A SYSTEMS APPROACH APPLIED TO PAVEMENT DESIGN AND RESEARCH

by

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A System Analysis of Pavement Design
and Research Implementation

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PREFACE

On May 10, 1968, a proposal for an unusual research study was submitted to the Texas Highway Department for consideration. Entitled "The Development of a Feasible Approach to Systematic Pavement Design and Research," it proposed a long range comprehensive research program to develop a pavement systems analysis and was also unusual in that it was a joint effort by three separate research agencies.

This is the first published report of work from that project. It presents the background of the problem, summarizes the project findings during the first year, and demonstrates the feasibility of using systems analysis to improve pavement design methods. Primarily the report presents the philosophy of the research approach, but it also includes a working systems model to show that such an approach is feasible for flexible pavements.

This report is also a background document, providing the framework for future work within the project, and can assist others in coordinated research efforts, the results of which may be implemented into the pavement design system through this project.

The material presented here summarizes the project activities for the first year. Other reports in preparation give more detail of specific project studies, such as development of a user's manual for the system, a sensitivity analysis of the system computer program, and documentation for a design system using the AASHO Interim Guides.

As an aid to the reader, terms used in the report are defined in Appendix C.

This project was initiated in December 1968 and is supported by the Texas Highway Department in cooperation with the Bureau of Public Roads of the Federal Highway Administration Department of Transportation. Their sponsorship and support are gratefully acknowledged.

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ABSTRACT

The complex nature of highway pavements and the demands placed on them by traffic and environment have resulted in a piecemeal and incomplete design methodology. It has become apparent from analysis of the problem that realistic analyses of pavement design and management problems can be obtained only by looking at the total pavement system, i.e., through systems analysis.

This report describes such an approach and presents a working systems model. More than 50 physical inputs and constraints are used in the model and the output is a set of recommended pavement design strategies based on the net present worth of the lowest total cost. From these the pavement designer or administrator may select his design. This approach gives him considerably expanded scope and flexibility in exploring design options and a better chance of achieving the best possible design with no loss of the normal decision-making power.

The report discusses possible ways of utilizing this initial working system to establish an overall system of pavement analysis and research implementation, i.e., a pavement management system. The factors required to put the design system into practice are discussed and a proposed organization for acquiring and using input data and storing performance information for future use is presented. In addition, a possible plan for implementing the approach into the Texas Highway Department procedure is discussed.

The results of the first year of effort on the project are discussed. It is concluded that a systems approach to pavement design and research is feasible and should be further pursued to develop more comprehensive pavement management techniques.

KEY WORDS: systems analysis, systems engineering, design, pavements, flexible pavements, pavement structure, optimization, pavement design, performance, analysis, research management, Texas Highway Department, Center for Highway Research, Texas Transportation Institute, computer program.

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CHAPTER 1. INTRODUCTION

Highway pavements can be viewed as complex structural systems involving many variables, e.g., combinations of load, environment, performance, pavement structure, construction, maintenance, materials, and economics. In order to design, build, and maintain better pavements, it is important that most aspects of a pavement system be more completely understood and that design and research be conducted within a systems framework. Some people think of pavements as inexpensive parts of the highway system; but they are not. An investment of approximately 20 billion dollars will be made in pavements for the Interstate Highway System alone, and millions more will be spent annually on maintenance and upgrading. Thus, it may be concluded that pavements are an important and expensive part of the total transportation system and that improvements in designing them could result in substantial savings.

The Problem

In recent years considerable research has been conducted to investigate many specific problems concerning components of pavement design. Each of the 50 states has been involved in such projects and the Bureau of Public Roads has sponsored a series of projects at the national level. Additional work has been supported by the National Cooperative Highway Research Program (NCHRP). Unfortunately, many of these efforts are fragmented and uncollated, and thus cannot be easily combined to improve design methods. As modern technology has developed and the complexity of the interaction of design factors has become better known, the need for a systematic approach to the overall problem of pavement design and management has become more evident. It is also evident that this approach should involve a team effort of interested research agencies and sponsors.

The AASHO Road Test illustrates the magnitude of the pavement design problem (Ref 1). Though it was a 30 million dollar research project it answered only a few of the important design questions, and it seems that no single experiment is big enough to answer all the questions.

The Systems Approach

Likewise, no single mathematical equation or model can be used to describe pavement behavior completely. Instead, a coordinated, systematic approach is needed; that is, a framework within which the multitude of physical and socioeconomic variables involved can be sorted out and related in a meaningful way. Such an approach has been called the "systems approach" (Ref 2). Because this terminology has many definitions,* a brief write-up of the approach involved within this project is given in Appendix D.

Actually, two applications of the systems concept are involved here: (1) the systematic approach to the general problem of managing pavements, i.e., designing, constructing, evaluating and maintaining better pavements; and (2) the development and continual improvement of a working pavement design or management system model. These applications are expanded in Chapters 4, 5, and 6.

A 1967 NCHRP project led to the first work in the applications of systems engineering to pavement design (Ref 2). In a similar but independent effort, Hutchinson and Haas (Ref 3), applied a systems approach to structuring the overall problem and several of the subsystem design problems. Simultaneously, the Texas Transportation Institute developed a working design model in connection with a cooperative research project with the Texas Highway Department. As a result of these studies, the Texas Highway Department, recognizing the need for a system for organizing and coordinating their pavement research program and updating their design system, initiated a project in cooperation with The University of Texas Center for Highway Research and the Texas Transportation Institute of Texas A&M University.

Scope of the Reports

This report is the first of a series from the project. Its objectives are to present the philosophy of the pavement systems analysis, describe developments leading up to the present project, lay the groundwork for future efforts, and describe the work accomplished during the first year of work.

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* It is important to note that the "systems" being considered can be the actual pavement structure or some component of it; the broad management framework or some component used to provide and operate this structure, or it can be some combination of both. In effect, the word "systems" has a broad meaning and its operational definition for a particular situation is determined by the manner in which the problem is structured.

Chapter 2 presents the history of the pavement research leading to this project and outlines the basic project concept. Chapter 3 is a brief systems analysis of the general phases of a pavement design system.

Chapter 4 summarizes the mathematical models used by presenting a working systems model and an example of its use.

Chapter 5 recommends organization and information flow channels required in the Texas Highway Department for implementing and managing the pavement design system. The actual form of the implementation is discussed in Chapter 6, and Chapter 7 presents an approach to current and continuing evaluation of the utility of the design system.

Chapter 8 summarizes the report and presents recommendations for continuing research and development activities.

CHAPTER 2. HISTORY OF PROJECT DEVELOPMENT

Early concepts of pavement design were concerned primarily with subgrade soil types, thicknesses of paving materials, and weight of applied traffic, and subsequent studies indicated the importance of repeated application of traffic loads. Thus, it is not surprising that the largest single study of pavement behavior and design ever made, the AASHO Road Test (Ref 1), involved these primary variables.

The value accruing from the AASHO Road Test experiment in relating axle weight, number of applications, and thickness of pavement required, as well as the development of the serviceability-performance concept, is recognized by most pavement designers and researchers, but many people also recognize the shortcomings of the Road Test, such as the extreme difficulty of extending the usefulness of the results to other subgrades soils and other environments.

The early attempts by the American Association of State Highway Officials to use the Road Test results in developing interim pavement design guides (Refs 4 and 5) pointed out many of the shortcomings of the program. As a result a series of research studies was initiated to "extend the AASHO Road Test." NCHRP proposed a nationwide study to coordinate these efforts (Refs 6 and 7), but after some effort in this direction, the proposed study was abandoned because of the general lack of support by the sponsors.

By late 1962 several states, including Texas, had begun research of this type, generally known as "satellite projects." In 1964, the Highway Research Board published general guidelines for conducting such experiments (Ref 7), and later a set of more specific recommendations, based largely on early experiences gained in conducting the Texas study, was published by the Texas Transportation Institute (Ref 8).

The Texas Study (Project 32)

The Texas study, which terminated in 1968, warrants further discussion since it resulted in the computerized flexible pavement design system that has been under intensive study in this project and forms the basis for the systems model described in Chapter 4. The satellite project had as a principal objective the determination of coefficients for Texas materials similar to the coefficients found in the Interim Guides for the AASHO Road Test materials. The Texas coefficients were to be determined from an analysis of changes in the serviceability index of existing Texas pavements for which the initial serviceability index, the traffic history, the laboratory strength of the materials, and the design thickness were known, could be measured, or could be estimated with acceptable accuracy.

Details of the research work and the findings of the Texas satellite project were published in fifteen reports issued during the life of the study. Findings germane to the present study (Project 123) are summarized below.

(1) Contrary to an important assumption made in planning the project, the initial serviceability index of individual test sections could not be estimated with acceptable accuracy (Ref 9). Thus, the changes in serviceability occurring in the interval from initial construction until the first serviceability index measurements were made, could not be estimated.

(2) Changes in the serviceability index observed over a period of four to five years following the first measurement showed no trends that could be related to age, traffic, materials, or pavement thickness. Apparently, the determination of material coefficients of the type used in the AASHO Road Test performance equation would require periodic measurements of the serviceability index over much longer periods -- perhaps ten or twenty years (Ref 9).

(3) Under certain conditions, coefficients of another kind, directly related to the stiffness of the materials in and beneath an existing pavement, can be estimated from surface deflections caused by a standard surface loading (Ref 10).

(4) Given the stiffness coefficients and thicknesses of the materials, the curvature of the surface of a flexible pavement subjected to a standard loading can be predicted with acceptable accuracy (Ref 10).

(5) The curvature of the surface of a flexible pavement subjected to a standard loading is related to its probable service life. The relation was quantified, based on AASHO Road Test data (Ref 9).

(6) The in situ stiffness of similar materials varies widely, but in a consistent manner, over the state of Texas (Ref 11).

(7) In the range above 32° F, low ambient temperatures affect pavement performance adversely. The effect was quantified, based on AASHO Road Test data (Ref 9).

(8) The effect of swelling clays on serviceability history was quantified, at least roughly (Ref 9).

(9) Conclusions 3 through 8 were combined to form the physical basis for a flexible pavement design system (Ref 12).

(10) The economic basis of the flexible pavement design system was the overall cost incurred over a selected period of time, including costs of initial construction, routine maintenance, seal coats, overlay construction, and delays to traffic during overlay construction.

Thus, the findings of Project 32 point out that an adequate pavement design method could not be generated by applying the traditional piecemeal approach to the problem. In fact, the project work produced a first-generation, working pavement systems model which, a priori, demonstrates the feasibility of developing a working systems design procedure. The general systems concept is discussed below. The specific working system is described in Chapter 4.

Systems Concept (Project 1-10)

It is important to reemphasize that after seven years of concerted effort at "extending the AASHO Road Test" in Texas, the research staff in cooperation with the Texas Highway Department came to the conclusion that it was necessary to develop a more coordinated approach to pavement analysis and design than had been anticipated at the beginning of the project (Ref 12).

Coincidentally, in 1967 NCHRP began a research contract (Project 1-10) (Ref 13) with Materials Research and Development Corporation which was entitled "Translating AASHO Road Test Findings - Basic Properties of Pavement Components." The general objective, as written in the project statement, was to provide the type of basic information required to adapt the information obtained on the AASHO Road Test to local environment. After a thorough study of the problem and a discussion of the desires of the supervising research advisory panel, the objective of that project was summarized and briefly restated as follows: "To formulate the overall pavement problem in broad theoretical terms" which would enable the solution of a variety of problems which have long plagued pavement engineers and which would provide a foundation for improved future developments (Ref 13).

With that beginning objective, Hudson and Finn concluded that while better materials characterization was important and should be sought, perhaps more important was the need to consider the whole range of pavement design factors. An indication of the new direction taken is the fact that after discussing the situation with a variety of knowledgeable people, the project staff changed the project emphasis so that the project report was entitled "Systems Approach to Pavement Design, Systems Formulation, Performance Definition and Materials Characterization" (Ref 2).

