO2, PROP, PSI, P1, P2, P2P, R, RATE, RC, RO,        SOLV  80
     5      TCKMAX, XLSD, XLSN, XLSO, XLW, XNC, XTBO, XTTO, X2          SOLV  90
      COMMON/ONE/SN(11)                                                 SOLV 100
               TK = 0.                                                  SOLV 110
               CT = 0.                                                  SOLV 120
               G = (PSI-P2)/(PSI-1.5)                                   SOLV 130
               SCOST = 0.                                               SOLV 140
               ISKIP = 0                                                SOLV 150
               ICOST = 0                                                SOLV 160
```

```
      CONST = SQRT(5.0-P2P)-SQRT(5.0-PSI)
      XKONST = 0.081*19.**3.23
      II = 1
      TPRIM = 0.
      XNPRIM = 0.
      P = PSI
C
      NUMBER = 0
      DO 102 J = 1, LAYER
        TK = TK+DMIN(J)
        CT = CT+COST(J)*DMIN(J)
102     DOVER(J) = DMIN(J)
      IF (TK .LE. TCKMAX) GO TO 112
        ISKIP = 1
    RETURN
112   IF (CT .LE. CMAX) GO TO 122
        ICOST = 1
    RETURN
122     I = 1
132   DO 142 K = 1, LAYER
        SN(K) = 0.
      DO 142 KK = 1, K
142     SN(K) = SN(K)+A(KK)*DOVER(KK)
        TP=(RC**2-RO**2)/XNC
        TMIN=10.**8
      DO 162 KK=1,LAYER
        B=0.4+XKONST/(SN(KK)+1.)**5.19
        BINV=1./B
        W=(0.62766*(G**BINV)*((SN(KK)+1)*XJ(KK+1))**9.3633)
  1           /R
        TIM=CL*(-RO+SQRT(RO**2+W*TP))/(RC-RO)
        IF(TIM.LT.XTTO)GO TO 192
        IF(TIM.GE.TMIN)GO TO 162
        TMIN=TIM
        MT=KK
162   CONTINUE
        B=0.4+XKONST/(SN(MT)+1.)**5.19
        Y=(1.051*R**0.1068)/XJ(MT+1)
    CALL TIME(II,T,SN(MT),XN,TPRIM,XNPRIM,ISW,BONE,BIP,G,CONST,Y,B,P)
      IF (ISW .EQ. 1) GO TO 192
172   IF (NUMBER .EQ. 1000) GO TO 232
        NUMBER = NUMBER+1
        Z(NUMBER, 1) = SN(LAYER)
        Z(NUMBER, 2) = T
      DO 182 K = 1, LAYER
182     Z(NUMBER, K+2) = DOVER(K)
192     XNCOST = CT+COST(1)*XINC(1)
      IF (XNCOST .GT. CMAX) GO TO 202
      IF (XNCOST .GT. SCOST) SCOST = XNCOST
      IF ((TK+XINC(1)) .GT. TCKMAX) GO TO 202
      IF ((DOVER(1)+XINC(1)) .GT. DMAX(1)) GO TO 202
        DOVER(1) = DOVER(1)+XINC(1)
        TK = TK+XINC(1)
        CT = CT+COST(1)*XINC(1)
      GO TO 132
202   IF (I .EQ. LAYER) GO TO 222
```

```
        DOVER(I) = DMIN(I)
        I = I+1
        TK = 0.
        CT = 0.
      DO 212 K = 1, LAYER
        CT = CT+COST(K)*DOVER(K)
212     TK = TK+DOVER(K)
        XNCOST = CT+COST(1)*XINC(I)
      IF (XNCOST .GT. CMAX) GO TO 202
      IF (XNCOST .GT. SCOST) SCOST = XNCOST
      IF ((TK+XINC(I)) .GT. TCKMAX) GO TO 202
      IF ((DOVER(I)+XINC(I)) .GT. DMAX(I)) GO TO 202
        DOVER(I) = DOVER(I)+XINC(I)
        TK = TK+XINC(I)
        CT = CT+COST(I)*XINC(I)
      GO TO 122
222 RETURN
232 WRITE (6,242)
    RETURN
C
242 FORMAT (1H1,76HTHERE ARE MORE THAN 2000 FEASIBLE INITIAL DESIGNS F
   1OR THIS SET OF MATERIALS.)
    END
C
    SUBROUTINE OUTPUT (BCOST, NMDGN, KNTOL, KOUNT, POLICY, NMBEST,
   1      ISKIP, ICOST, NUMBER, SCOST, XNDKP, ILAYER)
    COMMON INDEX(10), ITEST, ITYPE, LAYER, MATYPE, MODEL, NM,
   1      NPAGE, NPROB, NMB
    COMMON A(11), AN1(20), AN2(19), COST(11), DATA(11, 14), DMAX(11),
   1      MIN(11), DOVER(20), PSVGE(11), STNUM(10), TT(20), XINC(11),
   2      XJ(11), Z(1000, 6), AAS, ACCD, ACPR, ASN, ASO, BONE,
   3      CERR, CL, CLW, CMAT, CMAX, DDN2, DDO2, HPD, OVMAX, OVMIN,
   4      PPN2, PPO2, PROP, PSI, P1, P2, P2P, R, RATE, RC, RO,
   5      TCKMAX, XLSD, XLSN, XLSO, XLW, XNC, XTBO, XTTO, X2
    DIMENSION BTT(20), BDEXT(20), POLICY(50,30), XNDKP(5,50),
   1      LAYER(11), BBTT(20), BBDEXT(20), BALL(20)
      IF (NMDGN .NE. 1) GO TO 113
C
C  LIST THE INPUT DATA
C
    WRITE (6,533) AN1
          NPAGE = NPAGE+1
    WRITE (6,543) NPROB, AN2, NPAGE
    WRITE (6,553)
          NMP = NM+1
      DO 103 IJK = 1, NM
103 WRITE (6,563) ILAYER(IJK), (DATA(IJK, LK), LK = 2, 14)
    WRITE (6,573) (DATA(NMP, LK), LK = 3, 14)
    WRITE (6,653) NMB, NM
    WRITE (6,663) CL, XLW
    WRITE (6,673) RATE
    WRITE (6,583) R, PSI
    WRITE (6,593) P1, P2
    WRITE (6,603) P2P, BONE
    WRITE (6,613) RO, RC
    WRITE (6,623) XNC, PROP, ITYPE
```

```
          NPAGE = NPAGE+1
    WRITE (6,523) NPROB, AN2, NPAGE
    WRITE (6,683) XTTO, XTBO, CMAX
    WRITE (6,693) TCKMAX, OVMIN, OVMAX
    WRITE (6,703) ACPR, ACCD
    WRITE (6,713) XLSO, XLSN, XLSD, HPD
    WRITE (6,723) PPO2, PPN2
    WRITE (6,733) DDO2, DDN2, AAS
    WRITE (6,743) ASO, ASN, MODEL
    WRITE (6,633) X2, CLW
    WRITE (6,643) CERR, CMAT
          RATE = RATE/100.
113       LP1 = LAYER+1
C
C  PAGE HEADING DESCRIBING THE MATERIALS UNDER CONSIDERATION.
C
          NPAGE = NPAGE+1
    WRITE (6,523) NPROB, AN2, NPAGE
    WRITE (6,753) LAYER
      DO 123 L = 1, LAYER
          J = INDEX(L)
123 WRITE (6,563) ILAYER(J), (DATA(J, K), K = 2, 14)
    WRITE (6,573) (DATA(NMP, LK), LK = 3, 14)
C
C  OVERLAY POLICIES MUST NOW BE EXAMINED FOR EACH OF THE INITIAL
C  CONSTRUCTION DESIGNS. THIS IS DONE IN DO LOOP 69 BELOW
C
          KOUNT = 0
          BCOST = 10.**20
C***KOUNT IS A COUNTER THAT KEEPS TRACK OF THE NUMBER OF FEASIBLE
C   DESIGNS FOR THIS SET OF MATERIALS.
      IF (ICOST .EQ. 1) GO TO 503
      IF (ISKIP .EQ. 1) GO TO 513
      IF (NUMBER .EQ. 0) GO TO 493
          IMESS = 1
      DO 343 JL = 1, NUMBER
          CIC = 0.
      DO 133 KK = 1, LAYER
          CIC = CIC+Z(JL, KK+2)*COST(KK)
133       DOVER(KK) = Z(JL, KK+2)
          T = Z(JL, 2)
    CALL OVRLAY (IBT, T, BPTUC, BPOCCT, BPRM, AMINCT, BTT, BDEXT,
   1     BSAL, NOK)
      IF (NOK .EQ. 1) GO TO 343
          IMESS = 2
          KOUNT = KOUNT+1
          KNTOL = KNTOL+1
C
C  NOW CHECK TO SEE IF THE TOTAL COST(AMINCT) OF THE CURRENT DESIGN
C  RANKS AMONG THE BEST NMBEST DESIGNS SO FAR.
C
          AMINCT = AMINCT+CIC
      IF (KNTOL .NE. 1) GO TO 143
          NEW = 1
      GO TO 253
143       INUM = NMBEST
```

```
      IF (KNTOL .GT. INUM) GO TO 153
          INUM = KNTOL-1
153   IF (AMINCT .LT. POLICY(8, INUM)) GO TO 163
      IF (INUM .EQ. NMBEST) GO TO 293
          NEW = INUM+1
      GO TO 253
163       NEW = 1
173   IF (AMINCT .LT. POLICY(8, NEW)) GO TO 183
          NEW = NEW+1
      GO TO 173
183   IF (NEW .EQ. NMBEST) GO TO 253
          II = INUM-NEW+1
      IF (INUM .EQ. NMBEST) II = INUM-NEW
      DO 243 J = 1, II
          JJ = INUM-J+1
      IF (INUM .EQ. NMBEST) JJ = INUM-J
C--THE COST OF THE CURRENT DESIGN UNDER CONSIDERATION IS AMONG THE
C--BEST NMBEST SO FAR.  THIS DESIGN GOES IN THE NEW TH COLUMN AND ALL O
C--DESIGNS ARE SHIFTED DOWN ONE(FROM THE J TH TO THE (J+1) ST COLUMN).
      DO 193 K = 1, 9
193       POLICY(K, JJ+1) = POLICY(K, JJ)
C POLICY (9,JJ) CONTAINS THE NUMBER OF LAYERS OF THE DESIGN IN COLUMN
C  JJ (CANNOT BE MORE THAN 10 LAYERS.)
          NL = POLICY(9, JJ)+9
      DO 203 I = 10, NL
          XNDKP(I-9, JJ+1) = XNDKP(I-9, JJ)
203       POLICY(I, JJ+1) = POLICY(I, JJ)
C POLICY (20,JJ)CONTAINS THE NUMBER OF PERFORMANCE PERIOD FOR THE DESIGN
C COLUMN JJ(CAN NOT BE MORE THAN 10).
          POLICY(20, JJ+1) = POLICY(20, JJ)
          NP = POLICY(20, JJ)+29
      IF (NP .GT. 30) NP = 30
      DO 213 I = 21, NP
213       POLICY(I, JJ+1) = POLICY(I, JJ)
          KK = POLICY(20, JJ+1)+29
C IF KK=30, THERE WILL BE NO OVERLAYS IN THE DESIGN IN COLUMN JJ.
      IF (KK .EQ. 30) GO TO 233
      IF (KK .GT. 39) KK = 39
      DO 223 I = 31, KK
223       POLICY(I, JJ+1) = POLICY(I, JJ)
233   CONTINUE
243   CONTINUE
C--NOW INSERT THE CURRENT DESIGN IN COLUMN NEW OF THE ARRAY POLICY.
253       POLICY(1, NEW) = NMDGN
          POLICY(2, NEW) = CIC
          POLICY(3, NEW) = BPOCCT
          POLICY(4, NEW) = BPTUC
          POLICY(6, NEW) = BPRM
          POLICY(7, NEW) = BSAL
          POLICY(8, NEW) = AMINCT
          POLICY(9, NEW) = LAYER
      DO 263 I = 1, LAYER
          LJ = INDEX(I)
          XNDKP(I, NEW) = DATA(LJ, 2)
263       POLICY(I+9, NEW) = Z(JL, I+2)
          POLICY(20, NEW) = IBT
```

```
            KK = IBT
        IF (KK .GT. 10) KK = 10
        DO 273 I = 1, KK
273         POLICY(I+20, NEW) = BTT(I)
        IF (IBT .EQ. 1) GO TO 293
            IBTM = IBT-1
        DO 283 I = 1, IBTM
283         POLICY(I+30, NEW) = BDEXT(I+1)
293     CONTINUE
        IF (AMINCT .GE. BCOST) GO TO 343
C--BCOST IS THE TOTAL COST OF THE BEST DESIGN SO FAR FOR THE SET OF
C--MATERIALS UNDER CONSIDERATION. IF AMINCT IS LESS THAN BCOST THIS BEST
C--IS REPLACED BY THE CURRENT DESIGN UNDER CONSIDERATION.
            BCOST = AMINCT
            BICC = CIC
            BBPOCC = BPOCCT
            BBPTUC = BPTUC
            BBPRM = BPRM
            BBSAL = BSAL
            IBBT = IBT
        DO 303 KN = 1, IBBT
303         BBTT(KN) = BTT(KN)
C**IBBT WILL BE THE OPTIMAL NUMBER OF PERFORMANCE PERIODS.
        IF (IBBT .EQ. 1) GO TO 323
        DO 313 KN = 2, IBBT
313         BBDEXT(KN) = BDEXT(KN)
C**THE ARRAY BALL CONTAINS THE OPTIMAL INITIAL DESIGN.
323     DO 333 KN = 1, LAYER
333         BALL(KN) = Z(JL, KN+2)
343     CONTINUE
        IF (IMESS .EQ. 1) GO TO 483
C
C  PRINT THE OPTIMAL DESIGN FOR THE SET OF MATERIALS
C  UNDER CONSIDERATION.
C
      WRITE (6,763) NMDGN
        DO 353 K = 1, LAYER
            I = INDEX(K)
353   WRITE (6,773) (DATA(I, J), J = 3, 8), BALL(K)
      WRITE (6,783) BBTT(1)
        IF (IBBT .EQ. 1) GO TO 373
      WRITE (6,793)
        DO 363 I = 2, IBBT
            IM = I-1
            TOVER = BBDEXT(I)+1.0
363   WRITE (6,803) TOVER, BBTT(IM)
373   WRITE (6,963)BBTT(IBBT)
      WRITE (6,813) BICC, BBPRM, BBPOCC, BBPTUC, BBSAL, BCOST
      WRITE (6,823) KOUNT
      RETURN
483   WRITE (6,923)
      RETURN
493   WRITE (6,933)
      RETURN
503   WRITE (6,943)
      RETURN
```