That report developed a basic framework for considering pavement design problems (Fig 1), which, while only conceptual, shows the integration of many of the factors involved in the problem, including maintenance and economics.

Relationship of HPR Project 32 and NCHRP Project 1-10

Project 1-10 emphasized the importance of sorting out input variables, interactions, and outputs, as well as the development of significant decision criteria* which could be used in selecting the proper pavement design. The concept was to provide the decision maker with a series of alternative designs and the cost and expected performance characteristics of each, from which he could make an informed selection of design.

In the computer approach developed independently by Scrivner et al in Project 32 (Ref 12), the design problem was formulated in a way similar to that shown in Fig 2, and a solution was obtained.

Thus, two independent sources outlined approximately the same approach for solving the pavement design problem. Both sources recognized the need for a great deal of additional work; for example, the need to include the necessary feedback from observing pavements in the field, in order to validate and improve the methods developed by research.

Need for Current Research (Project 123)

During this time, another important aspect of the pavement management problem was being recognized by the Pavement Research Advisory Committee and the Research Section of the Texas Highway Department. For three years they grappled with the problem of developing a coordinated research program which could be used to vigorously prosecute the task of developing required solutions to priority pavement problems. They recognized that even though good work was

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* Decision criteria represent a set of rules which the designer used to judge alternatives and select the best or optimum one. These rules can range from a simple choice of the best alternative on a purely subjective basis to a sophisticated set of weighting functions for the outputs and an associated mathematical optimization model.

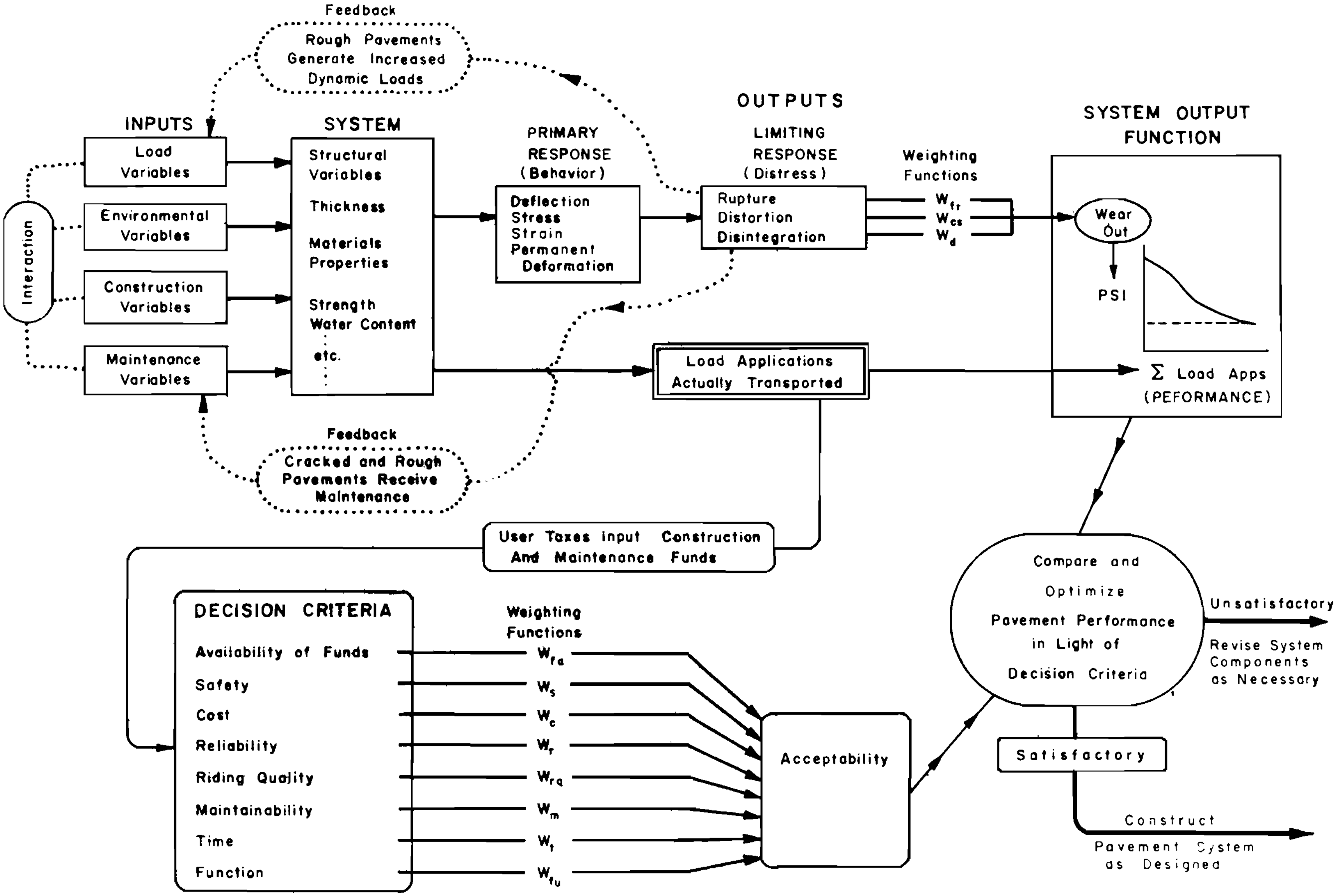

Fig 1. Ideal pavement system.

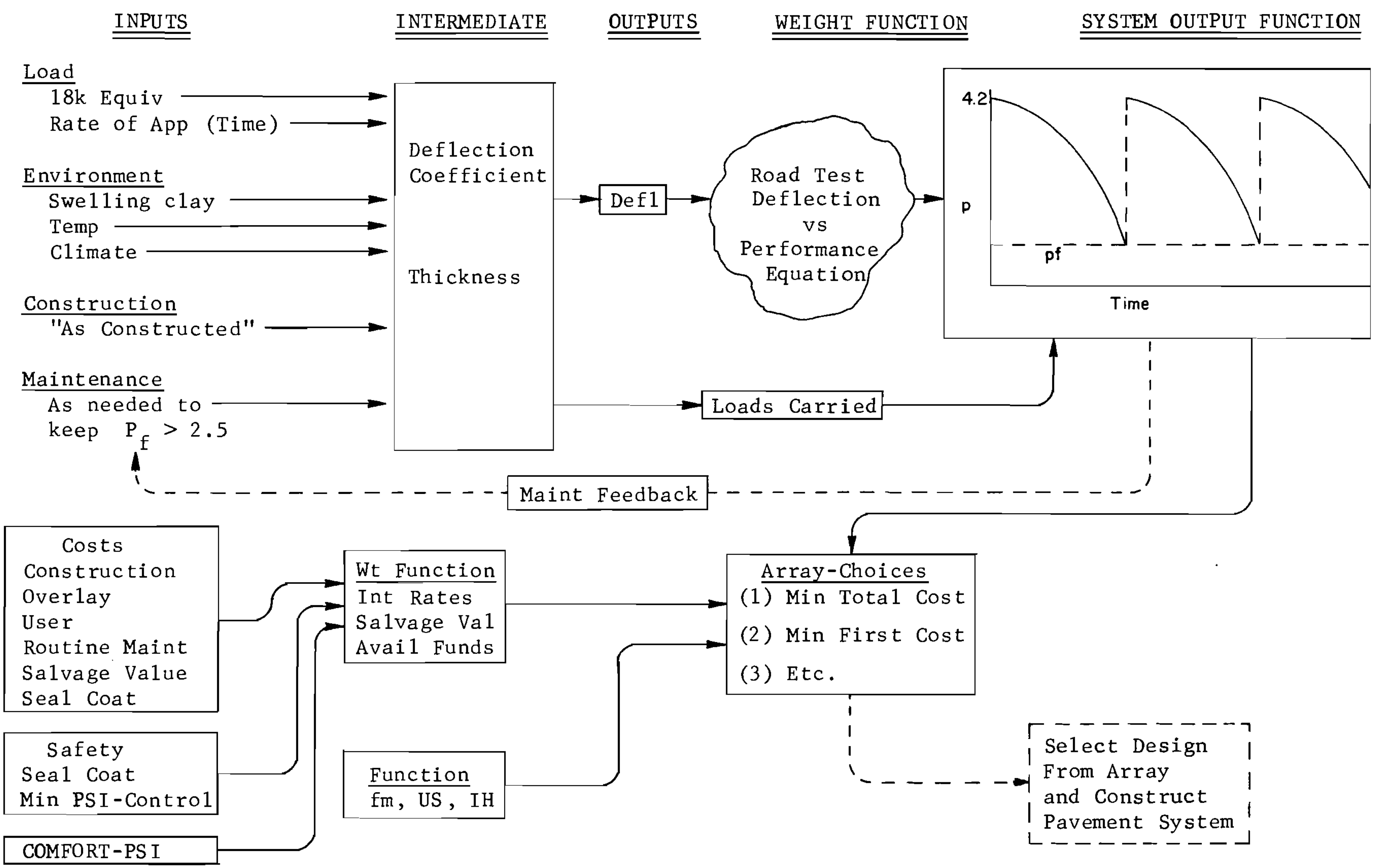

Fig 2. Working pavement system.

being done on individual projects, the resulting solutions often did not fit into a master plan and could not be readily applied.

The problem is somewhat analogous to having four tailors make a suit without a pattern. One tailor makes the sleeves of beautiful green material only to find that the second tailor has made the body of the coat of beautiful brown material and has not provided the proper openings for insetting the sleeves. The analogy can be expanded in many directions. Good reports are not written without outlines, nor buildings constructed without plans, yet many large research programs are conducted without a coordinated plan to tie the individual research efforts into a coordinated whole.

Furthermore, the management of long-term field studies to get empirical answers for the pavement design problem has proved to be complex and difficult, as demonstrated by the experience with Texas and other field studies. Some of the problems, environment for example, are so complicated that they have not yielded to theoretical analysis, and field studies are still necessary.

Development of the Current Project

With this background knowledge, the Texas Highway Department Pavement Research Committee and the Research Section of the Design Division, along with the staffs of The University of Texas Center for Highway Research and the Texas Transportation Institute, began a project to develop a coordinated long-term program of pavement research and design.

Initially, the proposed project was entitled "The Development of a Feasible Approach to Systematic Pavement Design and Research," indicating that the project staff was not sure that a job of this magnitude could be properly accomplished. However, the evidence clearly showed that such a coordinated effort was essential and two main questions remained: (1) "Can a good workable pavement system be developed?" and (2) "Can a framework for doing cooperative research of this magnitude be managed under a common project?".

After early difficulties in explaining a program of this magnitude and getting it approved at all levels, the project was started in December 1968. In April 1969, after only four months of work, a proposal for continuation of the program, beginning September 1969, was submitted as required. At that time the title was changed to "A Systems Analysis of Pavement Design and Research Implementation," because concerted study of the overall problem and particularly the computer program design method developed by the Texas Transportation Institute convinced the project staff that it was possible to carry out such a systems analysis in a meaningful, coordinated way.

Objectives

On the basis of the experience previously discussed, the Texas Highway Department requested that the project be formulated to coordinate and conduct pavement research with the following long-range goals:

(1) to develop a rational design and management system for all pavement types and

(2) to develop this system such that new research knowledge can be easily and efficiently incorporated as it becomes available and in turn to establish the necessary communication and information channels.

A number of work tasks are required to accomplish these goals. For the first year's work, the following specific tasks were defined:

(1) preliminary study of the problem,

(2) evaluation of the feasibility of a long-range project,

(3) formation of a small professional staff to study the overall problem in detail so that guidelines for conducting a project can be established, and

(4) analysis of the flexible pavement design system developed in Project 32 and a study for integrating it into the Texas Highway Department design procedure.