```
513   WRITE (6,953)
      RETURN
C
523   FORMAT (1H1,5X,5HPROB ,20A4,5H PAGE,I5)
533   FORMAT(1H1,5X,42HPROGRAM SAMP5 (SYSTEMS ANALYSIS MODEL FOR ,
     1 26HPAVEMENTS) REVISED 21MAY70,/,6X,20A4,/)
543   FORMAT (1H ,5X,5HPROB ,20A4,5H PAGE,I5)
553   FORMAT (1H0,20X,41HTHE CONSTRUCTION MATERIALS UNDER CONSIDER,
     1  10HATION ARE ,/,21X,9HMATERIALS,12X,4HCOST,4X,4HSTR.,4X,
     2  4HMIN.,4X,4HMAX.,2X,8HSALVAGE ,2X,4HSOIL,/,12X,5HLAYER,
     3  5H CODE,7X,4HNAME,8X,6HPER CY,2X,6HCOEFF.,2X,5HDEPTH,3X,
     4  5HDEPTH,4X,4HPCT.,2X,7HSUPPORT)
563   FORMAT (1H ,13X,I1,4X,A1,2X,6A3,F6.2,5F8.2)
573   FORMAT (1H ,21X,6A3,F6.2,5F8.2)
583   FORMAT(1H0,5X,42HENVIRONMENTAL AND SERVICEABILITY VARIABLES,/,11X,
     1  18HR-REGIONAL FACTOR.,62X,F10.1,/,11X,
     2  55HPSI-THE SERVICEABILITY INDEX OF THE INITIAL STRUCTURE. ,
     3  25X,F10.1)
593   FORMAT (11X,45HP1-THE SERVICEABILITY INDEX OF AN OVERLAY. ,
     1  35X,F10.1,/,11X,36HP2-THE MINIMUM ALLOWED VALUE OF THE ,
     2  39HSERVICEABILITY INDEX.(POINT AT WHICH AN,5X,F10.1,/,16X,
     3  25HOVERLAY MUST BE APPLIED.))
603   FORMAT (11X,42HP2P-THE LOWER BOUND ON THE SERVICEABILITY ,
     1  33HINDEX WHICH WOULD BE ACHIEVED IN ,5X,F10.1,/,16X,
     2  29HINFINITE TIME WITH NO TRAFFIC,/,11X,
     3  50HBONE-THE RATE AT WHICH NON-TRAFFIC FACTORS REDUCE ,
     4  25HTHE SERVICEABILITY INDEX.,5X,F10.3)
613   FORMAT(1H0,5X,26HLOAD AND TRAFFIC VARIABLES,/,11X,
     1  50HRO-THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE ,
     2  25HBEGINNING OF THE ANALYSIS,5X,F10.0,/,16X,
     3   7HPERIOD.,/,11X,35HRC-THE ONE-DIRECTION AVERAGE DAILY ,
     4  38HTRAFFIC AT THE END OF ANALYSIS PERIOD.,7X,F10.0)
623   FORMAT (11X,44HXNC-THE ONE-DIRECTION ACCUMULATED NUMBER OF ,
     1  30HEQUIVALENT 18-KIP AXLES DURING,6X,F10.0,/,16X,
     2  20HTHE ANALYSIS PERIOD.,/,11X,
     3  52HPROP-THE PERCENT OF ADT WHICH WILL PASS THROUGH THE ,
     4  20HOVERLAY ZONE DURING ,8X,F10.1,/,16X,15HEACH HOUR WHILE,
     5  28H OVERLAYING IS TAKING PLACE.,/,11X,15HITYPE-THE TYPE ,
     6  45HOF ROAD UNDER CONSTRUCTION.(1-RURAL,2-URBAN),20X,I10)
633   FORMAT (1H0,5X,21HMAINTENANCE VARIABLES,/,11X,14HX2-THE NUMBER ,
     1  56HOF DAYS PER YEAR THAT THE TEMPERATURE REMAINS BELOW 32F.,10X,
     2  F10.0,/,11X,30HCLW-THE COMPOSITE LABOR WAGE. ,50X,F10.2)
643   FORMAT (11X,41HCERR-THE COMPOSITE EQUIPMENT RENTAL RATE.,39X,F10.2
     1, /,11X,49HCMAT-THE RELATIVE MATERIAL COST(1.00 IS AVERAGE).,
     2  31X,F10.2)
653   FORMAT(1H0,5X,43HPROGRAM CONTROL AND MISCELLANEOUS VARIABLES/,11X,
     1  52HNMB-THE NUMBER OF OUTPUT PAGES FOR THE SUMMARY TABLE,
     2  18H(10 DESIGNS/PAGE).,10X,I10,/,11X,
     3  53HNM-THE TOTAL NUMBER OF MATERIALS AVAILABLE.EXCLUDING ,
     4   9HSUBGRADE.,18X,I10)
663   FORMAT (11X,45HCL-THE LENGTH OF THE ANALYSIS PERIOD(YEARS). ,
     1  35X,F10.0,/,11X,35HXLW-THE WIDTH OF EACH LANE(FEET).  ,45X,F10.0
     2)
673   FORMAT (11X,45HRATE-THE INTEREST RATE OR TIME VALUE OF MONEY,
     1  10H(PERCENT).,25X,F10.1)
683   FORMAT (1H0,5X,20HCONSTRAINT VARIABLES ,/,11X,
     1  51HXTTO-THE MINIMUM ALLOWED TIME TO THE FIRST OVERLAY.,
     2  29X,F10.1,/,11X,38HXTBO-THE MINIMUM ALLOWED TIME BETWEEN ,
     3   9HOVERLAYS.,33X,F10.1,/,11X,23HCMAX-THE MAXIMUM FUNDS ,
     4  35HAVAILABLE FOR INITIAL CONSTRUCTION.,22X,F10.2)
693   FORMAT (11X,45HTCKMAX-THE MAXIMUM ALLOWABLE TOTAL THICKNESS ,
     1  24HOF INITIAL CONSTRUCTION.,11X,F10.1,/,11X,10HOVMIN-THE ,
     2  43HMINIMUM THICKNESS OF AN INDIVIDUAL OVERLAY.,27X,F10.2,
     3  /,11X,47HOVMAX-THE ACCUMULATED MAXIMUM THICKNESS OF ALL ,
     4   9HOVERLAYS.,24X,F10.1)
703   FORMAT(1H0,5X,47HTRAFFIC DELAY VARIABLES ASSOCIATED WITH OVERLAY,
     1  21H AND ROAD GEOMETRICS.,/,11X,24HACPR-ASPHALTIC CONCRETE ,
     2  27HPRODUCTION RATE(TONS/HOUR).,29X,F10.1,/,11X,5HACCD-,
     3  55HASPHALTIC CONCRETE COMPACTED DENSITY(TONS/COMPACTED CY),
     4  20X,F10.2)
713   FORMAT (11X,47HXLSD-THE DISTANCE OVER WHICH TRAFFIC IS SLOWED ,
     1  25HIN THE OVERLAY DIRECTION.,8X,F10.2,/,11X,9HXLSN-THE ,
     2  56HDISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE NON-OVERLAY,
     3  11H DIRECTION.,4X,F10.2,/,11X,25HXLSD-THE DISTANCE AROUND ,
     4  24HTHE OVERLAY ZONE(MILES).,31X,F10.2,/,11X,8HHPD-THE ,
     5  53HNUMBER OF HOURS/DAY OVERLAY CONSTRUCTION TAKES PLACE.,
     6  19X,F10.1)
723   FORMAT(1H0,5X,47HTRAFFIC DELAY VARIABLES ASSOCIATED WITH TRAFFIC,
     1  19H SPEEDS AND DELAYS.,/,16X,24HTHE PERCENT OF VEHICLES ,
     2 47HTHAT WILL BE STOPPED BECAUSE OF THE MOVEMENT OF,/,17X,
     3  23HPERSONNEL OR EQUIPMENT.,/,11X,20HPPO2-IN THE OVERLAY ,
     4  10HDIRECTION.,50X,F10.2,/,11X,24HPPN2-IN THE NON-OVERLAY ,
     5  10HDIRECTION.,46X,F10.2)
733   FORMAT (16X,45HTHE AVERAGE DELAY PER VEHICLE STOPPED BECAUSE,
     1  19H OF THE MOVEMENT OF,/,17X,24HPERSONNEL AND EQUIPMENT.,
     2  /,11X,37HDDO2-IN THE OVERLAY DIRECTION(HOURS).,43X,F10.3,/,
     3  11X,41HDDN2-IN THE NON-OVERLAY DIRECTION(HOURS).,39X,F10.3,
     4  /,11X,45HAAS-THE AVERAGE APPROACH SPEED TO THE OVERLAY,
     5   6H AREA.,29X,F10.0)
743   FORMAT (16X,42HTHE AVERAGE SPEED THROUGH THE OVERLAY AREA,/,
     1  11X,34HASO-IN THE OVERLAY DIRECTION(MPH).,46X,F10.0,/,11X,
     2  38HASN-IN THE NON-OVERLAY DIRECTION(MPH).,42X,F10.0,/,11X,
     3  38HMODEL-THE TRAFFIC HANDLING MODEL USED.,42X,I10)
753   FORMAT (1H0,12X,7HFOR THE,I2,33H LAYER DESIGN WITH THE FOLLOWING ,
     1  10HMATERIALS.,/,21X,9HMATERIALS,12X,4HCOST,4X,4HSTR.,4X,4HMIN.
     2  4X,4HMAX.,2X,8HSALVAGE ,6H  SOIL,/,12X,5HLAYER,5H CODE,7X,
     3  4HNAME,8X,
     4      6HPER CY,2X,6HCOEFF.,2X,5HDEPTH,3X,5HDEPTH,4X,4HPCT.,
     5      3X,7HSUPPORT)
763   FORMAT ( /2X,I2,3X,58HTHE OPTIMAL DESIGN FOR THE MATERIALS UNDER
     1ONSIDERATION--/ 8X,45HFOR INITIAL CONSTRUCTION THE DEPTHS SHOULD B
     2E)
773   FORMAT ( 15X,6A3,F8.2, 7H INCHES)
783   FORMAT ( 8X,35HTHE LIFE OF THE INITIAL STRUCTURE =, F6.2,6H YEARS)
793   FORMAT ( 8X,23HTHE OVERLAY SCHEDULE IS)
803   FORMAT (15X,F5.2,43H INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER,
     1   F6.2, 7H YEARS.)
813   FORMAT ( /8X,56HTHE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIO
     1NS ARE/ 15X,25HINITIAL CONSTRUCTION COST, 9X,F6.3/15X, 30HTOTAL RO
     2UTINE MAINTENANCE COST, 4X,F6.3/15X, 31HTOTAL OVERLAY CONSTRUCTION
     3 COST, 3X,F6.3/15X,22HTOTAL USER COST DURING/25X, 20HOVERLAY CONST
     4RUCTION ,3X,F7.3,/,15X,13HSALVAGE VALUE,20X,F7.3,/,15X,
     5  18HTOTAL OVERALL COST,15X,F7.3)
823   FORMAT (//8X,51HNUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET -
     1-,I8)
923   FORMAT (//4X, 52HTHE MINIMUM TIME BETWEEN OVERLAYS IS TOO LONG AND
     1/OR/ 4X,52HTHE MAXIMUM ALLOWABLE TOTAL OVERLAY THICKNESS IS TOO/
     2   4X,52HSMALL TO OBTAIN A FEASIBLE OVERLAY POLICY FOR ANY OF/ 4X,
     3.  20HTHE INITIAL DESIGNS.)
933   FORMAT (//4X, 67HTHE CONSTRUCTION RESTRICTIONS ARE TOO BINDING TO
     1OBTAIN A STRUCTURE/ 4X,65HTHAT WILL MEET THE MINIMUM TIME TO THE F
     2IRST OVERLAY RESTRICTION.)
943   FORMAT (61HOFOR THE DESIGN UNDER CONSIDERATION THE FUNDS AVAILABLE
     1 TO BE/58H SPENT PER SQ. YD. ARE NOT ENOUGH TO COVER THE DESIGN W
     2TH/39H ALL MATERIALS AT THEIR MINIMUM DEPTHS.)
953   FORMAT (//4X, 52HEACH OF THE MATERIALS AT THEIR MINIMUM DEPTH RESU
     1LTS/ 4X,49HIN A TOTAL DEPTH THAT IS GREATER THAN THE MAXIMUM/ 4X,
     2   24HALLOWED TOTAL THICKNESS.)
963   FORMAT(8X,17HTHE TOTAL LIFE = ,F6.2,7H YEARS.)
      END
C
      SUBROUTINE OVRLAY (IBT, T, BPTUC, BPOCCT, BPRM, AMINCT, BTT,
     1       BDEXT, BSAL, NOK)
      COMMON INDEX(10), ITEST, ITYPE, LAYER, MATYPE, MODEL, NM,
     1       NPAGE, NPROB, NMB
      COMMON A(11), AN1(20), AN2(19), COST(11), DATA(11, 14), DMAX(11),
     1      MIN(11), DOVER(20), PSVGE(11), STNUM(10), TT(20), XINC(11),
     2       XJ(11), Z(1000, 6), AAS, ACCD, ACPR, ASN, ASO, BONE,
     3       CERR, CL, CLW, CMAT, CMAX, DDN2, DDO2, HPD, OVMAX, OVMIN,
     4       PPN2, PPO2, PROP, PSI, P1, P2, P2P, R, RATE, RC, RO,
     5       TCKMAX, XLSD, XLSN, XLSO, XLW, XNC, XTBO, XTTO, X2
      COMMON/ONE/SN(11)
      DIMENSION DADD(20), TN(20), XBI(20), DEXT(20), USERCT(20),
     1      RM(20), OCCT(20), BTT(20), BDEXT(20)
            TPRIM = 0.
            XN = (XNC/(CL*(RC+RO)))*(2.*RO*T+((RC-RO)/CL)*T*
     1          *2)
            NOK = 1
            LP1 = LAYER+1
            G2 = (P1-P2)/(P1-1.5)
            Q2 = SQRT(5.-P2P)-SQRT(5.-P1)
C
            BIP = BONE*EXP(-BONE*T)
            AMINCT = 10.0**8
            USERCT(1) = 0.0
            OCCT(1) = 0.
            DADD(1) = 0.0
            I = 1
C
C
C  DETERMINE THE COST OF ROUTINE MAINTENANCE DURING THE FIRST
C  PERFORMANCE PERIOD.
      CALL MAINT (TPRIM, T, RM(I))
C
            TT(I) = T
            TN(I) = XN
            XBI(I) = BIP
        IF (T .GE. CL) GO TO 144
```

```
C THE REMAINDER OF THE OVERLAY OPTIMIZATION RESEMBLES A **TREE**. IT     OVRL 380
C IS NECESSARY TO SELECT THE OVERLAY POLICY WITH THE LEAST COST.         OVRL 390
              ABDD = 0.0                                                 OVRL 400
C ABDD IS THE ACCUMULATED DEPTH OF ALL PREVIOUS OVERLAYS.                OVRL 410
              DSAV = DOVER(1)                                            OVRL 420
              TPRIM = T                                                  OVRL 430
              XNPRIM = XN                                                OVRL 440
              BI = BIP                                                   OVRL 450
              I = I+1                                                    OVRL 460
 104          DELD = OVMIN                                               OVRL 470
C THE DEPTH OF LAYER 1 IS = ORIGINAL D(1) + SUM OF PREVIOUS OVERLAYS +   OVRL 480
C  CURRENT OVERLAY DEPTH.                                                OVRL 490
 114          DOVER(1) = DSAV+ABDD+DELD                                  OVRL 500
        IF ((ABDD+DELD) .GT. OVMAX) GO TO 194                            OVRL 510
        DO 119 J=1,LAYER                                                 OVRL 520
              SN(J)=0.                                                   OVRL 530
        DO 119 JJ=1,J                                                    OVRL 540
 119          SN(J)=SN(J)+A(JJ)*DOVER(JJ)                                OVRL 550
              TP=(RC**2-RO**2)/XNC                                       OVRL 560
              TMIN=10.**8                                                OVRL 570
        DO 124 J = 1, LAYER                                              OVRL 580
              B=0.4+(0.081*19.**3.23)/(SN(J)+1.)**5.19                   OVRL 590
              BINV=1./B                                                  OVRL 600
              W=(.62766*(G2**BINV)*((SN(J)+1.)*XJ(J+1))**9.3633)         OVRL 610
     1              /R+XNPRIM                                           OVRL 620
              TIM=CL*(-RO+SQRT(RO**2+W*TP))/(RC-RO)                      OVRL 630
              IF((TIM-TPRIM).LT.XTBO)GO TO 129                           OVRL 640
              IF(TIM.GE.TMIN)GO TO 124                                   OVRL 650
              TMIN=TIM                                                   OVRL 660
              MT=J                                                       OVRL 670
 124    CONTINUE                                                         OVRL 680
              B=0.4+(0.081*19.**3.23)/(SN(MT)+1.)**5.19                  OVRL 690
              Y=(1.051*R**0.1068)/XJ(MT+1)                               OVRL 700
      CALL TIME(I,T,SN(MT),XN,TPRIM,XNPRIM,ISW,BI,BIP,G2,Q2,Y,B,P1)      OVRL 710
              IF(ISW.EQ.1)GO TO 129                                      OVRL 720
        GO TO 134                                                        OVRL 730
 129          DELD=DELD+0.5                                              OVRL 740
        GO TO 114                                                        OVRL 750
 134          DEXT(I) = DELD                                             OVRL 760
              ADT = RO+((RC-RO)/CL)*TPRIM                                OVRL 770
C DETERMINE THE PRESENT WORTH OF USER COST DURING THE I TH PERFORMANCE   OVRL 780
C PERIOD (DURING THE (I-1) OVERLAY).                                     OVRL 790
      CALL USER (ADT, T, TPRIM, PWTSY, ITIME, DELD)                      OVRL 800
              USERCT(I) = PWTSY                                          OVRL 810
C DETERMINE THE PRESENT WORTH OF OVERLAY CONSTRUCTION COST DURING THE I  OVRL 820
C PERFORMANCE PERIOD.                                                    OVRL 830
              OCCT(I) = (DEXT(I)*COST(1)+COST(1))/(1.+RATE)**ITIME       OVRL 840
C                                                                        OVRL 850
C DETERMINE THE PRESENT WORTH OF ROUTINE MAINTENANCE DURING THE          OVRL 860
C  I TH PERF. PERIOD.                                                    OVRL 870
      CALL MAINT (TPRIM, T, RM(I))                                       OVRL 880
C                                                                        OVRL 890
              DADD(I) = DELD                                             OVRL 900
              TT(I) = T                                                  OVRL 910
              TN(I) = XN                                                 OVRL 920
              XBI(I) = BIP                                               OVRL 930
```

```
C THE PREVIOUS OVERLAY WAS NOT SUFFICIENT TO LAST THROUGH THE ANALYSIS   OVRL 940
C PERIOD IF T IS LESS THAN CL.                                           OVRL 950
        IF (T .GE. CL) GO TO 144                                         OVRL 960
        IF ((ABDD+DELD) .GE. OVMAX) GO TO 194                            OVRL 970
              I = I+1                                                    OVRL 980
              TPRIM = T                                                  OVRL 990
              XNPRIM = XN                                                OVRL1000
              BI = BIP                                                   OVRL1010
              ABDD = ABDD+DADD(I-1)                                      OVRL1020
        GO TO 104                                                        OVRL1030
 144    CONTINUE                                                         OVRL1040
C DETERMINE THE PRESENT WORTH OF THE SALVAGE VALUE OF THE PAVEMENT. THIS OVRL1050
C WILL BE THE COST OF REBUILDING THE PAVEMENT AT THE END OF THE          OVRL1060
C ANALYSIS PERIOD.                                                       OVRL1070
              SALVGE = 0.                                                OVRL1080
        DO 154 J = 1, LAYER                                              OVRL1090
 154          SALVGE = SALVGE-DOVER(J)*COST(J)*PSVGE(J)/100.             OVRL1100
              SALVGE = SALVGE/(1.0+RATE)**CL                             OVRL1110
              POCCT = 0.                                                 OVRL1120
              PRM = 0.0                                                  OVRL1130
              PTUC = 0.0                                                 OVRL1140
        DO 164 J = 1, I                                                  OVRL1150
              POCCT = POCCT+OCCT(J)                                      OVRL1160
              PRM = PRM+RM(J)                                            OVRL1170
 164          PTUC = PTUC+USERCT(J)                                      OVRL1180
C EVALUATE THE COST OF THE ALTERNATIVE OVERLAY PROCEDURE AND COMPARE     OVRL1190
C TO THE CHEAPEST COST SO FAR.                                           OVRL1200
C TC-THE SUM OF ALL PRESENT WORTHS OF OVERLAY COSTS.                     OVRL1210
              TC = POCCT+PTUC+PRM+SALVGE                                 OVRL1220
        IF (AMINCT .LE. TC) GO TO 194                                    OVRL1230
              NOK = 2                                                    OVRL1240
              AMINCT = TC                                                OVRL1250
              BPOCCT = POCCT                                             OVRL1260
              BPTUC = PTUC                                               OVRL1270
              BPRM = PRM                                                 OVRL1280
              BSAL = SALVGE                                              OVRL1290
              IBT = I                                                    OVRL1300
        DO 174 JK = 1, I                                                 OVRL1310
 174          BTT(JK) = TT(JK)                                           OVRL1320
        IF (I .EQ. 1) GO TO 194                                          OVRL1330
        DO 184 JK = 2, I                                                 OVRL1340
 184          BDEXT(JK) = DEXT(JK)                                       OVRL1350
C SELECT A DIFFERENT OVERLAY POLICY(ANOTHER BRANCH OF THE TREE) AND      OVRL1360
C GO BACK TO STATEMENT 114 TO DETERMINE THE OVERLAY COSTS.               OVRL1370
 194    IF (I .LE. 2) GO TO 214                                          OVRL1380
              I = I-1                                                    OVRL1390
              DELD = DADD(I)+0.5                                         OVRL1400
              IM = I-1                                                   OVRL1410
              ABDD = 0.0                                                 OVRL1420
        DO 204 K = 1, IM                                                 OVRL1430
 204          ABDD = ABDD+DADD(K)                                        OVRL1440
              TPRIM = TT(IM)                                             OVRL1450
              XNPRIM = TN(IM)                                            OVRL1460
              BI = XBI(IM)                                               OVRL1470
        GO TO 114                                                        OVRL1480
 214  RETURN                                                             OVRL1490
```

```
      END                                                                OVRL1500
C
      SUBROUTINE TIME (I, T, SN, XNPRIM, TPRIM, XN, ISW, BI, BIP,        TIME  10
     1      G, Q,Y, B, P)                                                TIME  20
      COMMON INDEX(10), ITEST, ITYPE, LAYER, MATYPE, MODEL, NM,          TIME  30
     1      NPAGE, NPROB, NMB                                            TIME  40
      COMMON A(11), AN1(20), AN2(19), COST(11), DATA(11, 14), DMAX(11),DTIME  50
     1      MIN(11), DOVER(20), PSVGE(11), STNUM(10), TT(20), XINC(11),  TIME  60
     2      XJ(11), Z(1000, 6), AAS, ACCD, ACPR, ASN, ASO, BONE,         TIME  70
     3      CERR, CL, CLW, CMAT, CMAX, DDN2, DDO2, HPD, OVMAX, OVMIN,    TIME  80
     4      PPN2, PPO2, PROP, PSI, P1, P2, P2P, R, RATE, RC, RO,         TIME  90
     5      TCKMAX, XLSD, XLSN, XLSO, XLW, XNC, XTBO, XTTO, X2           TIME 100
C                                                                        TIME 110
C  AN ITERATIVE PROCEDURE TO DETERMINE HOW LONG THE OVERLAID             TIME 120
C  PAVEMENT (WITH STRUCTURAL NUMBER = SN) WILL LAST. THE RESULTING       TIME 130
C  PERFORMANCE PERIOD WILL END AT TIME T. IF ISW = 1,THE PERFORMANCE     TIME 140
C  PERIOD IS SHORTER THAN THE MINIMUM TIME BETWEEN OVERLAYS.             TIME 150
C                                                                        TIME 160
              ISW = 1                                                    TIME 170
              TEST=0.05                                                  TIME 180
              TBOT = TPRIM                                               TIME 190
              DELT = XTBO                                                TIME 200
        IF (I .EQ. 1) DELT = XTTO                                        TIME 210
        GO TO 115                                                        TIME 220
 105          TBOT = T                                                   TIME 230
              ISW = 0                                                    TIME 240
 115    IF (DELT .LT. TEST) GO TO 165                                    TIME 250
              T=TBOT+DELT                                                TIME 260
              XN = (XNC/(CL*(RC+RO)))*(2.*RO*T+((RC-RO)/CL)*T*           TIME 270
     1              *2)                                                  TIME 280
              XXN = XN-XNPRIM                                            TIME 290
              QP = Q*(1.-EXP(-BI*(T-TPRIM)))                             TIME 300
              GP = (QP**2+2.*QP*SQRT(5.-P))/(P-1.5)                      TIME 310
        IF (G .GT. GP) GO TO 125                                         TIME 320
        IF (ISW .EQ. 1) GO TO 165                                        TIME 330
              DELT = DELT/2.0                                            TIME 340
        GO TO 115                                                        TIME 350
 125          ERROR = -SN-1.+(Y*XXN**.1068)/(G-GP)**(.1068/B)            TIME 360
              IF(ABS(ERROR).LT.0.001) GO TO 160                          TIME 370
              IF(ERROR) 105,160,145                                      TIME 380
 135          XN = (XNC/(CL*(RC+RO)))*(2.*RO*T+((RC-RO)/CL)*T*           TIME 390
     1              *2)                                                  TIME 400
              XXN = XN-XNPRIM                                            TIME 410
              QP = Q*(1.-EXP(-BI*(T-TPRIM)))                             TIME 420
              GP = (QP**2+2.*QP*SQRT(5.-P))/(P-1.5)                      TIME 430
              ERROR = -SN-1.+(Y*XXN**.1068)/(G-GP)**(.1068/B)            TIME 440
        IF (ABS(ERROR) .LT. 0.001) GO TO 165                             TIME 450
        IF (ERROR) 155,165,145                                           TIME 460
 145    IF (ISW .EQ. 1) GO TO 165                                        TIME 470
              TTOP = T                                                   TIME 480
              DELT = DELT/2.0                                            TIME 490
              T = TTOP-DELT                                              TIME 500
              IF(DELT.LT.TEST)GO TO 165                                  TIME 510
        GO TO 135                                                        TIME 520
 155          TBOT = T                                                   TIME 530
              DELT = DELT/2.0                                            TIME 540
```