Project Administration

The Area III Research Committee on Pavement Design of the Texas Highway Department recognized that the solution of the pavement design problem would require a considerable effort. Therefore, it was concluded that rather than having continuing individual efforts at solving various pieces of the problem, the best end result would be obtained if all agencies working in this area would coordinate in an overall look at the problem. As a result, Project 123 was initiated as a joint effort between the Texas Highway Department, the Texas Transportation Institute, and the Center for Highway Research. Mr. James L. Brown was named to represent the Texas Highway Department and act as study supervisor. Professors W. R. Hudson and B. F. McCullough, The University of

Texas at Austin, and F. H. Scrivner, Texas Transportation Institute, were designated co-principal investigators.

Close coordination between the three agencies is maintained so that any design system developed will be within the use capabilities or potential use capabilities of the Texas Highway Department. Frequent meetings have been conducted among the project staff to coordinate the work on the project and to keep the representatives of the Texas Highway Department informed of the progress and direction of work.

Another important responsibility of this project is the monitoring of other research in the pavement design area. It is hoped that future pavement research sponsored by the Texas Highway Department can be conducted so that it can be inserted into the design system, and it is felt that coordination is also required between the Project 123 staff and others working in the pavement research area in Texas. In addition, it is felt that the project can serve as a guide to the Research Committee to designate research needs based on weak points of the design system. Sensitivity analyses are being used to evaluate the relative importance of the variables involved.

CHAPTER 3. ANALYSIS OF THE RESEARCH PROBLEM

As previously stated the long range objective of this project is to develop a feasible approach to systematic pavement design and research. Precisely, the objective is to develop the best possible pavement management system for the Texas Highway Department. Obviously, if the best pavement system is to be acquired, systematic procedures must be used in finding the best method. From a review of pertinent references (Refs 2, 3, and 12), it should be understood that a pavement design system is made up of not only a particular set of mathematical models or graphs as has often been assumed but also includes an implementation plan, equipment, and personnel necessary to implement the system.

The mathematical models are in essence descriptions of the physical problem, sometimes in the form of graphs or tables or, for easy, rapid solution, in the form of computer programs. The plan of attack involves the organization of the entire system, the flow of information within the system, and the arrangement of the computer programs which provide possible solutions. Equipment in this context refers to the hardware required to take field and laboratory measurements necessary for design inputs as well as the computer required to solve the mathematical model and store data. The personnel are the trained people who obtain the information and manipulate the other elements to obtain the final solution.

Too often in the past, a narrow view of the pavement design problem has produced unsatisfactory conditions under which to construct, maintain, and manage the highway pavement network. As will be shown more fully later, feedback information such as maintenance performed, maintenance cost, and pavement performance histories is vital to the development and use of an adequate pavement design system. Too often in the past, the narrow concept of design has been used to refer to picking a pavement thickness off a chart and writing it on a set of proposed plans. This definition will not suffice for high-speed, high-volume, modern highways and transportation facilities.

The research problem then involves accepting that present concepts, although helpful in many ways, are too narrow and that a broader, more coordinated approach to the pavement design problem is necessary. Systems analysis has provided such an approach in many areas. It seems logical that it might provide some answers here.

Project Approach

In approaching the problem of creating the best pavement design system, it is logical to use the systems analysis method. Although stated in many ways, the method basically involves the phases shown in Fig 3, with perhaps the most important concept being that as the problem is more fully understood it must be redefined in the light of the improved information. Such a restatement has been used in this project from the outset, as can be traced in the project proposals. The current objectives for the project are as follows:

(1) to develop a working systems model which will provide a coordinated framework for more rational pavement design including as many pertinent variables as possible and

(2) to provide a rational framework for structuring a research program and enumerating important research areas in the pavement area including construction, maintenance, economics, materials, and performance.

The second step, establishing systems requirements, was partially accomplished in NCHRP Study 1-10 (Ref 13) and Project 32 (Ref 14). It manifests itself in the particular form of the working models discussed in the next chapter. A complete discussion of the establishing of system requirements is not given in this report but will be the subject of a subsequent report, where it can be treated more fully.

Steps 3 and 4 merge together for this type of analysis since alternate ways of modeling the problem, e.g., pavement behavior, may automatically generate alternate solutions because each model will provide a unique solution. The many different possible answers generated by the solution of a particular systems model for a specific pavement design situation could be considered a set of alternate solutions. This is described in Chapter 4 in some detail as the output of the particular systems analysis model studied herein.

There are other ramifications of these two steps also. This manifests itself in this project by the development of several operating models, one

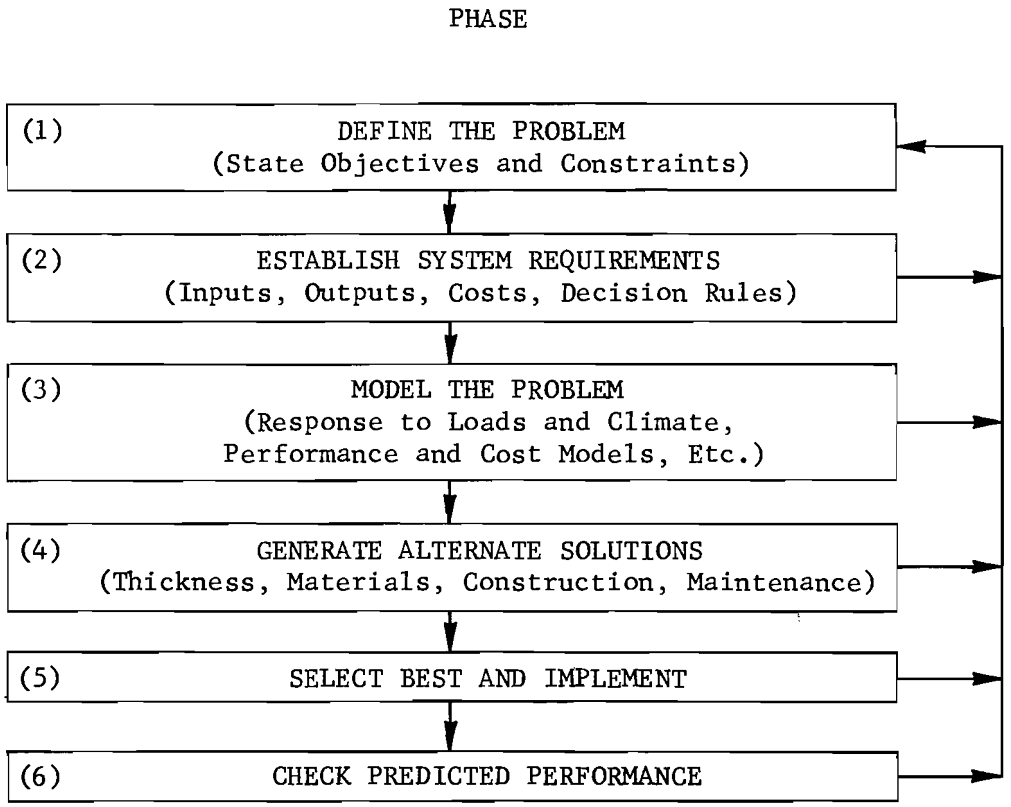

Fig 3. Major phases of the systems analysis method.

based largely on deflection correlation information from the Road Test, another set of design equations developed almost entirely from the AASHO Interim Guides. Subsequently, many additional alternate solutions may be generated, as discussed in Chapter 5. This involves cyclic improvements of the pavement management system and is an essential step in solving the problem.

The fifth step, that of implementation, is also extremely important from many aspects. It is important from the point of view of putting research results to use as soon as possible on a broad scale. It is further vital that an implementation plan be developed which is feasible for putting the system into practice. This involves management and operational details of an administrative rather than a research nature which must be considered in a project such as this. The concepts involved are discussed briefly in Chapter 6 and will be discussed in more detail as further project studies are completed and reported.

The performance evaluation phase is vital and requires that records be kept of problems encountered in using the system as well as of observation of pavements designed and built by use of the system. These records become the feedback required for improving the system, and in turn the pavement itself as maintenance is required. Because of the time required to obtain such feedback information, the project has been proposed as a continuing study. Consequently, any decisions for continuing the study must at this time be based on the soundness of the overall approach and the capabilities of the people involved.

CHAPTER 4. THE WORKING SYSTEMS MODEL

In previous chapters, the general background of the problem and the project have been discussed. Chapter 2 presents the overall systems concepts and shows that such methods are essential to the ultimate development of a realistic pavement design and management system and Chapter 3 structures the problem for solution. This chapter attacks steps 3 and 4 in the systems analysis process, i.e., modeling the problem and developing alternate solutions. Development of a working systems model which fulfills, at least as an initial step, objectives 1 and 2 of the project as stated in Chapter 3, is shown.

Many kinds of models are used in systems engineering. The most important useful type for analytical work is the mathematical model, which is of two types: (1) explicit, such as equations and algorithms and (2) implicit, such as charts, tables, and graphs.

The models used in this project are explicit models which were first formulated and solved as a set by Scrivner, Moore, McFarland, and Carey in Report 32-11, "A Systems Approach to the Flexible Pavement Design Problem" (Ref 12). As previously discussed, this work was the outgrowth of the attempt to apply the AASHO Road Test to Texas conditions. A complete technical description of the original work is given in Ref 12.

It is important to note that the set of mathematical models has an accompanying computer program for reaching solutions. The set of models and its pertinent computer program are called a working systems model, and for easy identification this general approach to the problem has been named Flexible Pavement System (FPS). Since improvements are constantly being made, a number has been added to the system ID. FPS-1 is the initial working system from Project 32, and FPS-2, FPS-3, etc. designate subsequent versions of the basic concept developed within Project 123. The background steps for revising FPS-2 to develop FPS-3 and FPS-4 are given in Appendix B.

Purpose of FPS

The primary purpose of FPS is to provide the designer with a means for investigating a large variety of pavement design options in a systematic and efficient manner. It is not intended to supplant any decision-making prerogative but rather to give him increased scope and flexibility.

The mathematical models developed for FPS are based on the established objectives of providing from available materials a pavement capable of being maintained above a specific level of serviceability over a specified period of time, at a minimum overall cost (Ref 12). As a result, the computer program was written to provide an output of feasible pavement designs, sorted by increasing total cost, in order for the designer or decision-maker to make his choice as quickly and easily as possible.

Figure 4 is an example output of the eight most optimal designs for a typical example problem. Figure 5 is a printout of input data for the FPS model, as supplied by the designer, and is useful as an additional output record of supporting information for the decision maker. The output in Fig 4 also provides information for each alternative on (1) a cost breakdown, (2) initial construction configuration, and (3) overlay end seal coat schedules. A detailed breakdown of costs is shown in Fig 4. These are used for calculating the cost breakdown of Fig 4, which is shown in terms of present value, i.e., discounted using the interest rate specified by the designer.

Inputs for FPS

Each FPS program consists of a set of mathematical models, all explicitly stated. These models can be broken down into four types: (1) physical, (2) economic, (3) optimization, and (4) interaction. Before discussing the models used in FPS, it would be useful to introduce the variables and give a general description of FPS.

A large number of input variables are considered in FPS. This is not intended to make the system cumbersome but rather to initially incorporate as many variables as possible that are considered to be important. Sensitivity analyses, which are further discussed in Chapter 7, are being conducted to determine the relative importance of these variables. Combined with subsequent performance evaluation information, it is possible that some variables may be eliminated and also, of course, that some new factors may be added.