```
        IF (DELT .LT. TEST) GO TO 165                                    TIME 550
              T = TBOT+DELT                                              TIME 560
        GO TO 135                                                        TIME 570
 160          ISW=0                                                      TIME 580
 165          BIP = BI*EXP(-BI*(T-TPRIM))                                TIME 590
      RETURN                                                             TIME 600
      END                                                                TIME 610
C
      SUBROUTINE USER (ADT, T, TPRIM, PWTSY, ITIME, DELD)                USER  10
      COMMON INDEX(10), ITEST, ITYPE, LAYER, MATYPE, MODEL, NM,          USER  20
     1      NPAGE, NPROB, NMB                                            USER  30
      COMMON A(11), AN1(20), AN2(19), COST(11), DATA(11, 14), DMAX(11),DUSER  40
     1      MIN(11), DOVER(20), PSVGE(11), STNUM(10), TT(20), XINC(11),  USER  50
     2      XJ(11), Z(1000, 6), AAS, ACCD, ACPR, ASN, ASO, BONE,         USER  60
     3      CERR, CL, CLW, CMAT, CMAX, DDN2, DDO2, HPD, OVMAX, OVMIN,    USER  70
     4      PPN2, PPO2, PROP, PSI, P1, P2, P2P, R, RATE, RC, RO,         USER  80
     5      TCKMAX, XLSD, XLSN, XLSO, XLW, XNC, XTBO, XTTO, X2           USER  90
      DIMENSION CCSR(6,7), CCSU(6,7), CURS(6,2), COD(1,2), TRAFIO(4,3)   USER 100
C THE FOLLOWING ARE TABLES CONTAINING THE USER COSTS.                    USER 110
C  COST OF SLOWING DOWN IN A RURAL AREA                                  USER 120
      DATA CCSR/8.473,18.2,31.55,50.36,77.932,120.546,0.,9.413,21.491,   USER 130
     1      39.609,66.233,106.979,2*0.,11.354,28.422,53.917,92.482,3    USER 140
     2      *0., 15.795,39.941,76.022,4*0.,22.612,56.405,5*0.,32.485,6  USER 150
     3      *0./                                                         USER 160
C  COST OF SLOWING DOWN IN AN URBAN AREA                                 USER 170
      DATA CCSU/5.869, 11.769, 19.5, 30.03, 45.002, 67.868, 0.,          USER 180
     1      5.602, 12.857, 22.933, 37.338, 58.992, 2*0., 6.501,          USER 190
     2      15.976, 29.61, 49.114, 3*0., 8.607, 21.448, 40.242,          USER 200
     3      4*0., 11.856, 29.36, 5*0., 16.432,6*0./                      USER 210
C  COST OF OPERATING AT A REDUCED SPEED                                 USER 220
      DATA CURS/393.47, 214.53, 156.05, 129.03, 115.51,110.16, 362.43,   USER 230
     1      197.06, 142.57, 116.84, 103.24, 96.73/                       USER 240
C  COST OF DELAY                                                         USER 250
      DATA COD/3499.76,3263.11/                                          USER 260
      DATA TRAFIO/1350.,3000.,1400.,3000.,2700.,4500.,2800.,4700.,       USER 270
     1      4350.,6200.,4500.,6400./                                     USER 280
C  HPSY-PRODUCTION RATE IN HOURS PER SQ. YARD OF OVERLAY.                USER 290
              HPSY = ACCD*(DELD+1.)/(36.*ACPR)                           USER 300
              LO = (ASO/10.0)+0.5                                        USER 310
              LN = (ASN/10.0)+0.5                                        USER 320
              K = (AAS/10.0)+0.5                                         USER 330
        IF (LO .GT. 6) LO = 6                                            USER 340
        IF (LN .GT. 6) LN = 6                                            USER 350
        IF (K .GT. 6) K = 6                                              USER 360
              TIPH = ADT*PROP/100.                                       USER 370
              NLRO = 1                                                   USER 380
              NLRN = 1                                                   USER 390
C                                                                        USER 400
C  MODEL 1                                                               USER 410
C                                                                        USER 420
              PO1 = 0.                                                   USER 430
              PN1 = 0.                                                   USER 440
              DO1 = 0.                                                   USER 450
              DN1 = 0.                                                   USER 460
              PO2 = PPO2/100.                                            USER 470
              PN2 = PPN2/100.                                            USER 480
```

```
              DO2 = DDO2
              DN2 = DDN2
              D = 1./12.
         GO TO (156,106,116,126,146), MODEL
C
C  MODEL 2
C
 106          AQ = XLSO*TIPH/ASO
              PO1 = 0.5*(1.-EXP(-AQ))**2
              PN1 = PO1
              DO1 = (1.+EXP(2.*AQ))*(EXP(AQ)-AQ-1.)/(2.*TIPH*PO1
     1              *(EXP(2.*AQ)-EXP(AQ)+1.))
              DN1 = DO1
         GO TO 156
C
C  MODEL 3
C
 116          OUTRAT = TRAFIO(2*ITYPE-1, NLRO)
              RECOVY = TRAFIO(2*ITYPE, NLRO)
         IF (TIPH .LE. OUTRAT) GO TO 156
              PO1 = HPD*(TIPH-OUTRAT)/(2.*TIPH*D)
         IF (PO1 .GT. 1.) PO1 = 1.
              DO1 = HPD*(TIPH-OUTRAT)*(RECOVY-OUTRAT)/(2.*TIPH
     1                *PO1*(RECOVY-TIPH))
         GO TO 156
C
C  MODEL 4
C
 126          OUTRAT = TRAFIO(2*ITYPE-1, NLRO)
              RECOVY = TRAFIO(2*ITYPE, NLRO)
         IF (TIPH .LE. OUTRAT) GO TO 136
              PO1 = HPD*(TIPH-OUTRAT)/(2.*TIPH*D)
         IF (PO1 .GT. 1.) PO1 = 1.
              DO1 = HPD*(TIPH-OUTRAT)*(RECOVY-OUTRAT)/(2.*TIPH
     1                *PO1*(RECOVY-TIPH))
 136          OUTRAT = TRAFIO(2*ITYPE-1, NLRN)
         IF (TIPH .LE. OUTRAT) GO TO 156
              PN1 = HPD*(TIPH-OUTRAT)/(2.*TIPH*D)
         IF (PN1 .GT. 1.) PN1 = 1.
              DN1 = HPD*(TIPH-OUTRAT)*(RECOVY-OUTRAT)/(2.*TIPH
     1                *PN1*(RECOVY-TIPH))
         GO TO 156
C
C  MODEL 5
C
 146          OUTRAT = TRAFIO(2*ITYPE-1, NLRO)
              RECOVY = TRAFIO(2*ITYPE, NLRO)
         IF (TIPH .LE. OUTRAT) GO TO 156
              PO1 = HPD*(TIPH-OUTRAT)/(2.*TIPH*D)
         IF (PO1 .GT. 1.) PO1 = 1.
              DO1 = HPD*(TIPH-OUTRAT)*(RECOVY-OUTRAT)/(2.*TIPH
     1                *PO1*(RECOVY-TIPH))
 156     CONTINUE
C
C  NOW COLLECT ALL PERTINENT INFORMATION SO THAT THE USER COST
C  FOR THE OVERLAY CAN BE COMPUTED.
```

```
USER 490
USER 500
USER 510
USER 520
USER 530
USER 540
USER 550
USER 560
USER 570
USER 580
USER 590
USER 600
USER 610
USER 620
USER 630
USER 640
USER 650
USER 660
USER 670
USER 680
USER 690
USER 700
USER 710
USER 720
USER 730
USER 740
USER 750
USER 760
USER 770
USER 780
USER 790
USER 800
USER 810
USER 820
USER 830
USER 840
USER 850
USER 860
USER 870
USER 880
USER 890
USER 900
USER 910
USER 920
USER 930
USER 940
USER 950
USER 960
USER 970
USER 980
USER 990
USER1000
USER1010
USER1020
USER1030
USER1040
```

```
C
         GO TO (166,176), ITYPE                                          USER1050
C  COST OF STOPPING FROM APPROACH SPEED IN A RURAL AREA.                USER1060
 166          CO1 = CCSR(K, 1)/1000.                                    USER1070
              CN1 = CO1                                                 USER1080
C COST OF SLOWING TO THRU SPEED IN A RURAL AREA.                        USER1090
              CO4 = CCSR(K, LO+1)/1000.                                 USER1100
              CN4 = CCSR(K, LN+1)/1000.                                 USER1110
         GO TO 186                                                      USER1120
C  COST OF STOPPING FROM APPROACH SPEED IN AN URBAN AREA.               USER1130
 176          CO1 = CCSU(K, 1)/1000.                                    USER1140
              CN1 = CO1                                                 USER1150
C COST OF SLOWING TO THRU SPEED IN AN URBAN AREA.                       USER1160
              CO4 = CCSU(K, LO+1)/1000.                                 USER1170
              CN4 = CCSU(K, LN+1)/1000.                                 USER1180
C COST OF DELAY DUE TO CONGESTION OUTSIDE THE RESTRICTED AREA.          USER1190
 186          CO2 = DO1*COD(1, ITYPE)/1000.                             USER1200
              CN2 = DN1*COD(1, ITYPE)/1000.                             USER1210
C COST OF DRIVING AT A REDUCED SPEED.                                   USER1220
         IF (MODEL .EQ. 5) GO TO 196                                    USER1230
              CO3 = (CURS(LO, ITYPE)-CURS(K, ITYPE))*XLSO/1000.         USER1240
              CN3 = (CURS(LN, ITYPE)-CURS(K, ITYPE))*XLSN/1000.         USER1250
         GO TO 206                                                      USER1260
 196          CO3 = (CURS(LO, ITYPE)*XLSD-CURS(K, ITYPE)*XLSO)          USER1270
     1                /1000.                                            USER1280
              CN3 = (CURS(LN, ITYPE)-CURS(K, ITYPE))*XLSN/1000.         USER1290
C EXCESS COST OF STOPPING FROM THRU SPEED + COST OF IDLE TIME,ALL       USER1300
C WITHIN THE RESTRICTED AREA.                                           USER1310
 206     GO TO (216,226), ITYPE                                         USER1320
 216          CO5 = CCSR(LO, 1)/1000.+DO2*COD(1, ITYPE)/1000.           USER1330
              CN5 = CCSR(LN, 1)/1000.+DN2*COD(1, ITYPE)/1000.           USER1340
         GO TO 236                                                      USER1350
 226          CO5 = CCSU(LO, 1)/1000.+DO2*COD(1, ITYPE)/1000.           USER1360
              CN5 = CCSU(LN, 1)/1000.+DN2*COD(1, ITYPE)/1000.           USER1370
 236          TUCH = TIPH*(PO1*(CO1+CO2+CO3)+(1.-PO1)*(CO3+CO4)         USER1380
     1                +PO2*CO5)+TIPH*(PN1*(CN1+CN2+CN3)+(1.-PN1)*(CN3   USER1390
     2                +CN4)+PN2*CN5)                                    USER1400
              TUCSY = HPSY*TUCH                                         USER1410
              ITIME = TPRIM+0.5                                         USER1420
C DETERMINE THE PRESENT WORTH OF THE USER COSTS.                        USER1430
              PWTSY = TUCSY/(1.+RATE)**ITIME                            USER1440
         RETURN                                                         USER1450
         END                                                            USER1460
C                                                                       USER1470
         SUBROUTINE MAINT (TPRIM, T, MTOT)                              MAIN  10
         COMMON INDEX(10), ITEST, ITYPE, LAYER, MATYPE, MODEL, NM,      MAIN  20
     1       NPAGE, NPROB, NMB                                          MAIN  30
         COMMON A(11), AN1(20), AN2(19), COST(11), DATA(11, 14), DMAX(11),DMAIN  40
     1       MIN(11), DOVER(20), PSVGE(11), STNUM(10), TT(20), XINC(11),  MAIN  50
     2       XJ(11), Z(1000, 6), AAS, ACCD, ACPR, ASN, ASO, BONE,       MAIN  60
     3       CERR, CL, CLW, CMAT, CMAX, DDN2, DDO2, HPD, OVMAX, OVMIN,  MAIN  70
     4       PPN2, PPO2, PROP, PSI, P1, P2, P2P, R, RATE, RC, RO,       MAIN  80
     5       TCKMAX, XLSD, XLSN, XLSO, XLW, XNC, XTBO, XTTO, X2         MAIN  90
C                                                                       MAIN 100
         REAL LAB, MAT, MTOT                                            MAIN 110
C                                                                       MAIN 120
```

```
C         DATA ARRAY FOR PERCENTAGE OF MAINTENANCE REQUIREMENTS         MAIN 130
      DATA PLW,PERR,PMAT/0.60,0.19,0.21/                                MAIN 140
      DATA DLW,DERR,DMAT/0.75,0.21,0.04/                                MAIN 150
      DATA PLWR,PERRR,PMATR/0.44,0.21,0.35/                             MAIN 160
      DATA DLWR,DERRR,DMATR/0.59,0.37,0.04/                             MAIN 170
C                                                                       MAIN 180
C                                                                       MAIN 190
C         T - YEARS OF MAINTENANCE                                      MAIN 200
C                                                                       MAIN 210
C                                                                       MAIN 220
C                                                                       MAIN 230
         IF (ITYPE .EQ. 2) GO TO 107                                    MAIN 240
              XLWX = PLWR                                               MAIN 250
              XERR = PERRR                                              MAIN 260
              XMAT = PMATR                                              MAIN 270
              YLW = DLWR                                                MAIN 280
              YERR = DERRR                                              MAIN 290
              YMAT = DMATR                                              MAIN 300
         GO TO 117                                                      MAIN 310
 107          XLWX = PLW                                                MAIN 320
              XERR = PERR                                               MAIN 330
              XMAT = PMAT                                               MAIN 340
              YLW = DLW                                                 MAIN 350
              YERR = DERR                                               MAIN 360
              YMAT = DMAT                                               MAIN 370
 117     CONTINUE                                                       MAIN 380
C                                                                       MAIN 390
C                                                                       MAIN 400
              MTOT = 0.0                                                MAIN 410
              TF = T-TPRIM+1.0                                          MAIN 420
         IF (T .GT. CL) TF = CL-TPRIM+1.0                               MAIN 430
              NT = TF                                                   MAIN 440
         DO 127 I = 1, NT                                               MAIN 450
C                                                                       MAIN 460
              TOT = 0.0                                                 MAIN 470
              XI1 = (I-1)                                               MAIN 480
              YP = 19.72*(XI1)**2.+13.72*X2-183.                        MAIN 490
         IF (YP .LE. 0.0) GO TO 127                                     MAIN 500
              LAB = YP*XLWX*CLW                                         MAIN 510
              EQUIP = YP*XERR*CERR                                      MAIN 520
              MAT = YP*XMAT*CMAT                                        MAIN 530
              TOT = (LAB+EQUIP+MAT)/(1+RATE)**(XI1+TPRIM)               MAIN 540
         IF (I .EQ. NT) GO TO 137                                       MAIN 550
              MTOT = MTOT+TOT                                           MAIN 560
 127     CONTINUE                                                       MAIN 570
C                                                                       MAIN 580
 137          T1 = NT                                                   MAIN 590
              FTOT = TOT*(T1-TF+1.0)                                    MAIN 600
              TOT = TOT-FTOT                                            MAIN 610
              MTOT = MTOT+TOT                                           MAIN 620
              MTOT = MTOT/(1760.*16.)                                   MAIN 630
C          MTOT IS THE TOTAL MAINTENANCE COST FOR (T-TPRIM) YEARS.      MAIN 640
C                                                                       MAIN 650
      RETURN                                                            MAIN 660
      END                                                               MAIN 670
```

APPENDIX D

COMPLETE OUTPUT LIST OF EXAMPLE PROBLEM