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PROB      1                A SAMPLE PROBLEM

                         SUMMARY OF THE MOST OPTIMAL DESIGNS
                          IN ORDER OF INCREASING TOTAL COST

                             1       2       3       4       5       6       7       8
*************************************************************************************
DESIGN NUMBER                3       3       2       3       3       2       2       3
INIT. CONST. COST          2.000   2.278   1.944   2.306   2.347   2.222   2.292   2.375
OVERLAY CONST. COST         .882    .543    .882    .532    .517    .543    .517    .517
USER COST                   .203    .125    .203    .123    .120    .125    .120    .121
SEAL COAT COST              .233    .384    .233    .380    .374    .384    .374    .374
ROUTINE MAINT. COST         .166    .190    .166    .190    .192    .190    .192    .192
SALVAGE VALUE              -.679   -.711   -.612   -.715   -.730   -.644   -.663   -.734
*************************************************************************************
*************************************************************************************
TOTAL COST                 2.804   2.810   2.816   2.816   2.821   2.821   2.832   2.845
*************************************************************************************
*************************************************************************************
NUMBER OF LAYERS             3       3       2       3       3       2       2       3
*************************************************************************************
LAYER DEPTH (INCHES)
     D( 1)                  1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
     D( 2)                  8.5    10.5    12.0    11.0    11.0    14.0    14.5    11.5
     D( 3)                  6.5     6.5     0.0  [illegible]  6.5     0.0     0.0     6.0
*************************************************************************************
*************************************************************************************
NO.OF PERF.PERIODS           4       3       4       3       3       3       3       3
*************************************************************************************
PERF. TIME (YEARS)
     T( 1)                 4.906   6.250   4.969   6.406   6.531   6.281   6.563   6.656
     T( 2)                 9.945  12.383  10.008  12.773  13.094  12.453  13.164  13.453
     T( 3)                16.195  20.039  16.336  20.703  21.336  20.148  21.445  21.969
     T( 4)                23.812   0.000  24.031   0.000   0.000   0.000   0.000   0.000
*************************************************************************************
OVERLAY POLICY(INCH)
(EXCLUDING LEVEL-UP)
     O( 1)                  1.0      .5     1.0      .5      .5      .5      .5      .5
     O( 2)                   .5      .5      .5      .5      .5      .5      .5      .5
     O( 3)                   .5     0.0      .5     0.0     0.0     0.0     0.0     0.0
*************************************************************************************
NUMBER OF SEAL COATS         2       3       2       3       3       3       3       3
*************************************************************************************
SEAL COAT SCHEDULE
   (YEARS)
   SC( 1)                  9.906   5.000   9.969   5.000   5.000   5.000   5.000   5.000
   SC( 2)                 14.945  11.250  15.008  11.406  11.531  11.281  11.563  11.656
   SC( 3)                  0.000  17.383   0.000  17.773  18.094  17.453  18.164  18.453
*************************************************************************************
```

Fig 4. Summary of the 8 most optimal designs for the example problem.

```
  PROB      1                    A SAMPLE PROBLEM

         THE CONSTRUCTION MATERIALS UNDER CONSIDERATION ARE

     MATERIAL          COST/C.Y.  ST.COEF. MIN.DEPTH MAX.DEPTH SALV.PCT.
ASPHALTIC CONCRETE       10.00       .82      1.00     10.00     45.00
CR. LIMESTONE-1           5.00       .55      6.00     16.00     75.00
GRAVEL-1                  3.00       .35      6.00     16.00    100.00
SUBGRADE                  0.00       .22      0.00      0.00      0.00

  NUMBER OF OUTPUT PAGES DESIRED(8 DESIGNS/PAGE)                              3
  NUMBER OF INPUT MATERIAL TYPES                                              3
  MAX FUNDS AVAILABLE PER SQ.YD. FOR INITIAL DESIGN (DOLLARS)              5.00
  LENGTH OF THE ANALYSIS PERIOD (YEARS)                                    20.0
  INTEREST RATE OR TIME VALUE OF MONEY (PERCENT)                            5.0
  ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR)                           75.0
  ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/C.Y.)                         1.80
  MAXIMUM ALLOWED THICKNESS OF INITIAL CONSTRUCTION (INCHES)               36.0

  DISTRICT TEMPERATURE CONSTANT                                            30.0
  SERVICEABILITY INDEX OF THE INITIAL STRUCTURE                             4.2
  SERVICEABILITY INDEX P1 AFTER AN OVERLAY                                  3.8
  MINIMUM SERVICEABILITY INDEX P2                                           3.0
  SWELLING CLAY PARAMETERS -- P2 PRIME                                     1.50
                                    B1                                    .0800

  ONE-DIRECTION ADT AT BEGINNING OF ANALYSIS PERIOD (VEHICLES/DAY)        12000
  ONE-DIRECTION ADT AT END OF ANALYSIS PERIOD (VEHICLES/DAY)              18000
  ONE-DIRECTION  20-YR ACCUMULATED NO. OF EQUIVALENT 18-KIP AXLES       2000000

  MINIMUM TIME TO FIRST OVERLAY (YEARS)                                     2.0
  MINIMUM TIME BETWEEN OVERLAYS (YEARS)                                     5.0
  MIN TIME TO FIRST SEAL COAT AFTER OVERLAY OR INITIAL CONST.(YEARS)        5.0
  MINIMUM TIME BETWEEN SEAL COATS (YEARS)                                   3.0
  NUMBER OF OPEN LANES IN RESTRICTED ZONE IN O.D.                             1
  NUMBER OF OPEN LANES IN RESTRICTED ZONE IN N.O.D.                           2

  C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE O.D. (MILES)            .50
  C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE N.O.D. (MILES)          .50
  PROPORTION OF ADT ARRIVING EACH HOUR OF CONSTRUCTION (PERCENT)            6.0
  OVERLAY CONSTRUCTION TIME (HOURS/DAY)                                    10.0
  THE ROAD IS IN A RURAL AREA.

  PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN O.D. (PERCENT)        2.0
  PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN N.O.D. (PERCENT)      0.0
  AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN O.D. (HOURS)                   .100
  AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN N.O.D. (HOURS)                 .100
  AVERAGE APPROACH SPEED TO THE OVERLAY ZONE (MPH)                         60.0
  AVERAGE SPEED THROUGH OVERLAY ZONE IN O.D. (MPH)                         40.0
  AVERAGE SPEED THROUGH OVERLAY ZONE IN N.O.D. (MPH)                       55.0
  TRAFFIC MODEL USED IN THE ANALYSIS                                          3