```
PROGRAM SAMPS (SYSTEMS ANALYSIS MODEL FOR PAVEMENTS) REVISED 21MAY70
     A RUN TO SOLVE THE AVERAGE VALUE PROBLEM.            6JUN70 DLP

PROB 4000      ALL VARIABLES AT ENGINEERING AVERAGE                                    PAGE    1

              THE CONSTRUCTION MATERIALS UNDER CONSIDERATION ARE
              MATERIALS                  COST     STR.     MIN.     MAX.   SALVAGE    SOIL
     LAYER CODE        NAME            PER CY   COEFF.    DEPTH    DEPTH    PCT.   SUPPORT
       1     A  ASPHALTIC CONCRETE     10.00      .44     6.00     8.00    50.00     0.00
       2     B  CRUSHED STONE           5.00      .14     5.00     8.00    50.00     9.20
       3     C  GRAVEL                  2.00      .11     5.00    10.00    50.00     6.90
                SUBGRADE              -0.00     -0.00    -0.00    -0.00    -0.00     4.25

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
     XLW-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           2.5
          OVERLAY MUST BE APPLIED.)
     P2P-THE LOWER BOUND ON THE SERVICEABILITY INDEX WHICH WOULD BE ACHIEVED IN            1.5
          INFINITE TIME WITH NO TRAFFIC
     MONE-THE RATE AT WHICH NON-TRAFFIC FACTORS REDUCE THE SERVICEABILITY INDEX.           .120

LOAD AND TRAFFIC VARIABLES
     R0-THE ONE-DIRECTION AVERAGE DAILY TRAFFIC AT THE BEGINNING OF THE ANALYSIS          10000
          PERIOD.
     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          5000000
          THE ANALYSIS PERIOD.
     PROP-THE PERCENT OF ADT WHICH WILL PASS THROUGH THE OVERLAY ZONE DURING               6.0
          EACH HOUR WHILE OVERLAYING IS TAKING PLACE.
     ITYPE-THE TYPE OF ROAD UNDER CONSTRUCTION.(1-RURAL,2-URBAN).                          1
```

```
PROB A000      ALL VARIABLES AT ENGINEERING AVERAGE                                    PAGE    2

CONSTRAINT VARIABLES
     XTTO-THE MINIMUM ALLOWED TIME TO THE FIRST OVERLAY.                                  2.0
     XTBO-THE MINIMUM ALLOWED TIME BETWEEN OVERLAYS.                                      3.0
     CMAX-THE MAXIMUM FUNDS AVAILABLE FOR INITIAL CONSTRUCTION.                          5.00
     TCKMAX-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
     ACCU-ASPHALTIC CONCRETE COMPACTED DENSITY(TONS/COMPACTED CY)                        1.80
     XLSO-THE DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE OVERLAY DIRECTION.             .60
     XLSN-THE DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE NON-OVERLAY DIRECTION.         .60
     XLSD-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.
          THE PERCENT OF VEHICLES THAT WILL BE STOPPED BECAUSE OF THE MOVEMENT OF
           PERSONNEL OR EQUIPMENT.
     PPO2-IN THE OVERLAY DIRECTION.                                                      5.00
     PPN2-IN THE NON-OVERLAY DIRECTION.                                                  5.00
          THE AVERAGE DELAY PER VEHICLE STOPPED BECAUSE OF THE MOVEMENT OF
           PERSONNEL AND EQUIPMENT.
     DDO2-IN THE OVERLAY DIRECTION(HOURS).                                               .150
     DDN2-IN THE NON-OVERLAY DIRECTION(HOURS).                                           .150
     AAS-THE AVERAGE APPROACH SPEED TO THE OVERLAY AREA.                                  50
          THE AVERAGE SPEED THROUGH THE OVERLAY ARE
     ASO-IN THE OVERLAY DIRECTION(MPH).                                                   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
     CMAI-THE RELATIVE MATERIAL COST(1.00 IS AVERAGE).                                   1.00


PROB A000      ALL VARIABLES AT ENGINEERING AVERAGE                                    PAGE    3

        FOR THE 1 LAYER DESIGN WITH THE FOLLOWING MATERIALS.
              MATERIALS                 COST     STR.     MIN.     MAX.   SALVAGE    SOIL
      LAYER CODE        NAME          PER CY   COEFF.    DEPTH    DEPTH     PCT.   SUPPORT
        1     A  ASPHALTIC CONCRETE   10.00      .44     6.00     8.00    50.00     0.00
                 SUBGRADE             -0.00    -0.00    -0.00    -0.00    -0.00     4.25

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 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER  2.56 YEARS.
          1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER  5.80 YEARS.
          1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER  9.83 YEARS.
          1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 14.75 YEARS.
     THE TOTAL LIFE =  20.56 YEARS.


     THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE
          INITIAL CONSTRUCTION COST            2.159
          TOTAL ROUTINE MAINTENANCE COST        .588
          TOTAL OVERLAY CONSTRUCTION COST      1.127
          TOTAL USER COST DURING
                  OVERLAY CONSTRUCTION          .271
          SALVAGE VALUE                        -.510
          TOTAL OVERALL COST                   3.628


     NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET --        4
```

PROB A000 ALL VARIABLES AT ENGINEERING AVERAGE PAGE 4

FOR THE 2 LAYER DESIGN WITH THE FOLLOWING MATERIALS.

LAYER	CODE	MATERIALS NAME	COST PER CY	STR. COEFF.	MIN. DEPTH	MAX. DEPTH	SALVAGE PCT.	SOIL SUPPORT
1	A	ASPHALTIC CONCRETE	10.00	.44	6.00	8.00	50.00	0.00
2	B	CRUSHED STONE	5.00	.14	5.00	8.00	50.00	9.20
		SUBGRADE	-0.00	-0.00	-0.00	-0.00	-0.00	4.25

2 THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE

ASPHALTIC CONCRETE 7.00 INCHES

CRUSHED STONE 5.00 INCHES

THE LIFE OF THE INITIAL STRUCTURE = 3.44 YEARS

THE OVERLAY SCHEDULE IS

1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 3.44 YEARS.

1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 7.84 YEARS.

1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 13.37 YEARS.

THE TOTAL LIFE = 20.93 YEARS.

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

INITIAL CONSTRUCTION COST	2.639
TOTAL ROUTINE MAINTENANCE COST	.627
TOTAL OVERLAY CONSTRUCTION COST	.863
TOTAL USER COST DURING OVERLAY CONSTRUCTION	.208
SALVAGE VALUE	-.576
TOTAL OVERALL COST	3.761

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET -- 63

PROB A000 ALL VARIABLES AT ENGINEERING AVERAGE PAGE 5

FOR THE 3 LAYER DESIGN WITH THE FOLLOWING MATERIALS.

LAYER	CODE	MATERIALS NAME	COST PER CY	STR. COEFF.	MIN. DEPTH	MAX. DEPTH	SALVAGE PCT.	SOIL SUPPORT
1	A	ASPHALTIC CONCRETE	10.00	.44	6.00	8.00	50.00	0.00
2	B	CRUSHED STONE	5.00	.14	5.00	8.00	50.00	9.20
3	C	GRAVEL	2.00	.11	5.00	10.00	50.00	6.90
		SUBGRADE	-0.00	-0.00	-0.00	-0.00	-0.00	4.25

3 THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE

ASPHALTIC CONCRETE 6.00 INCHES

CRUSHED STONE 5.00 INCHES

GRAVEL 5.00 INCHES

THE LIFE OF THE INITIAL STRUCTURE = 3.69 YEARS

THE OVERLAY SCHEDULE IS

1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 3.69 YEARS.

1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 8.47 YEARS.

1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 14.52 YEARS.

THE TOTAL LIFE = 21.88 YEARS.

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

INITIAL CONSTRUCTION COST	2.639
TOTAL ROUTINE MAINTENANCE COST	.624
TOTAL OVERLAY CONSTRUCTION COST	.825
TOTAL USER COST DURING OVERLAY CONSTRUCTION	.203
SALVAGE VALUE	-.576
TOTAL OVERALL COST	3.715

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET -- 315

PROB 4000 ALL VARIABLES AT ENGINEERING AVERAGE PAGE 6

A SUMMARY OF THE BEST DESIGN FOR EACH COMBINATION
OF MATERIALS, IN ORDER OF INCREASING TOTAL COST.

DESIGN NUMBER	TOTAL COST
1	3.628
3	3.715
2	3.741

ALL MATERIAL COMBINATIONS HAVE FEASIBLE DESIGNS.

PROB 4000 ALL VARIABLES AT ENGINEERING AVERAGE PAGE 7

SUMMARY OF THE BEST DESIGN STRATEGIES,
IN ORDER OF INCREASING TOTAL COST

	1	2	3	4	5	6	7	8	9	10
MATERIAL ARRANGEMENT	A	A	A	A	ABC	ABC	ABC	ABC	ABC	AB
INIT. CONST. COST	2.153	2.222	2.014	2.083	2.639	2.917	2.917	2.708	2.708	2.639
OVERLAY CONST. COST	1.127	1.092	1.309	1.262	.825	.558	.570	.802	.802	.863
USER COST	.271	.252	.303	.297	.203	.130	.138	.201	.202	.208
ROUTINE MAINT. COST	.588	.633	.594	.592	.624	.710	.714	.631	.633	.627
SALVAGE VALUE	-.510	-.550	-.510	-.523	-.575	-.602	-.602	-.589	-.589	-.576
TOTAL COST	3.628	3.650	3.710	3.710	3.715	3.719	3.737	3.753	3.756	3.761
NUMBER OF LAYERS	1	1	1	1	3	3	3	3	3	2
LAYER DEPTH (INCHES)										
D(1)	7.75A	8.00A	7.25A	7.50A	6.00A	6.00A	6.25A	6.25A	6.00A	7.00A
D(2)					5.00B	5.00B	5.00B	5.00B	5.00B	5.00B
D(3)					5.00C	10.00C	8.75C	5.00C	6.25C	
NO.OF PERF.PERIODS	5	4	5	5	4	3	3	4	4	4
PERF. TIME (YEARS)										
I(1)	2.563	2.813	2.031	2.281	3.688	4.781	4.688	3.906	3.938	3.438
I(2)	5.797	7.734	5.266	5.844	8.469	11.625	11.344	9.063	9.234	7.844
I(3)	9.828	14.016	9.297	10.250	1[illegible].516	20.531	20.062	15.672	15.891	13.375
I(4)	14.750	21.750	14.219	15.594	2[illegible].875			23.641	24.047	20.031
I(5)	20.656		20.125	22.062						
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)										
O(1)	1.5	2.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5
O(2)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
O(3)	1.5	1.5	1.5	1.5	1.5			1.5	1.5	1.5
O(4)	1.5		1.5	1.5						

SUMMARY OF THE BEST DESIGN STATEGIES,
IN ORDER OF INCREASING TOTAL COST

	11	12	13	14	15	16	17	18	19	20
MATERIAL ARRANGEMENT	ABC	ABC	AB	ABC	ABC	ABC	ABC	ABC	ABC	ABC
INIT. CONST. COST	2.7[illegible]	2.847	2.708	2.986	.986	2.986	2.986	2.986	2.986	2.986
OVERLAY CONST. COST	.412	.651	.825	.558	.558	.558	.558	.558	.558	.558
USER COST	.203	.159	.203	.137	.137	.137	.136	.136	.136	.136
ROUTINE MAINT. COST	.625	.722	.624	.707	.707	.707	.708	.708	.709	.710
SALVAGE VALUE	-.5[illegible]	-.615	-.589	-.615	-.615	-.615	-.615	-.615	-.615	-.615
TOTAL COST	3.75[illegible]	3.754	3.771	3.773	3.773	3.774	3.774	3.774	3.775	3.775
NUMBER OF LAYERS	[illegible]	3	2	3	3	3	3	3	3	3
LAYER DEPTH (INCHES)										
D(1)	6.00A	5.00A	7.25A	6.00A	5.50A	6.25A	6.75A	6.25A	7.00A	7.25A
D(2)	5.50[illegible]	5.00B	5.00B	5.50B	5.00B	5.00B	5.00B	5.50B	5.00B	5.00B
D(3)	5.00C	8.75C		10.00C	8.75C	10.00C	7.50C	8.75C	6.25C	5.00C
NO.OF PERF.PERIODS	4	3	4	3	3	3	3	3	3	3
PERF. TIME (YEARS)										
I(1)	3.613	4.531	3.688	4.875	4.906	4.938	4.813	4.813	4.781	4.781
I(2)	8.922	10.812	8.469	12.000	12.078	12.156	11.844	11.797	11.766	11.625
I(3)	15.344	20.047	14.516	21.422	21.547	21.766	21.125	21.031	20.859	20.531
I(4)	23.125		21.875							
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)										
O(1)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
O(2)	1.5	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
O(3)	1.5		1.5							

SUMMARY OF THE BEST DESIGN STATEGIES,
IN ORDER OF INCREASING TOTAL COST

	21	22	23	24	25	26	27	28	29	30
MATERIAL ARRANGEMENT	ABC	ABC	AB	AB	ABC	ABC	ABC	ABC	ABC	ABC
INIT. CONST. COST	2.986	2.986	2.708	2.708	2.986	2.986	2.986	2.778	2.778	2.778
OVERLAY CONST. COST	.558	.558	.835	.836	.570	.570	.570	.780	.780	.772
USER COST	.136	.136	.203	.205	.138	.138	.138	.198	.198	.198
ROUTINE MAINT. COST	.710	.710	.625	.624	.713	.713	.714	.641	.643	.658
SALVAGE VALUE	-.615	-.615	-.589	-.589	-.615	-.615	-.615	-.602	-.602	-.602
TOTAL COST	3.775	3.775	3.783	3.783	3.792	3.792	3.793	3.795	3.798	3.804
NUMBER OF LAYERS	3	3	2	2	3	3	3	3	3	3
LAYER DEPTH (INCHES)										
D(1)	6.50A	6.00A	6.75A	7.00A	6.75A	6.25A	7.00A	6.25A	6.00A	6.00A
D(2)	5.50B	6.00B	6.00B	5.50B	5.50B	6.00B	5.50B	5.50B	5.50B	5.00B
D(3)	7.50C	8.75C			8.25C	7.50C	5.00C	5.00C	6.25C	7.50C
NO.OF PERF.PERIODS	3	3	4	4	3	3	3	4	4	4
PERF. TIME (YEARS)										
I(1)	4.781	4.781	3.531	3.563	4.688	4.688	4.688	4.063	4.156	4.281
I(2)	11.625	11.625	8.078	8.297	11.484	11.437	11.344	9.547	9.688	10.141
I(3)	20.672	20.625	13.750	14.156	20.391	20.297	20.062	16.531	16.719	17.547
I(4)			20.594	21.328				25.016	25.250	26.594
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)										
O(1)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
O(2)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
O(3)			1.5	1.5				1.5	1.5	1.5

THE TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED WAS 382

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 Dynaflect. 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 Vesić 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:

$$\underline{DI}(\underline{x}, t) = \underset{s=0}{\overset{s=t}{\underline{F}}}[\underline{C}(\underline{x}, s), \underline{S}(\underline{x}, s), \underline{D}(\underline{x}, s)\underline{x}, t] \qquad \text{(E-1)}$$

in which

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

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:

$$\underline{C}(\underline{x}, t) = F \text{ (load, environment, construction, maintenance, and structural variables; space and time)} \qquad \text{(E-2)}$$

For distortion:

$$\underline{S}(\underline{x}, t) = F \text{ (load, environment, construction, maintenance, and structural variables; space and time)} \qquad \text{(E-3)}$$

For disintegration:

$$\underline{D}(\underline{x}, t) = F \text{ (load, environment, construction, maintenance, and structural variables; space and time)} \qquad \text{(E-4)}$$

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

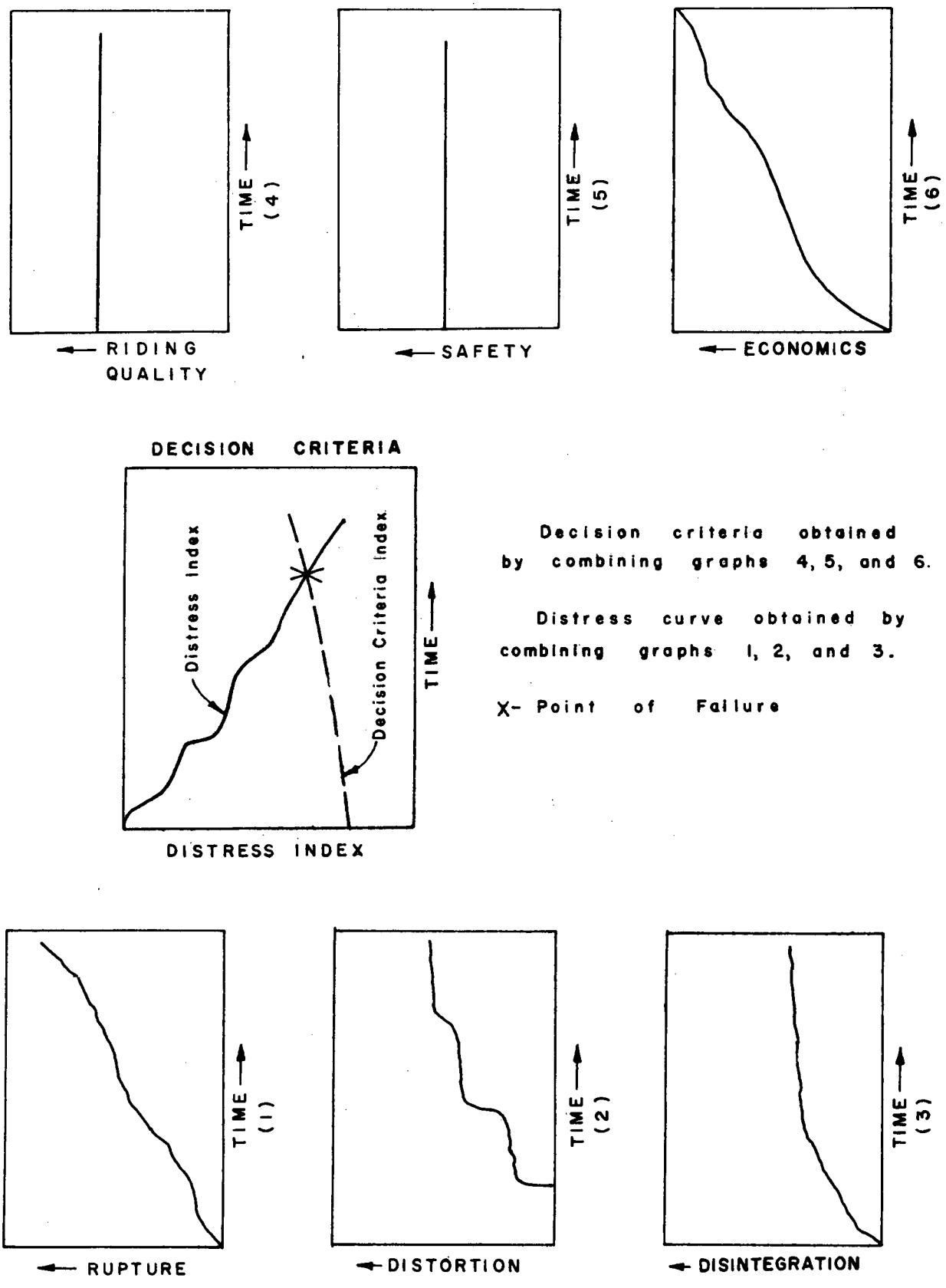


Figure E-1. Failure concept.

$$\underline{DCI}(\underline{x}, t) = F \text{ (riding quality, economics, safety, maintainability, and other factors; space and time)} \quad \text{(E-5)}$$

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.

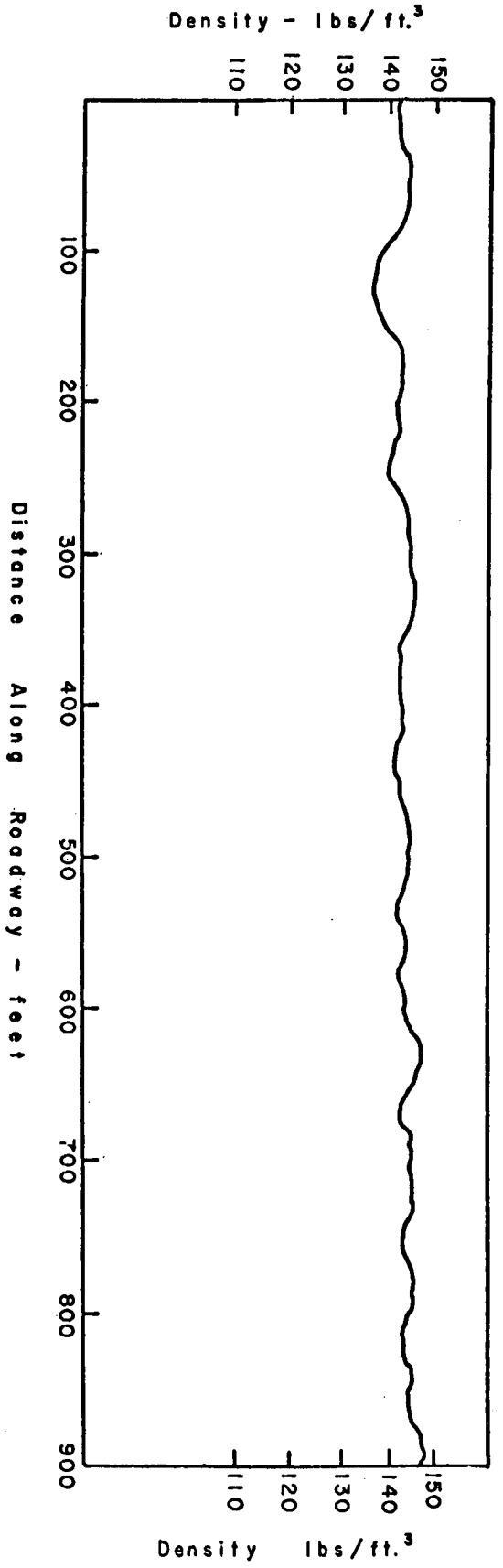
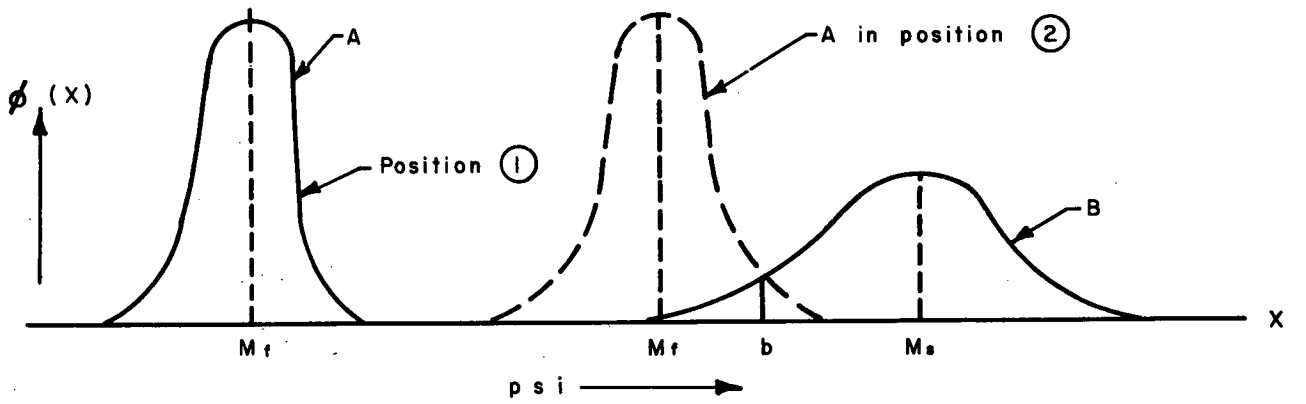


Figure F-1. Continuous distribution of density on a crushed limestone base (52).



A = Density Function for the Stress in a Specimen.

B = Density Function for the Strength in a Specimen.

Figure F-2. Probability concept of distress.

and B and is represented by the shaded area in Figure F-2. This may be stated as follows:

$$P\{D\} = A\Omega B \qquad \text{(F-1)}$$

in which

$P\{D\}$ = probability of distress being experienced; and
Ω = 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:

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

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 abscissa for a normal curve is

$$f(x) = (1/(2\pi)^{1/2})e^{-1/2x^2} \qquad \text{(F-3)}$$

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

$$F(x) = \int_a^b f(x)\,dx \qquad \text{(F-4)}$$

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 $\pm\infty = 1$:

$$F(x) = \int_{-\infty}^{+\infty} f(x)\,dx = 1 \qquad \text{(F-5)}$$

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

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

For curve B, the density function is

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

in which