  FIRST YEAR COST OF ROUTINE MAINTENANCE (DOLLARS/LANE MILE)              50.00
  INCREMENTAL INCREASE IN MAINT. COST PER YEAR (DOLLARS/LANE MILE)        20.00
  COST OF A SEAL COAT (DOLLARS/LANE MILE)                               1500.00
  WIDTH OF EACH LANE (FEET)                                               12.00
  MINIMUM OVERLAY THICKNESS (INCHES)                                         .5
  ACCUMULATED MAXIMUM DEPTH OF ALL OVERLAYS (INCHES)                         8.0
```

Fig 5. Input data for the example problem.

Table 1 shows the total number of inputs involved, broken down for ten selected subdivisions, while Table 2 gives a more detailed breakdown. Appendix A shows a complete computer printout of these inputs for an example problem. The total number of inputs is determined by the number of materials considered. For example, Table 1 shows that if three materials ($n = 3$) are considered, then FPS-3 requires 62 numerical inputs to be supplied. The increase in inputs, as a function of the number of layer materials specified, is shown in Fig 6.

Many of the inputs shown in Tables 1 and 2 are self-explanatory but others may require some brief discussion. The following listing and explanations are for this purpose.

1. <u>Program controls</u> are required to control the operation of the program.
2. <u>Unit costs</u> are the economic inputs required for the computation of the costs of each pavement design.
3. <u>Material properties</u> define the characteristics of each material.
4. <u>Environmental factor</u> is a district temperature constant which is based on the mean temperature of the area where the pavement is to be constructed and is used in the prediction of the behavior of each pavement design.
5. <u>Serviceability index values</u> are used to predict the life of an initial design or an overlay by determining the serviceability level of the pavement after initial construction and after overlay construction and the minimum value of serviceability that will be allowed during the analysis period.
6. <u>Seal coat schedule</u> variables describe the restraints imposed on seal coats by the designer and are used in the determination of a seal coat schedule for each pavement design.
7. <u>Constraints</u> are variables that are often implicit in a design problem but must be explicitly stated in FPS. They are important in controlling the design and management scheme which is produced by the program, and they are also vital controlling factors in keeping the computer run time for a given problem within reasonable limits.
8. <u>Traffic demand inputs</u> describe the expected traffic which the pavement must serve during its lifetime.
9. <u>Traffic control inputs</u> are used in the computation of users' costs by determining how traffic will be handled during overlay construction. The traffic models are shown in Figs 1 through 5 of Appendix B.
10. <u>Miscellaneous parameters</u> are variables which don't fit in any other group, as shown in Table 2.

TABLE 1. SUMMARY OF PROGRAM INPUTS, FPS-3

Type of Input		Number of Inputs*
Program control		n + 3
Unit cost		2n + 4
Material property		n + 4
Environment		1
Serviceability index		3
Seal coat schedule		2
Constraint		2n + 6
Traffic demand		6
Traffic control		13
Miscellaneous		2
	TOTAL	6n + 44

* n is the number of materials considered for use above the foundation. This does not imply that the optimum solution will use all of these. This is the maximum, and the optimum may consist of only one or two layers, depending upon the relative costs, etc., involved.

TABLE 2. PROGRAM INPUTS, FPS-3

(1) Program controls

- (a) Number of materials considered for use above subgrade
- (b) Layer assignment of each material
- (c) Length of analysis period (years)
- (d) Number of output pages desired (8 designs/page)

(2) Unit costs

- (a) Interest rate or time value of money (percent)
- (b) In-place cost of each material above subgrade (dollars/compacted CY)
- (c) Salvage value of each material above subgrade (percent of construction cost)
- (d) First year cost of routine maintenance (dollars/lane-mile)
- (e) Annual increase in cost of routine maintenance (dollars/lane-mile/year)
- (f) Seal coat cost (dollars/lane-mile)

(3) Material properties

- (a) Strength coefficient of each material, including foundation
- (b) Asphaltic concrete compacted density (tons/CY)
- (c) Swelling clay parameter, P_2'
- (d) Swelling clay parameter, b_1

(4) Environmental factor (district temperature constant)

(5) Serviceability index values

- (a) Initial
- (b) After overlay
- (c) Minimum allowable

(6) Seal coat schedule

- (a) Time to first seal coat after initial or overlay construction (years)
- (b) Time between seal coats (years)

(7) Constraints

- (a) On initial construction
  1. Maximum allowable cost (dollars/SY)
  2. Minimum compacted thickness of each material (inches)
  3. Maximum compacted thickness of each material (inches)
  4. Maximum compacted total thickness (inches)
- (b) On overlay construction
  1. Minimum thickness of a single overlay (inches)
  2. Maximum accumulated thickness of all overlays (inches)
  3. Minimum time to first overlay (years)
  4. Minimum time between overlays (years)

(continued)

TABLE 2. (Continued)

(8) Traffic demand inputs
    (a) Project location (rural or urban)
    (b) One direction ADT
        1. At beginning of analysis period
        2. At end of analysis period
    (c) One direction equivalent number of 18-kip axles at end of analysis period
    (d) Percent of ADT arriving each hour of construction
    (e) Average approach speed to the overlay zone (mph)

(9) Traffic control inputs
    (a) Traffic model used in analysis
    (b) Overlay construction time (hours/day)
    (c) Number of open lanes
        1. In overlay direction
        2. In non-overlay direction
    (d) Center-line distance (miles) over which traffic is slowed while traveling
        1. In overlay direction
        2. In non-overlay direction
    (e) Detour distance (miles around overlay zone) in overlay direction
    (f) Percent of vehicles stopped by construction equipment while traveling
        1. In overlay direction
        2. In non-overlay direction
    (g) Average time (hours) a vehicle is stopped by construction equipment when traveling
        1. In overlay direction
        2. In non-overlay direction
    (h) Average speed (mph) through restricted zone
        1. In overlay direction
        2. In non-overlay direction

(10) Miscellaneous parameters
    (a) Asphaltic concrete production rate (tons/hour)
    (b) Lane width (feet)

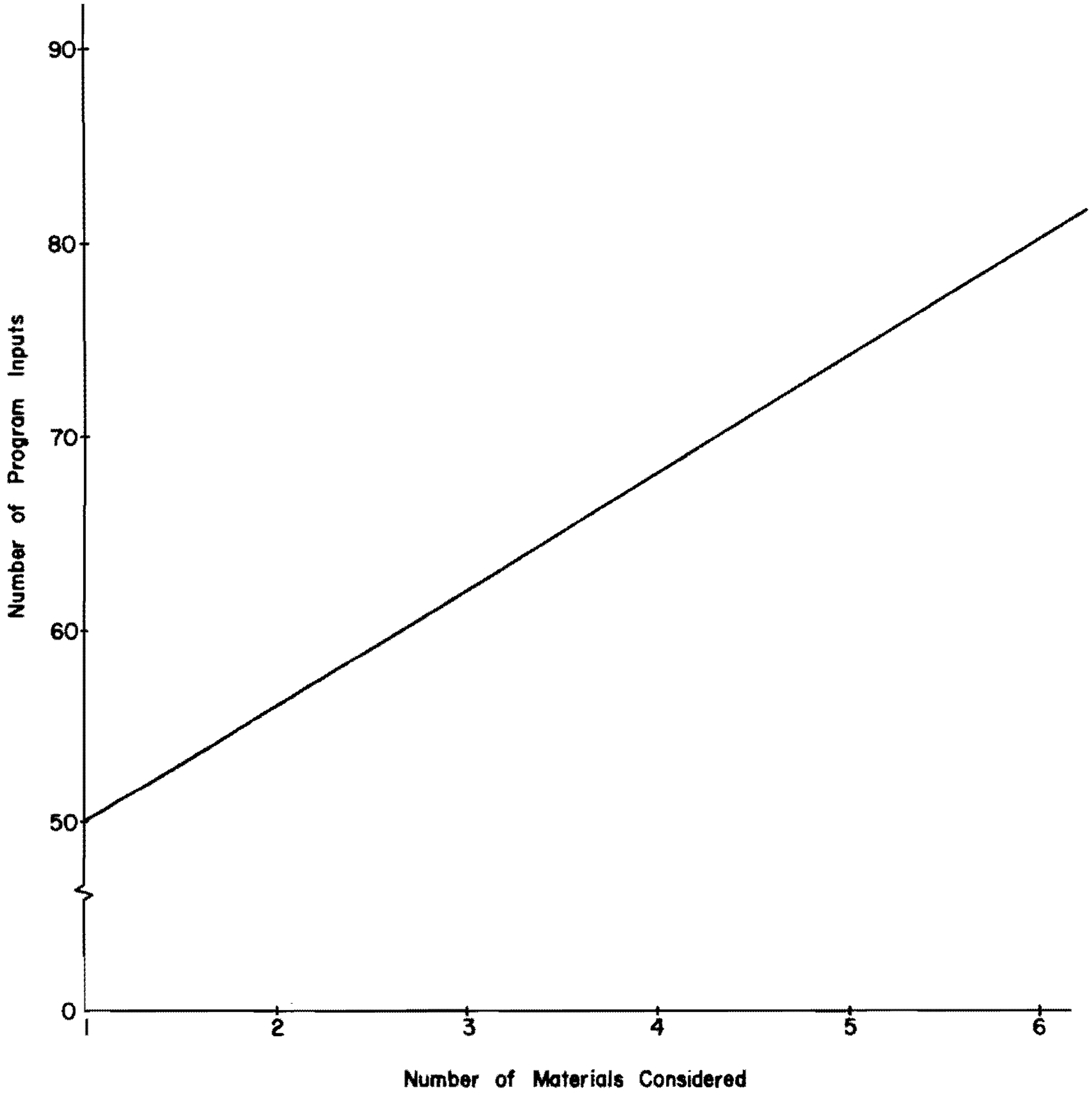


Fig 6. Program inputs as a function of number of materials considered, FPS-3.

General Description of FPS