μ = mean value of quantities being considered;
σ = 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:

$$F(x_A)=F(x_B) \qquad \text{(F-8)}$$

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

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

$$b=\frac{(\beta\mu_B-\mu_A)\pm\sqrt{(\mu_A-\beta\mu_B)^2-(1-\beta)\left[2\sigma_A^2\log e\,\frac{\sigma_A}{\sigma_B}+\mu_A^2-\beta\mu_B^2\right]}}{\beta-1} \qquad \text{(F-9)}$$

in which

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

Special case ($\sigma_A=\sigma_B$)

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

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

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

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

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

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:

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

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

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:

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

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:

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

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.

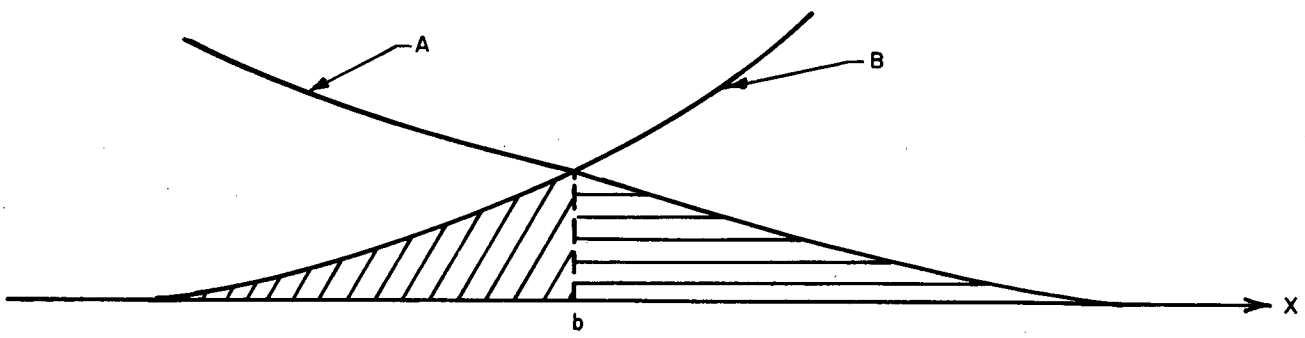


Figure F-3. Enlargement of the intersection area of Figure F-2.

Readjusting to account for signs, the following expression is obtained that may be used directly with the probability tables:

$$P\{D\}=2-F\left(\frac{b-\mu_A}{\sigma_A}\right)-F\left(\frac{\mu_B-b}{\sigma_B}\right) \qquad \text{(F-18)}$$

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

$\bar{S}$ = the mean value of the flexural strength of the concrete;
σ_s = standard deviation of the concrete flexural strength;
$\bar{f}$ = mean working stress in the concrete; and
σ_f = standard deviation of the working stress in the concrete.

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:

$$P\{D\}=2-F\left(\frac{b-\bar{f}}{\sigma_f}\right)-F\left(\frac{\bar{S}-b}{\sigma_s}\right) \qquad \text{(F-19)}$$

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.

CASE ONE	CASE TWO
$\bar{f}$=500 psi	$\bar{f}$=500 psi
σ_f= 20 psi	σ_f= 20 psi
$\bar{S}$=600 psi	$\bar{S}$=600 psi
σ_s= 20 psi	σ_s= 40 psi

Using these values in Eqs. F-7 and F-18, the following values are obtained:

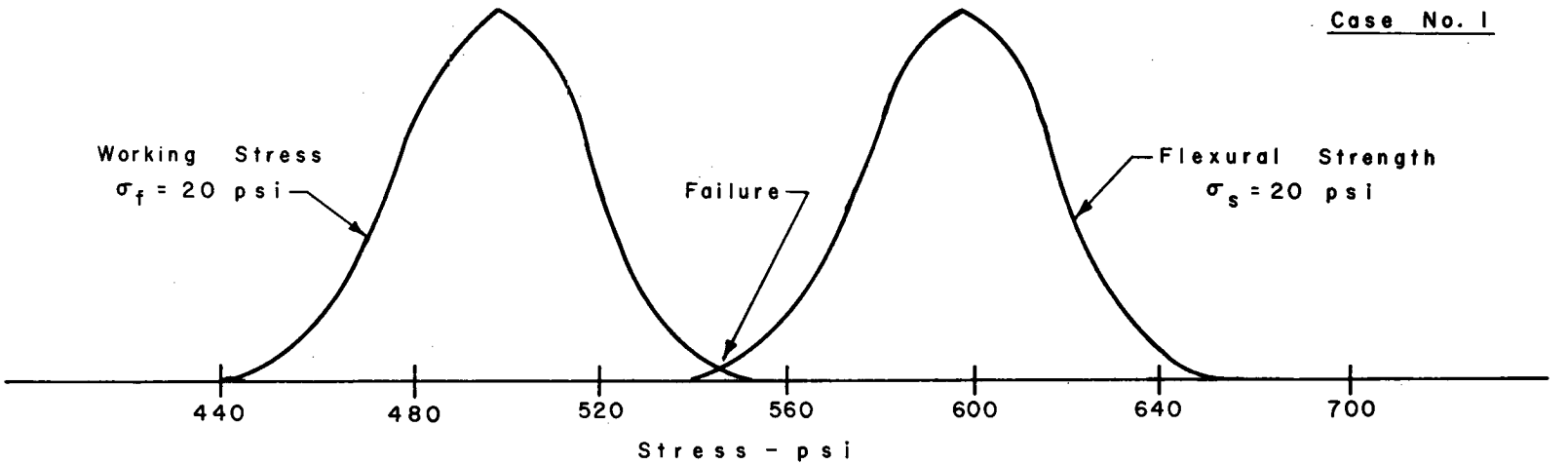
Case One	Case Two
$P\{D\}$=1.24 percent	$P\{D\}$=8.95 percent

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.



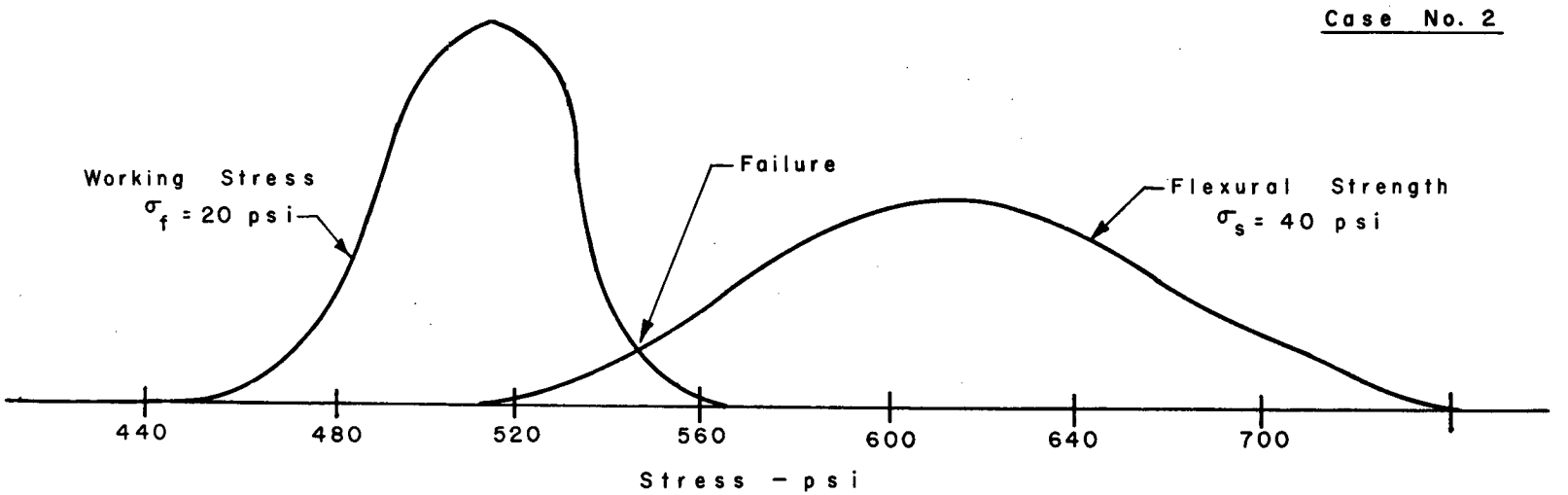


Figure F-4. Failure for two conditions.

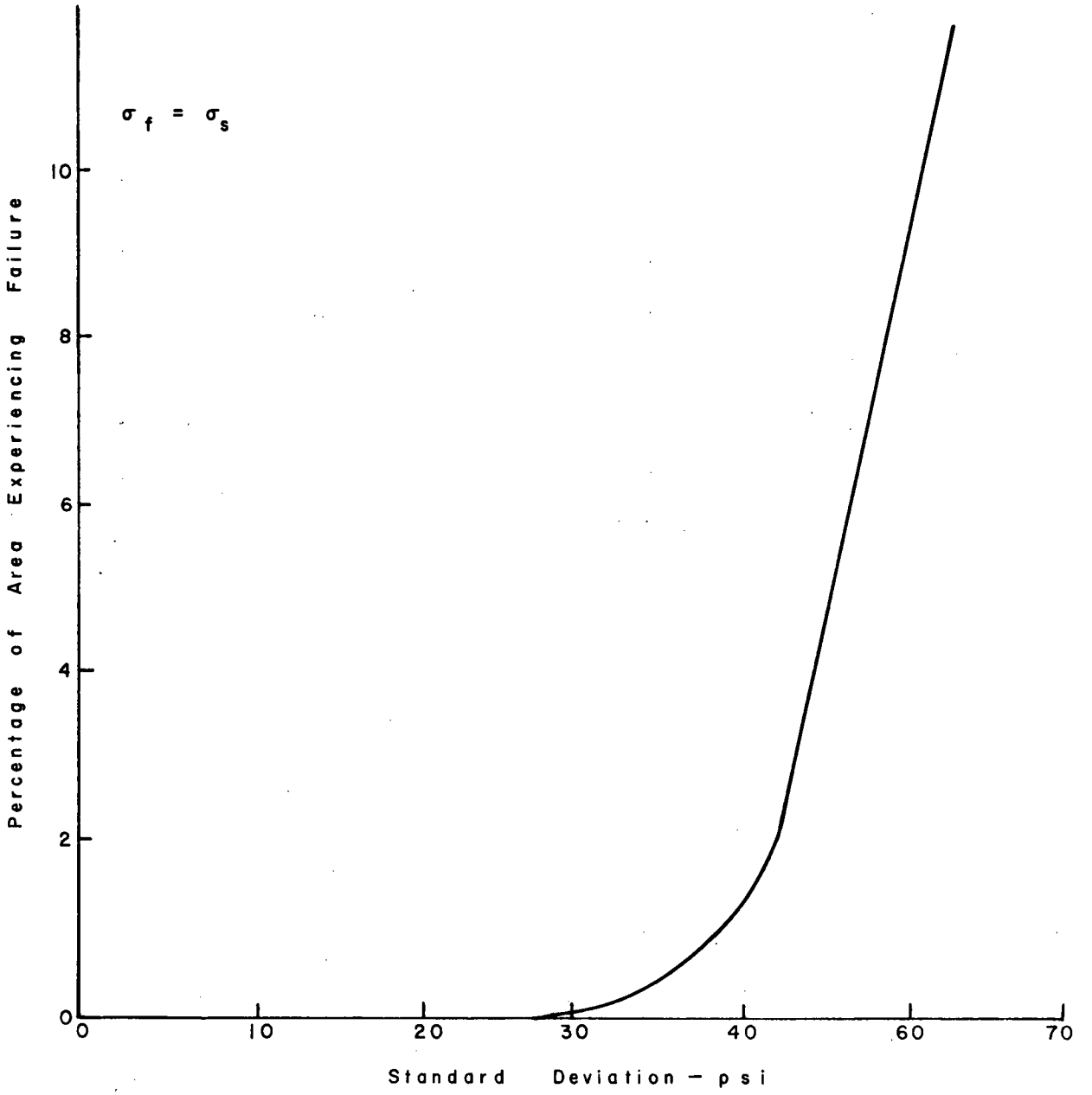


Figure F-5. Effect of standard deviation of stress and strength on failure for a given condition.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Rep. No. *Title*

—* A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report (Proj. 4-3(2)), 81 p., $1.80

1 Evaluation of Methods of Replacement of Deteriorated Concrete in Structures (Proj. 6-8), 56 p., $2.80

2 An Introduction to Guidelines for Satellite Studies of Pavement Performance (Proj. 1-1), 19 p., $1.80

2A Guidelines for Satellite Studies of Pavement Performance, 85 p.+9 figs., 26 tables, 4 app., $3.00

3 Improved Criteria for Traffic Signals at Individual Intersections—Interim Report (Proj. 3-5), 36 p., $1.60

4 Non-Chemical Methods of Snow and Ice Control on Highway Structures (Proj. 6-2), 74 p., $3.20

5 Effects of Different Methods of Stockpiling Aggregates—Interim Report (Proj. 10-3), 48 p., $2.00

6 Means of Locating and Communicating with Disabled Vehicles—Interim Report (Proj. 3-4), 56 p. $3.20

7 Comparison of Different Methods of Measuring Pavement Condition—Interim Report (Proj. 1-2), 29 p., $1.80

8 Synthetic Aggregates for Highway Construction (Proj. 4-4), 13 p., $1.00

9 Traffic Surveillance and Means of Communicating with Drivers—Interim Report (Proj. 3-2), 28 p., $1.60

10 Theoretical Analysis of Structural Behavior of Road Test Flexible Pavements (Proj. 1-4), 31 p., $2.80

11 Effect of Control Devices on Traffic Operations—Interim Report (Proj. 3-6), 107 p., $5.80

12 Identification of Aggregates Causing Poor Concrete Performance When Frozen—Interim Report (Proj. 4-3(1)), 47 p., $3.00

13 Running Cost of Motor Vehicles as Affected by Highway Design—Interim Report (Proj. 2-5), 43 p., $2.80

14 Density and Moisture Content Measurements by Nuclear Methods—Interim Report (Proj. 10-5), 32 p., $3.00

15 Identification of Concrete Aggregates Exhibiting Frost Susceptibility—Interim Report (Proj. 4-3(2)), 66 p., $4.00

16 Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals (Proj. 6-3), 21 p., $1.60

17 Development of Guidelines for Practical and Realistic Construction Specifications (Proj. 10-1), 109 p., $6.00

18 Community Consequences of Highway Improvement (Proj. 2-2), 37 p., $2.80

19 Economical and Effective Deicing Agents for Use on Highway Structures (Proj. 6-1), 19 p., $1.20

* Highway Research Board Special Report 80.

Rep. No. *Title*

20 Economic Study of Roadway Lighting (Proj. 5-4), 77 p., $3.20

21 Detecting Variations in Load-Carrying Capacity of Flexible Pavements (Proj. 1-5), 30 p., $1.40

22 Factors Influencing Flexible Pavement Performance (Proj. 1-3(2)), 69 p., $2.60

23 Methods for Reducing Corrosion of Reinforcing Steel (Proj. 6-4), 22 p., $1.40

24 Urban Travel Patterns for Airports, Shopping Centers, and Industrial Plants (Proj. 7-1), 116 p., $5.20

25 Potential Uses of Sonic and Ultrasonic Devices in Highway Construction (Proj. 10-7), 48 p., $2.00

26 Development of Uniform Procedures for Establishing Construction Equipment Rental Rates (Proj. 13-1), 33 p., $1.60

27 Physical Factors Influencing Resistance of Concrete to Deicing Agents (Proj. 6-5), 41 p., $2.00

28 Surveillance Methods and Ways and Means of Communicating with Drivers (Proj. 3-2), 66 p., $2.60

29 Digital-Computer-Controlled Traffic Signal System for a Small City (Proj. 3-2), 82 p., $4.00

30 Extension of AASHO Road Test Performance Concepts (Proj. 1-4(2)), 33 p., $1.60

31 A Review of Transportation Aspects of Land-Use Control (Proj. 8-5), 41 p., $2.00

32 Improved Criteria for Traffic Signals at Individual Intersections (Proj. 3-5), 134 p., $5.00

33 Values of Time Savings of Commercial Vehicles (Proj. 2-4), 74 p., $3.60

34 Evaluation of Construction Control Procedures—Interim Report (Proj. 10-2), 117 p., $5.00

35 Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests (Proj. 1-3(3)), 117 p., $5.00

36 Highway Guardrails—A Review of Current Practice (Proj. 15-1), 33 p., $1.60

37 Tentative Skid-Resistance Requirements for Main Rural Highways (Proj. 1-7), 80 p., $3.60

38 Evaluation of Pavement Joint and Crack Sealing Materials and Practices (Proj. 9-3), 40 p., $2.00

39 Factors Involved in the Design of Asphaltic Pavement Surfaces (Proj. 1-8), 112 p., $5.00

40 Means of Locating Disabled or Stopped Vehicles (Proj. 3-4(1)), 40 p., $2.00

41 Effect of Control Devices on Traffic Operations (Proj. 3-6), 83 p., $3.60

42 Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index (Proj. 14-1), 144 p., $5.60

43 Density and Moisture Content Measurements by Nuclear Methods (Proj. 10-5), 38 p., $2.00

44 Traffic Attraction of Rural Outdoor Recreational Areas (Proj. 7-2), 28 p., $1.40

45 Development of Improved Pavement Marking Materials—Laboratory Phase (Proj. 5-5), 24 p., $1.40

46 Effects of Different Methods of Stockpiling and Handling Aggregates (Proj. 10-3), 102 p., $4.60

47 Accident Rates as Related to Design Elements of Rural Highways (Proj. 2-3), 173 p., $6.40

48 Factors and Trends in Trip Lengths (Proj. 7-4), 70 p., $3.20

49 National Survey of Transportation Attitudes and Behavior—Phase I Summary Report (Proj. 20-4), 71 p., $3.20

Rep. No.	Title
50	Factors Influencing Safety at Highway-Rail Grade Crossings (Proj. 3-8), 113 p., $5.20
51	Sensing and Communication Between Vehicles (Proj. 3-3), 105 p., $5.00
52	Measurement of Pavement Thickness by Rapid and Nondestructive Methods (Proj. 10-6), 82 p., $3.80
53	Multiple Use of Lands Within Highway Rights-of-Way (Proj. 7-6), 68 p., $3.20
54	Location, Selection, and Maintenance of Highway Guardrails and Median Barriers (Proj. 15-1(2)), 63 p., $2.60
55	Research Needs in Highway Transportation (Proj. 20-2), 66 p., $2.80
56	Scenic Easements—Legal, Administrative, and Valuation Problems and Procedures (Proj. 11-3), 174 p., $6.40
57	Factors Influencing Modal Trip Assignment (Proj. 8-2), 78 p., $3.20
58	Comparative Analysis of Traffic Assignment Techniques with Actual Highway Use (Proj. 7-5), 85 p., $3.60
59	Standard Measurements for Satellite Road Test Program (Proj. 1-6), 78 p., $3.20
60	Effects of Illumination on Operating Characteristics of Freeways (Proj. 5-2) 148 p., $6.00
61	Evaluation of Studded Tires—Performance Data and Pavement Wear Measurement (Proj. 1-9), 66 p., $3.00
62	Urban Travel Patterns for Hospitals, Universities, Office Buildings, and Capitols (Proj. 7-1), 144 p., $5.60
63	Economics of Design Standards for Low-Volume Rural Roads (Proj. 2-6), 93 p., $4.00
64	Motorists' Needs and Services on Interstate Highways (Proj. 7-7), 88 p., $3.60
65	One-Cycle Slow-Freeze Test for Evaluating Aggregate Performance in Frozen Concrete (Proj. 4-3(1)), 21 p., $1.40
66	Identification of Frost-Susceptible Particles in Concrete Aggregates (Proj. 4-3(2)), 62 p., $2.80
67	Relation of Asphalt Rheological Properties to Pavement Durability (Proj. 9-1), 45 p., $2.20
68	Application of Vehicle Operating Characteristics to Geometric Design and Traffic Operations (Proj. 3-10), 38 p., $2.00
69	Evaluation of Construction Control Procedures—Aggregate Gradation Variations and Effects (Proj. 10-2A), 58 p., $2.80
70	Social and Economic Factors Affecting Intercity Travel (Proj. 8-1), 68 p., $3.00
71	Analytical Study of Weighing Methods for Highway Vehicles in Motion (Proj. 7-3), 63 p., $2.80
72	Theory and Practice in Inverse Condemnation for Five Representative States (Proj. 11-2), 44 p., $2.20
73	Improved Criteria for Traffic Signal Systems on Urban Arterials (Proj. 3-5/1), 55 p., $2.80
74	Protective Coatings for Highway Structural Steel (Proj. 4-6), 64 p., $2.80
74A	Protective Coatings for Highway Structural Steel—Literature Survey (Proj. 4-6), 275 p., $8.00
74B	Protective Coatings for Highway Structural Steel—Current Highway Practices (Proj. 4-6), 102 p., $4.00
75	Effect of Highway Landscape Development on Nearby Property (Proj. 2-9), 82 p., $3.60
76	Detecting Seasonal Changes in Load-Carrying Capabilities of Flexible Pavements (Proj. 1-5(2)), 37 p., $2.00
77	Development of Design Criteria for Safer Luminaire Supports (Proj. 15-6), 82 p., $3.80
78	Highway Noise—Measurement, Simulation, and Mixed Reactions (Proj. 3-7), 78 p., $3.20
79	Development of Improved Methods for Reduction of Traffic Accidents (Proj. 17-1), 163 p., $6.40
80	Oversize-Overweight Permit Operation on State Highways (Proj. 2-10), 120 p., $5.20
81	Moving Behavior and Residential Choice—A National Survey (Proj. 8-6), 129 p., $5.60
82	National Survey of Transportation Attitudes and Behavior—Phase II Analysis Report (Proj. 20-4), 89 p., $4.00
83	Distribution of Wheel Loads on Highway Bridges (Proj. 12-2), 56 p., $2.80
84	Analysis and Projection of Research on Traffic Surveillance, Communication, and Control (Proj. 3-9), 48 p., $2.40
85	Development of Formed-in-Place Wet Reflective Markers (Proj. 5-5), 28 p., $1.80
86	Tentative Service Requirements for Bridge Rail Systems (Proj. 12-8), 62 p., $3.20
87	Rules of Discovery and Disclosure in Highway Condemnation Proceedings (Proj. 11-1(5)), 28 p., $2.00
88	Recognition of Benefits to Remainder Property in Highway Valuation Cases (Proj. 11-1(2)), 24 p., $2.00
89	Factors, Trends, and Guidelines Related to Trip Length (Proj. 7-4), 59 p., $3.20
90	Protection of Steel in Prestressed Concrete Bridges (Proj. 12-5), 86 p., $4.00
91	Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research (Proj. 16-1), 70 p., $3.20
92	Valuation and Condemnation of Special Purpose Properties (Proj. 11-1(6)), 47 p., $2.60
93	Guidelines for Medial and Marginal Access Control on Major Roadways (Proj. 3-13), 147 p., $6.20
94	Valuation and Condemnation Problems Involving Trade Fixtures (Proj. 11-1(9)), 22 p., $1.80
95	Highway Fog (Proj. 5-6), 48 p., $2.40
96	Strategies for the Evaluation of Alternative Transportation Plans (Proj. 8-4), 111 p., $5.40
97	Analysis of Structural Behavior of AASHO Road Test Rigid Pavements (Proj. 1-4(1)A), 35 p., $2.60
98	Tests for Evaluating Degradation of Base Course Aggregates (Proj. 4-2), 98 p. $5.00
99	Visual Requirements in Night Driving (Proj. 5-3), 38 p., $2.60
100	Research Needs Relating to Performance of Aggregates in Highway Construction (Proj. 4-8), 68 p., $3.40
101	Effect of Stress on Freeze-Thaw Durability of Concrete Bridge Decks (Proj. 6-9), 70 p., $3.60
102	Effect of Weldments on the Fatigue Strength of Steel Beams (Proj. 12-7), 114 p., $5.40
103	Rapid Test Methods for Field Control of Highway Construction (Proj. 10-4), 89 p., $5.00
104	Rules of Compensability and Valuation Evidence for Highway Land Acquisition (Proj. 11-1), 77 p., $4.40

Rep. No.	Title
105	Dynamic Pavement Loads of Heavy Highway Vehicles (Proj. 15-5), 94 p., $5.00
106	Revibration of Retarded Concrete for Continuous Bridge Decks (Proj. 18-1), 67 p., $3.40
107	New Approaches to Compensation for Residential Takings (Proj. 11-1(10)), 27 p., $2.40
108	Tentative Design Procedure for Riprap-Lined Channels (Proj. 15-2), 75 p., $4.00
109	Elastomeric Bearing Research (Proj. 12-9), 53 p., $3.00
110	Optimizing Street Operations Through Traffic Regulations and Control (Proj. 3-11), 100 p., $4.40
111	Running Costs of Motor Vehicles as Affected by Road Design and Traffic (Proj. 2-5a and 2-7), 97 p., $5.20
112	Junkyard Valuation—Salvage Industry Appraisal Principles Applicable to Highway Beautification (Proj. 11-3(2)), 41 p., $2.60
113	Optimizing Flow on Existing Street Networks (Proj. 3-14), 414 p., $15.60
114	Effects of Proposed Highway Improvements on Property Values (Proj. 11-1(1)), 42 p., $2.60
115	Guardrail Performance and Design (Proj. 15-1(2)), 70 p., $3.60
116	Structural Analysis and Design of Pipe Culverts (Proj. 15-3), 155 p., $6.40
117	Highway Noise—A Design Guide for Highway Engineers (Proj. 3-7), 79 p., $4.60
118	Location, Selection, and Maintenance of Highway Traffic Barriers (Proj. 15-1(2)), 96 p., $5.20
119	Control of Highway Advertising Signs—Some Legal Problems (Proj. 11-3(1)), 72 p., $3.60
120	Data Requirements for Metropolitan Transportation Planning (Proj. 8-7), 90 p., $4.80
121	Protection of Highway Utility (Proj. 8-5), 115 p., $5.60
122	Summary and Evaluation of Economic Consequences of Highway Improvements (Proj. 2-11), 324 p., $13.60
123	Development of Information Requirements and Transmission Techniques for Highway Users (Proj. 3-12) 239 p., $9.60
124	Improved Criteria for Traffic Signal Systems in Urban Networks (Proj. 3-5) 86 p., $4.80
125	Optimization of Density and Moisture Content Measurements by Nuclear Methods (Proj. 10-5A), 86 p., $4.40
126	Divergencies in Right-of-Way Valuation (Proj. 11-4), 57 p., $3.00
127	Snow Removal and Ice Control Techniques at Interchanges (Proj. 6-10), 90 p., $5.20
128	Evaluation of AASHO Interim Guides for Design of Pavement Structures (Proj. 1-11), 111 p., $5.60
129	Guardrail Crash Test Evaluation—New Concepts and End Designs (Proj. 15-1(2)), 89 p., $4.80
130	Roadway Delineation Systems (Proj. 5-7), 349 p., $14.00
131	Performance Budgeting System for Highway Maintenance Management (Proj. 19-2(4)), 213 p., $8.40
132	Relationships Between Physiographic Units and Highway Design Factors (Proj. 1-3(1)), 161 p., $7.20
133	Procedures for Estimating Highway User Costs, Air Pollution, and Noise Effects (Proj. 7-8), 127 p., $5.60
134	Damages Due to Drainage, Runoff, Blasting, and Slides (Proj. 11-1(8)), 24 p., $2.80
135	Promising Replacements for Conventional Aggregates for Highway Use (Proj. 4-10), 53 p., $3.60
136	Estimating Peak Runoff Rates from Ungaged Small Rural Watersheds (Proj. 15-4), 85 p., $4.60
137	Roadside Development—Evaluation of Research (Proj. 16-2), 78 p., $4.20
138	Instrumentation for Measurement of Moisture—Literature Review and Recommended Research (Proj. 21-1), 60 p., $4.00
139	Flexible Pavement Design and Management—Systems Formulation (Proj. 1-10), 64 p., $4.40

Synthesis of Highway Practice

No.	Title
1	Traffic Control for Freeway Maintenance (Proj. 20-5, Topic 1), 47 p., $2.20
2	Bridge Approach Design and Construction Practices (Proj. 20-5, Topic 2), 30 p., $2.00
3	Traffic-Safe and Hydraulically Efficient Drainage Practice (Proj. 20-5, Topic 4), 38 p., $2.20
4	Concrete Bridge Deck Durability (Proj. 20-5, Topic 3), 28 p., $2.20
5	Scour at Bridge Waterways (Proj. 20-5, Topic 5), 37 p., $2.40
6	Principles of Project Scheduling and Monitoring (Proj. 20-5, Topic 6), 43 p., $2.40
7	Motorist Aid Systems (Proj. 20-5, Topic 3-01), 28 p., $2.40
8	Construction of Embankments (Proj. 20-5, Topic 9), 38 p., $2.40
9	Pavement Rehabilitation—Materials and Techniques (Proj. 20-5, Topic 8), 41 p., $2.80
10	Recruiting, Training, and Retaining Maintenance and Equipment Personnel (Proj. 20-5, Topic 10), 35 p., $2.80
11	Development of Management Capability (Proj. 20-5, Topic 12), 50 p., $3.20
12	Telecommunications Systems for Highway Administration and Operations (Proj. 20-5, Topic 3-03), 29 p., $2.80
13	Radio Spectrum Frequency Management (Proj. 20-5, Topic 3-03), 32 p., $2.80
14	Skid Resistance (Proj. 20-5, Topic 7), 66 p., $4.00
15	Statewide Transportation Planning—Needs and Requirements (Proj. 20-5, Topic 3-02), 41 p., $3.60
16	Continuously Reinforced Concrete Pavement (Proj. 20-5, Topic 3-08), 23 p., $2.80
17	Pavement Traffic Marking—Materials and Application Affecting Serviceability (Proj. 20-5, Topic 3-05), 44 p., $3.60

THE NATIONAL ACADEMY OF SCIENCES is a private, honorary organization of more than 700 scientists and engineers elected on the basis of outstanding contributions to knowledge. Established by a Congressional Act of Incorporation signed by President Abraham Lincoln on March 3, 1863, and supported by private and public funds, the Academy works to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance.

Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U. S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE HIGHWAY RESEARCH BOARD, organized November 11, 1920, as an agency of the Division of Engineering, is a cooperative organization of the highway technologists of America operating under the auspices of the National Research Council and with the support of the several highway departments, the Federal Highway Administration, and many other organizations interested in the development of transportation. The purpose of the Board is to advance knowledge concerning the nature and performance of transportation systems, through the stimulation of research and dissemination of information derived therefrom.

HIGHWAY RESEARCH BOARD
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
2101 Constitution Avenue Washington, D. C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 42970

000015
LIBRARY

IDAHO DEPT OF HIGHWAYS
P O BOX 7129
BOISE ID 83707