In order to understand FPS, it is necessary to know generally how the data are handled. Figure 7, a summary flow chart of FPS, can be used as a guide to illustrate the mechanics of the computer program.

First the input data are read and printed out. All possible designs are computed and each design is then individually considered.

Based on the cost per square yard per inch calculated for each material from the input cost per cubic yard, the initial design cost is calculated. If the cost exceeds the maximum funds available for the initial design, this design is not feasible and consideration goes to the next design.

If the cost restriction is met, the design thickness is compared with the input value for the maximum allowable thickness of the initial construction. If the design thickness is greater, this design is not feasible and consideration goes to the next design.

The expected life of the initial design construction is calculated using the serviceability indices and swelling clay parameters and anticipated traffic. If the design life is less than the specified minimum time to the first overlay, this design is discarded and consideration is passed to the next design.

The optimal overlay policy is selected for that design. If the overlay policy lasts the entire analysis period, this design is a feasible design and the total cost is calculated. The program then considers the next design and continues until all possible designs are either discarded or designated as feasible designs.

The feasible designs are sorted by total cost and a set of optimal designs are printed in order of increasing total cost as shown in the sample output (Fig 4 and Appendix A).

Mathematical Models

Physical Models. Physical models are used to simulate what will happen in the real world of a pavement throughout the analysis period. In order to do this, three kinds of mathematical models are used.

(1) Traffic models predict the amount, type, and distribution of traffic and consist of a traffic equation which predicts the amount of traffic which will have passed at any time, an equivalency equation which relates traffic volume and weight distribution to equivalent

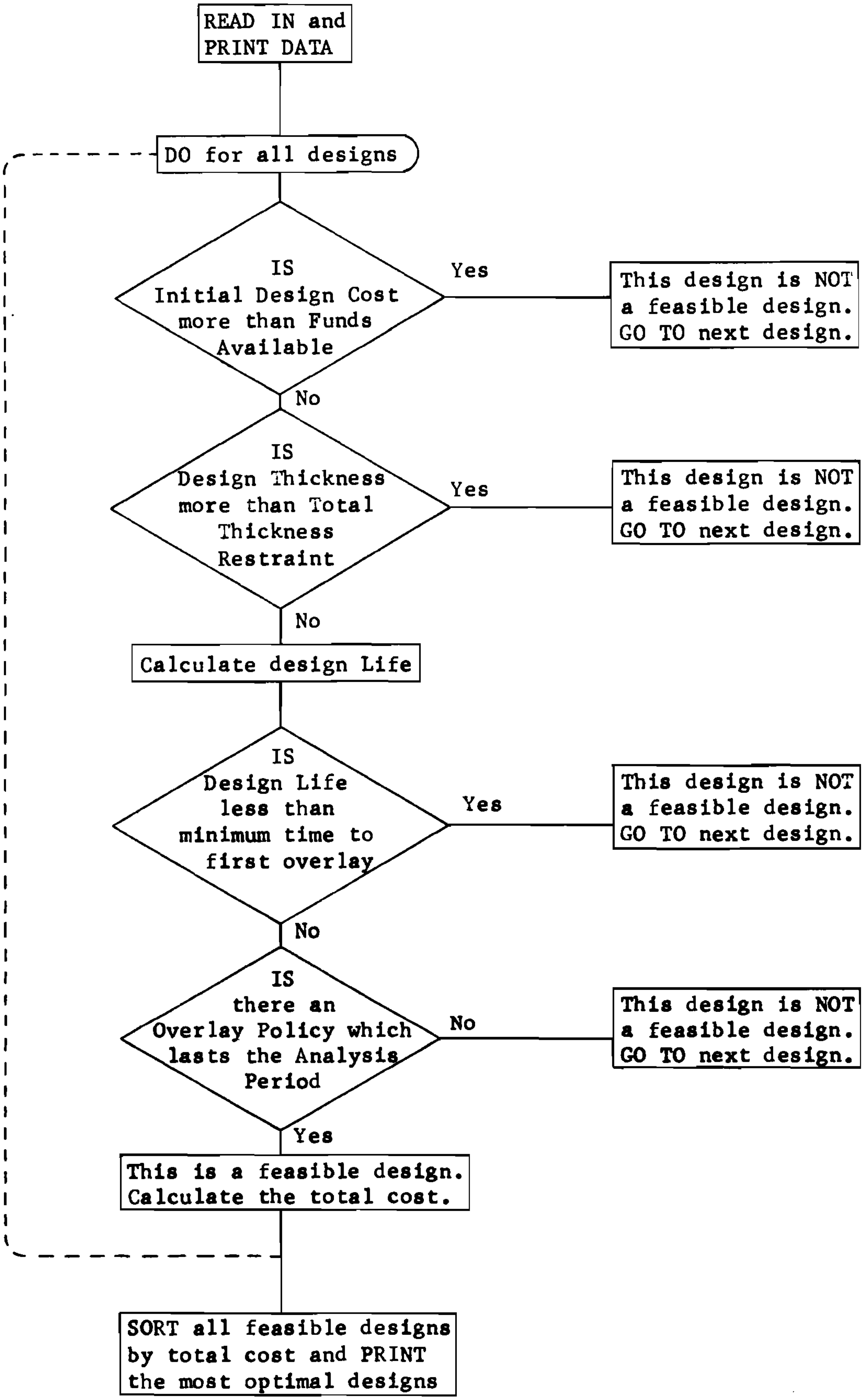


Fig 7. Summary flow chart illustrating mechanics of the FPS Program.

18-kip (18,000 pounds) single axles, and a set of traffic handling models for use in overlay construction.

(2) Environmental models predict the environmental conditions and include an ambient temperature model, an in situ stiffness coefficients model, a regional factor model, and a swelling clay model.

(3) Performance models predict the behavior of the pavement based on the Present Serviceability Index (PSI) concept developed in the AASHO Road Test and include a pavement strength model which may be based on either a SCI (Surface Curvature Index) model (Ref 10) or structural number and soil support models (Ref 4).

Economic Models. Economic models are used to determine the total cost of a design as well as a breakdown of that cost. All costs are converted to present value at appropriate interest rates which are supplied by the user. The present value represents the amount of money which would, if invested at the present time, generate adequate funds to accomplish the design scheme as specified. There are seven types of economic models used in FPS. These are (1) an initial construction cost model, which determines the cost of the initial construction based on the cost per compacted cubic yard of each material used; (2) a seal coat cost model, which determines when a seal coat is needed and how much it will cost; (3) an overlay construction cost model, which together with a physical model determines when and how much to overlay as well as the cost; (4) a routine maintenance model, which predicts the cost of routine maintenance based on the overlay and seal coat schedules; (5) a users' cost model, which determines the cost to the users due to traffic delays because of overlay construction; (6) a salvage value model, which determines the value of the pavement remaining at the end of the analysis period; and (7) a total overall cost model, which relates all costs during the analysis period to their present value at the beginning of the period.

Optimization Models. Two optimization models are used in FPS to determine a set of optimal designs, based on overall cost. The two models used in FPS-3 are

(1) A modified branch and bound technique systematically determines which initial construction designs will lead to a set of optimal designs. The criterion used in this technique is a relationship between strength and cost. Stated in simple terms, it is that if a design is more expensive and at the same time has less strength than some other design then it cannot produce a better design and is therefore discarded.

(2) In the determination of the optimal overlay policy for each initial design it was found that the best technique is to look at all possible policies.

Interaction Models. An interaction model is an algorithm which defines the interactions between two or more other models. For example, in finding the life of initial and overlay construction designs, a time must be determined which will satisfy both the performance and traffic models. Because of the complexity of these models, it is necessary to use an iterative technique.

Example Problem

An example design problem is used here to clarify the FPS programs. A general description of the problem is given verbally. The exact input values used in the analysis are shown in Fig 5 and in Appendix A.

> A highway on the Interstate system is to be constructed through a rural area. It will carry high-speed traffic and must be maintained at a high level of serviceability, i.e., above 3.0, throughout the analysis period (20 years). Due to construction difficulties, it is anticipated that the serviceability index after an overlay construction will be lower than the initial construction serviceability index. Gravel and crushed limestone are readily available at moderate costs near the construction site, and dynaflect tests on these materials shows average strength coefficients. The district has fairly hot weather with an average temperature in the low 60's. The highway passes through an area of moderate to heavy swelling clay which has caused a great deal of deterioration on adjacent roads in past years. The Accumulated Daily Traffic (ADT) on this section of roadway is expected to be fairly high with an average yearly growth rate of 2.5 percent, low volumes of trucks, and heavy axles. Availability of construction funds is not a limiting restriction.

The complete computer output for this example problem, using FPS-3, consists of a listing of all input parameters used in the solution and a summary of the 24 optimal designs (Appendix A). The first eight designs are also given in Fig 4.

In this example all 24 designs are either two or three layer designs with either two or three overlays during the analysis period. One-layer design was considered by the computer, but was apparently more expensive than either two or three-layer designs in all cases. These 24 designs vary in total cost from $2.80 to $2.92 per square yard.

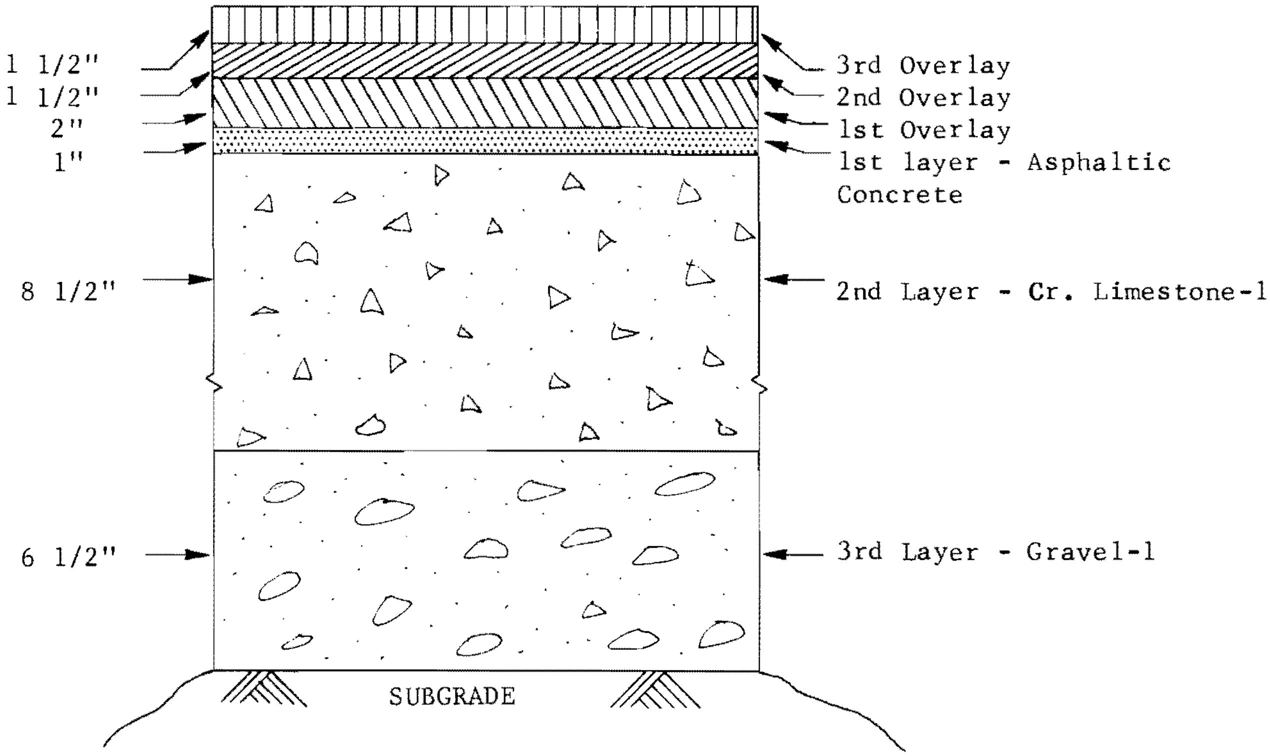


Fig 8. Cross-section of design number 1, including overlays.

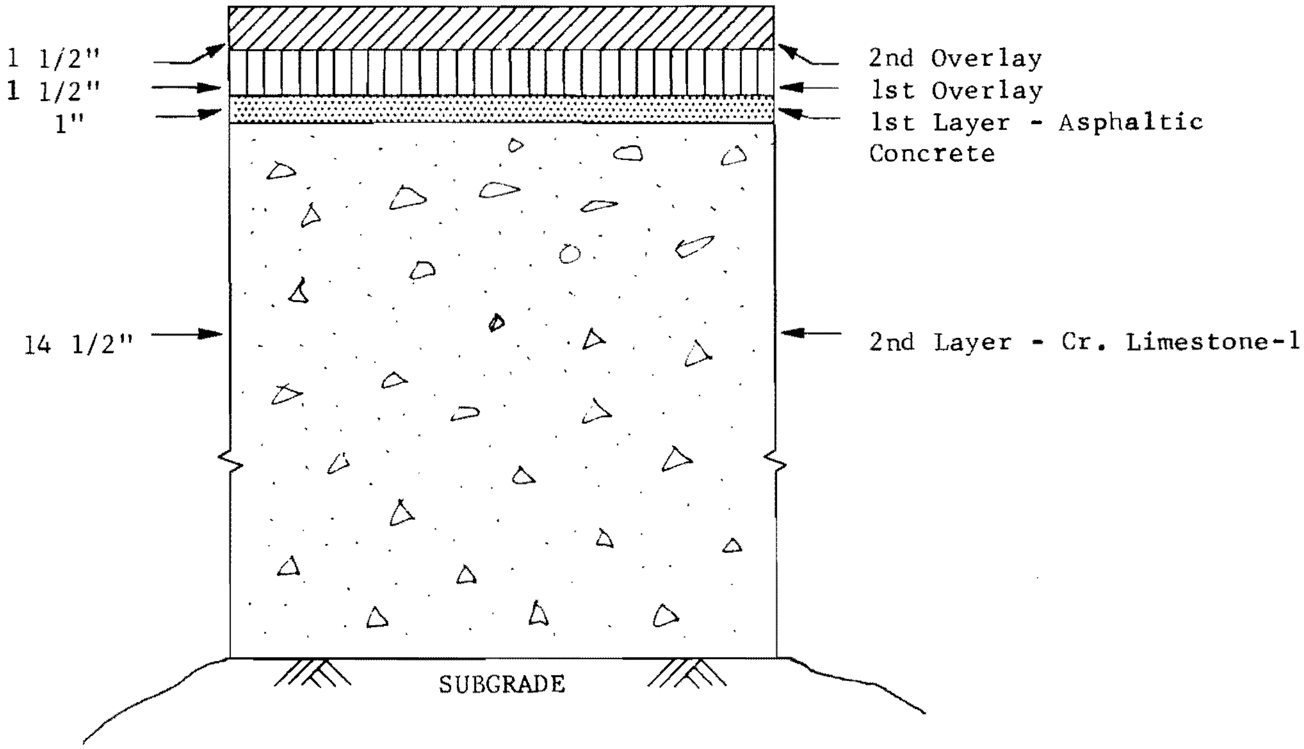


Fig 9. Cross-section of design number 7, including overlays.

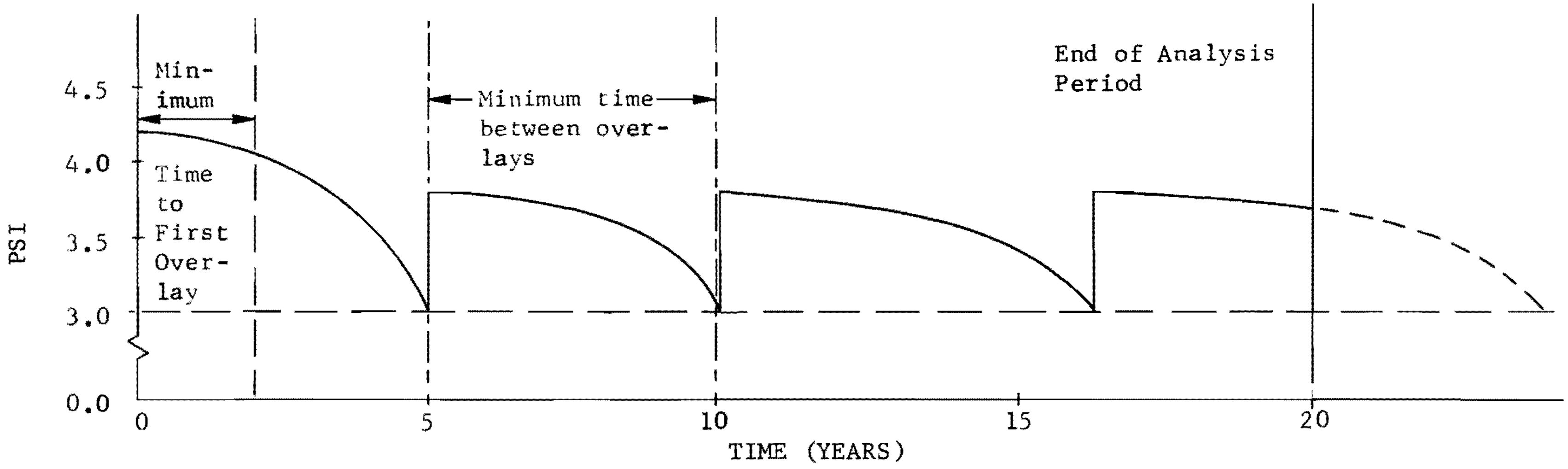


Fig 10. Serviceability history of design number 1.

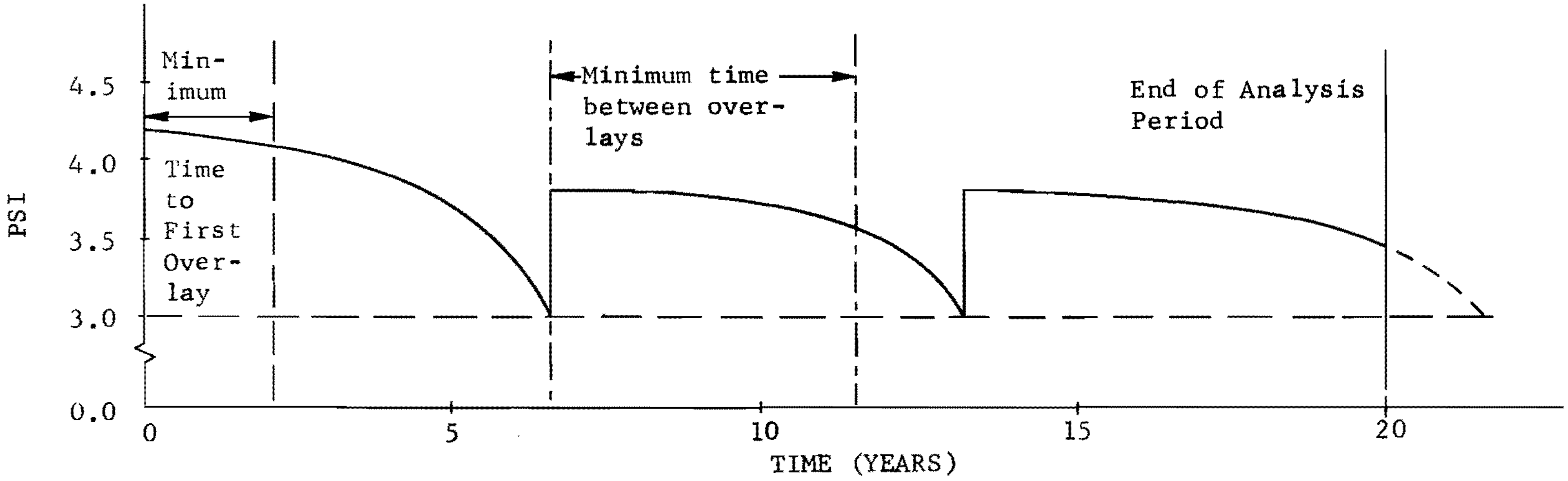


Fig 11. Serviceability history of design number 7.

To illustrate the choice available to the design engineer, design number 1 (the most optimal design) and design number 7 (the seventh most optimal design) have been selected for detailed discussion.

Figures 8 and 9 show a cross section of the pavement at the end of the analysis period of designs number 1 and 7, respectively. As can be seen, design number 1 is a three-layer design with three overlays, and design number 7 is a two-layer design with two overlays.

To show the contrast in the performance of these two possible pavement designs, Figs 10 and 11 show the predicted serviceability history of the two designs. From these figures, it can be noted that the minimum time to the first overlay was not a limiting factor, but that the minimum time between overlays was just met in the case of design number 1, and may have been a limiting factor.

Figure 4, the cost breakdown of the two designs, shows that design number 1 required less money on initial construction, seal coats, and routine maintenance, but had higher overlay construction and users' costs. The net result of this was a $.03 per square yard cheaper design.

CHAPTER 5. COMPOSITION OF THE PAVEMENT DESIGN SYSTEM

The pavement design system used in this report consists of a number of subsystems, each of which is instrumental in the design operation. Thus far, the concentration has been on the working systems models and the computer program or software to make them operate. This has been deliberate, because the first objective of the project has been to determine whether or not such useful working models could be developed. Having illustrated this feasibility, it is now desirable to set the perspective for the total system and the other subsystems. The major components of the total system, software, hardware, organization, information, and research management subsystems, are discussed in this chapter.

Software Subsystem (Computer Programs)

The software subsystem of the pavement design system is those computer programs which are utilized to analyze a particular design problem and to generate the feasible design alternates. The particular software systems or working systems models used thus far in this report have been called FPS-3 and are described in Chapter 4. A user's manual for this program has been developed by the Texas Highway Department portion of the project staff (Ref 15). The manual provides detailed information on all phases of the program. The realistic nature of this type of development indicates that a series of software subsystems will be generated, each in some way an improvement over the others. Chapter 6 discusses this aspect of the project in some detail.

Hardware

Hardware subsystems required for the implementation of the pavement design system are the Dynaflect for determining material properties and a computer for use with the software subsystem. For ultimate production use, user personnel, such as district highway personnel, will require knowledge of the operation of the Dynaflect (Ref 15). However, the only requirement for the success of the system is that someone make appropriate Dynaflect readings. Details of operation will be worked out at a later date.

Presently, computer hardware to handle the FPS programs is available at the Texas Highway Department Division of Automation, The University of Texas at Austin, and Texas A&M University. In routine operation, the THD will handle solutions at the Automation Division, with necessary data input from several sources.

Organization Subsystem

The proposed organization of the Texas Highway Department Pavement Design System may ultimately involve all 25 districts and the Houston Urban Project. Austin divisions in it will probably include Planning Survey, Materials and Tests, Finance, Maintenance Operations, Automation, and Highway Design. On the District level, the organization could include the Resident Engineer, District Pavement Design Function, District Laboratory, District Maintenance, and District Administration. Ideally, the pavement design system could function through a Pavement Design Section in the Highway Design Division which would be familiar with the design operations of each of the Texas Highway Districts.

In view of the Texas Highway Department's decentralized organization, it is not the intent of this document to establish any hierarchy in the manpower organization of the Pavement Design System. However, the information flow diagrams to be presented later do indicate one possible manpower organization.

To be feasible, the Texas Highway Department Pavement Design System must have the flexibility to allow revisions as technology advances. Ideally the Pavement Design System manpower requirement would include the capabilities of the researchers conducting Project 123, tied to the design system through the Highway Design Division.

The recommended pavement design system is based on the current Texas Highway Department organization, with all current pavement design functions a part of the system. The design system organization also includes numerous functions which do not exist in the Texas Highway Department at this time.

Information Subsystem

The information flow required to operate the pavement design system consists of research information, design information, and feedback data. These three components, described separately, are combined to form a proposed information flow diagram for the pavement design system.

Research Information. In the pavement design system, research information will be obtained primarily from the Texas Highway Department Cooperative Research Program and from research programs outside the Texas Highway Department such as the National Cooperative Highway Research Program (NCHRP) and the California Highway Department's research program. They will provide information in those cases where research results are applicable and usable. Figure 12 illustrates the flow of research information from other research groups and the THD research program to Project 123, which then incorporates usable information into the working model of the pavement design system. The working system is implemented through the Highway Design Research Section (D-8R) of the Texas Highway Department. The training of departmental personnel in both operational and technical aspects of the working system models is expected to be a major effort required in this implementation effort. The writing of user's manuals, as mentioned previously, is a more specific example of the effort required in this step. From this point, the research information having been implemented by D-8R becomes design information and will be passed on as such. It is anticipated that Project 123 will point out needed research. These ideas in the form of research problem statements will be transmitted back to the Texas Highway Department research program, as indicated on Fig 12.

Design Information. The application of the design computer programs (software) requires design information. The design information flow in the design system is illustrated in Fig 13, which shows a district pavement design function. The district pavement design office has the working design system available and receives design input from the divisions. The Automation Division Data Storage System could provide historical data from previous projects, and the Materials and Tests Division could provide results for tests that could be performed only in the central headquarters laboratory. Planning Survey Division already provides traffic volume data, and the District Maintenance Office provides input such as cost data. The District Laboratory could provide test results and other material availability information that might be

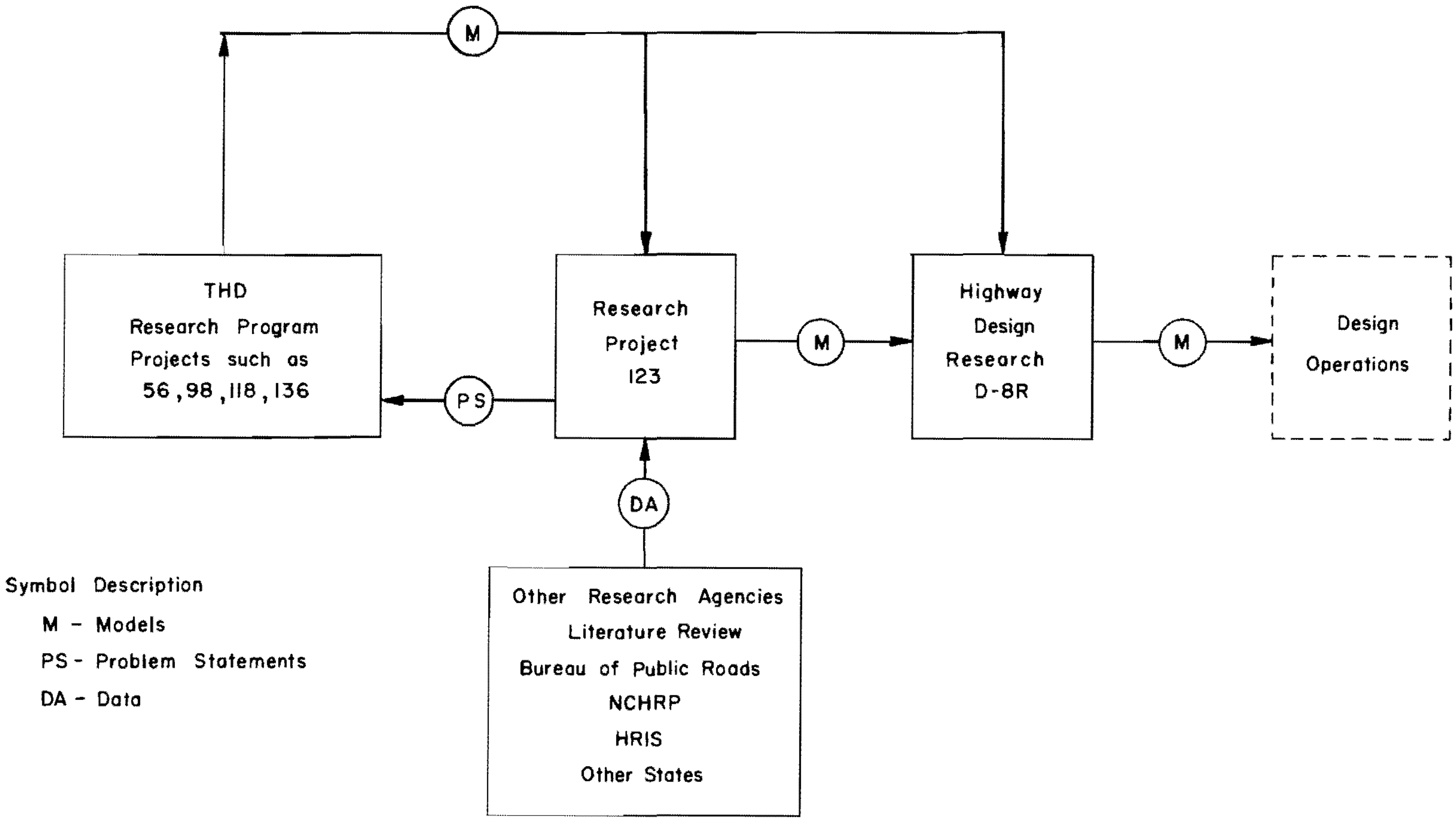


Fig 12. Research information flow component of the information subsystem.

Symbol Description

M - Models
I - Input
CI - Coded Input
A - Feasible Design Alternates
D - Selected Design
PSE - Plans, Specifications, & Estimates

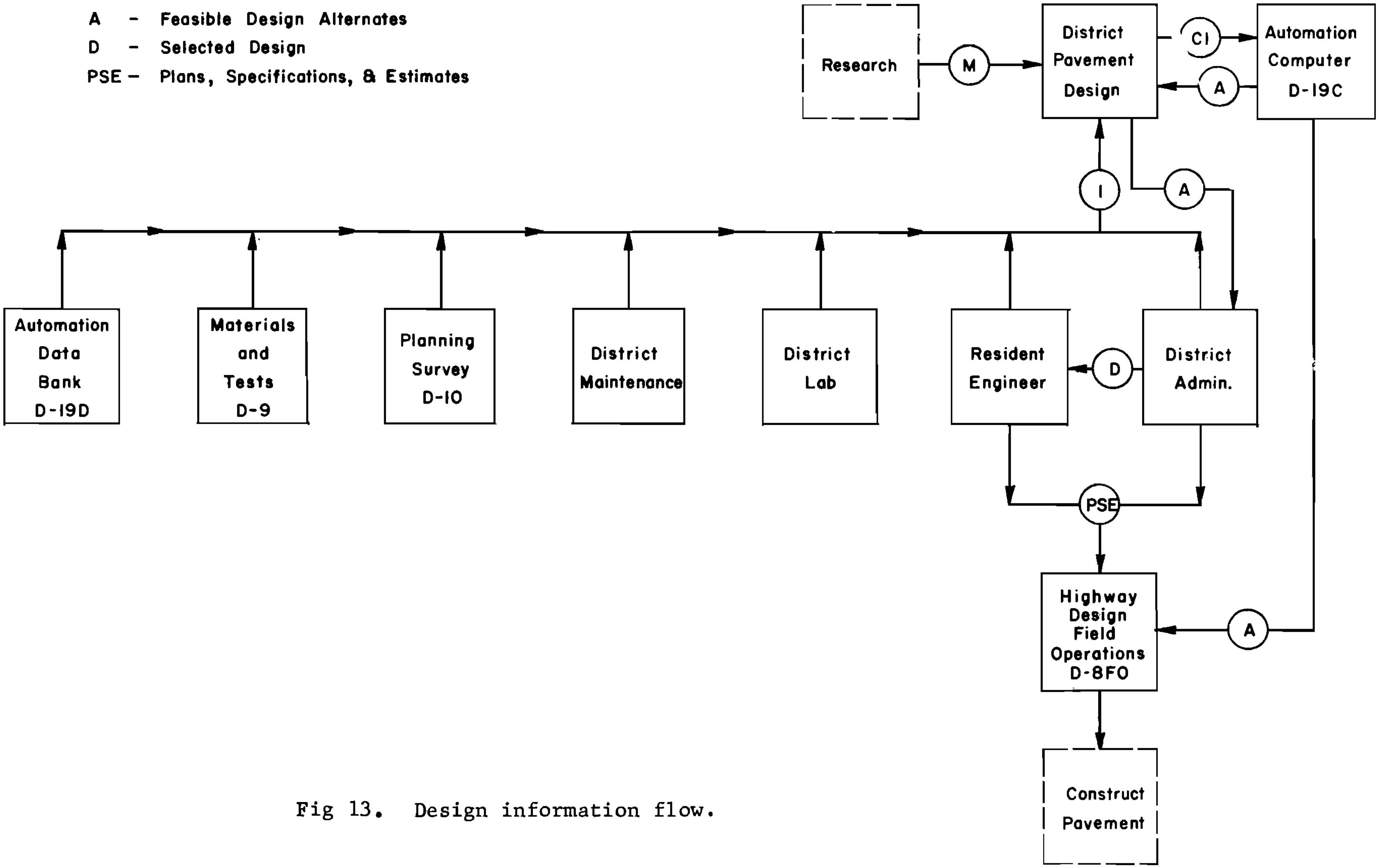
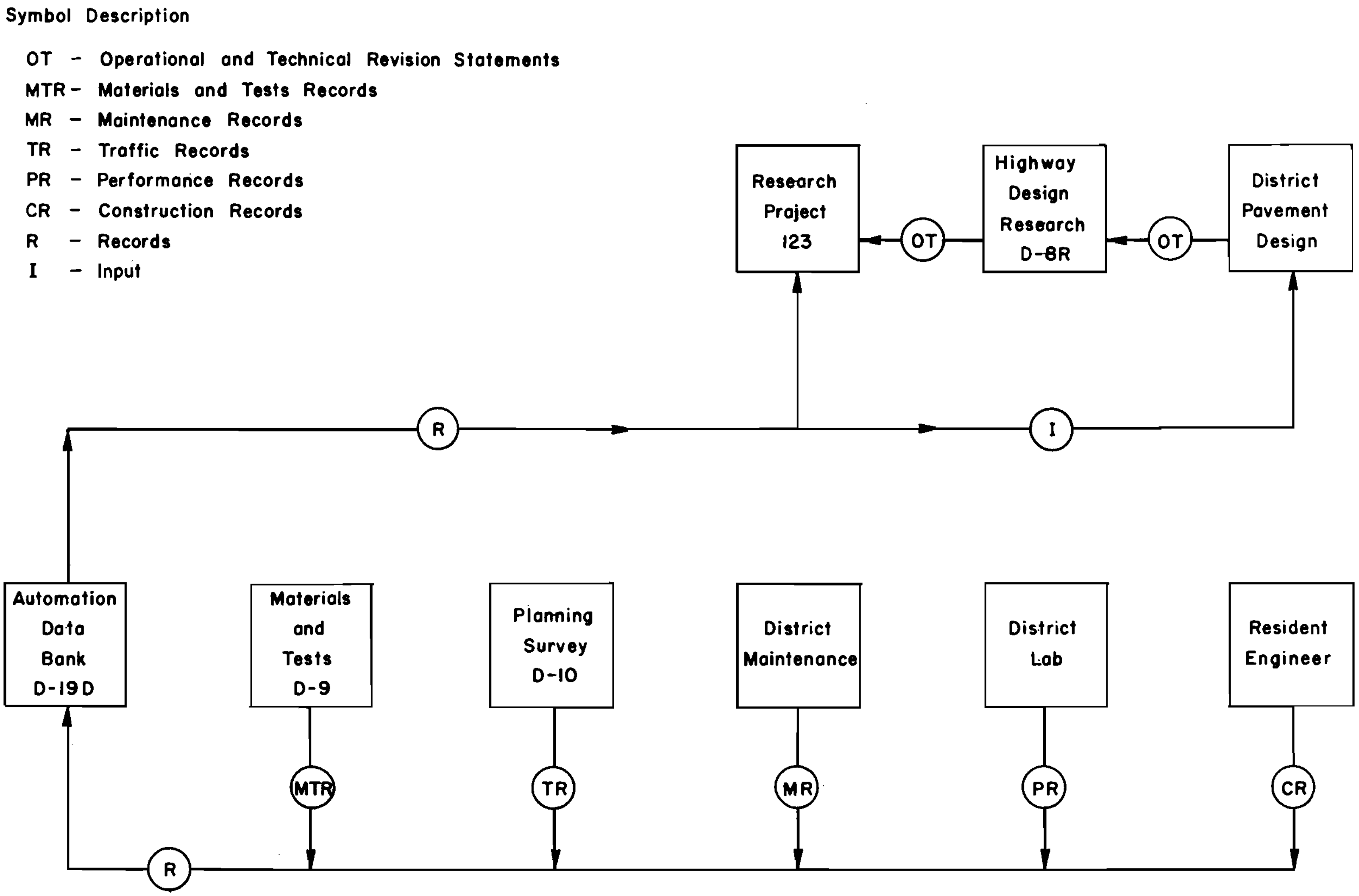


Fig 13. Design information flow.

necessary. The resident engineer and the District Administration could also provide input for the pavement design. After receiving the necessary inputs the district pavement design function would code the input and transmit it to the Automation Division Computer, which, using the working design system software (computer program), would generate the feasible design alternates and transmit them to the district pavement design function with a copy to the Highway Design Field Operations (D-8FO). The feasible design alternates would then be presented to the district administration for selection of the design. The resident engineer (or plan preparation function) would then incorporate the selected design into plans, specifications, and estimates (PSE), which are transmitted to D-8FO, the current practice. After reviewing the plans, D-8FO transmits the PSE to the Bureau of Public Roads for approval and subsequent contract for construction. At this point, the design information flow ends, and the cycle of information flow can be completed with the proposed feedback loop.

Feedback Information. The feedback loop consists of the records kept and transmitted to a central data system and subsequently to Project 123. In Fig 14 the entire proposed feedback is illustrated. The feedback loop provides sound documentation for evaluating and upgrading the pavement design system and also serves as a source of input information for design. The resident engineer would provide construction records; the district laboratory, performance records; the district maintenance office, maintenance records; the Planning Survey Division, traffic records; and the Materials and Tests Division, materials test records. All these data could be received by the Automation Division Data Bank (D-19D) which in turn would provide the records to Project 123 for evaluation of the system. These records in the Data Bank could also be called upon by the district pavement design function (Fig 13) for design input. Another item of feedback is the operational technical revision statements, which the district pavement design function might furnish Project 123 through D-8R (Fig 14). The operational and technical revision statement would contain suggestions for revision of the system based on use by a District.

The only portion of the information flow currently in use is that of research information, which is identical with current THD practice. The current pavement design functions have been utilized to prepare the design information component of the information system. Those parts of the design information component which are not currently in use are merely proposed here, not


Symbol Description

OT - Operational and Technical Revision Statements
MTR - Materials and Tests Records
MR - Maintenance Records
TR - Traffic Records
PR - Performance Records
CR - Construction Records
R - Records
I - Input

Fig 14. Feedback information flow.

recommended or specified, since they do involve manpower requirements. The entire concept of feedback is new in the context used here. The information flow for the feedback is simply a possible solution that is not researched or practiced at the present time.

To make the information flow complete, Figs 12, 13, and 14 are combined to form the information flow for the Texas Highway Department Pavement Design System. The flow of information as shown in Fig 15 is in a general clockwise direction starting with the research information.

Summary

Each of the described subsystems is essential for proper functioning of the Pavement Design System. Several of these subsystems currently exist within the Texas Highway Department, but coordination of the activities will be required as illustrated by the feedback information flow system summarized in Fig 14. The need for the feedback information loop or data cannot be over-emphasized since it is used to reevaluate and supply design information for the pavement design system.

Another important factor is the role of Project 123 to coordinate and formulate research findings into a format for implementation. Unfortunately, in the past this transition between research findings and implementation has not been provided, for a variety of reasons. Now, for the THD to obtain full benefit of research being conducted, this transition is a necessity, and organizational and information flow frameworks such as described in this chapter are a prime prerequisite.

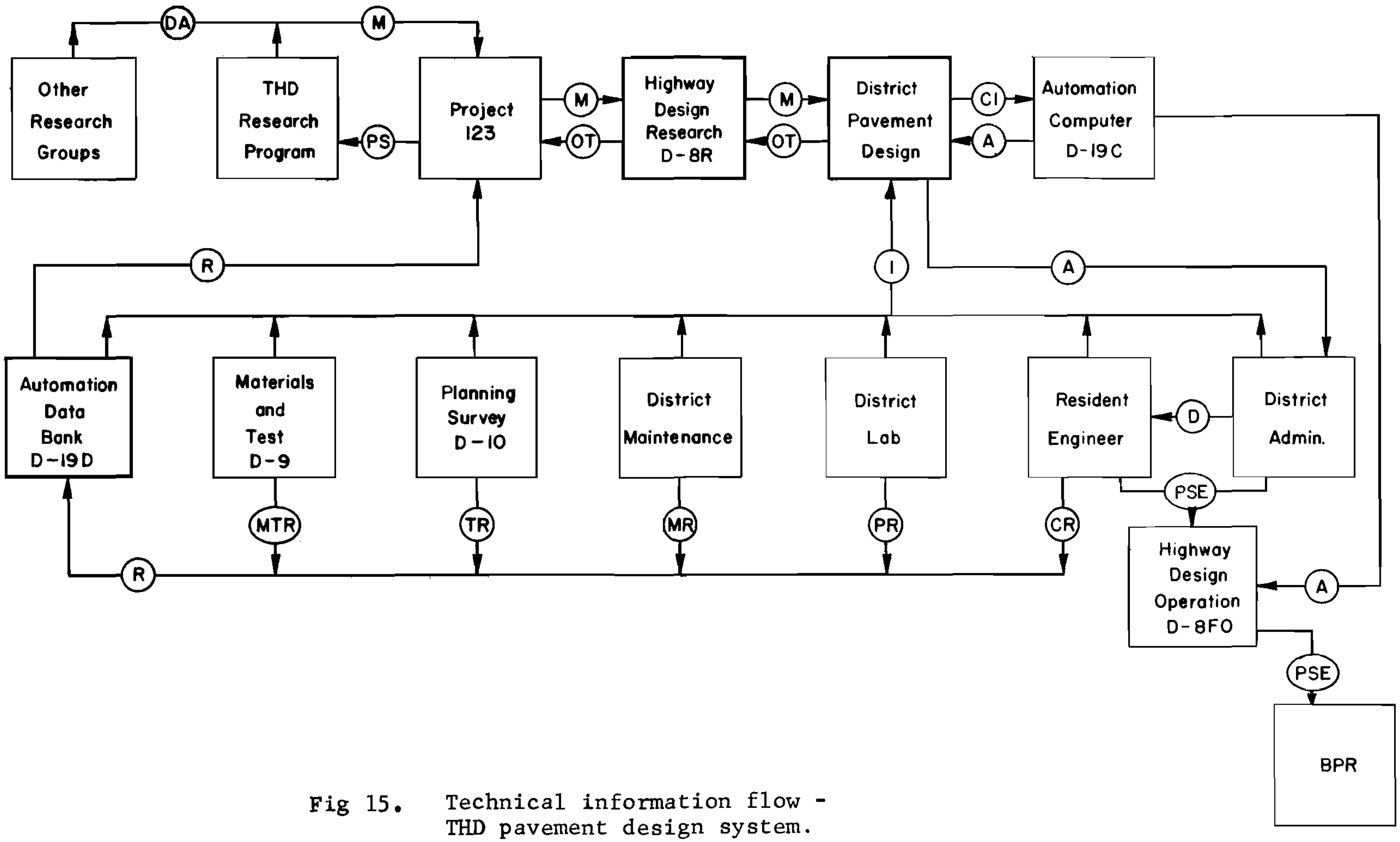


Fig 15. Technical information flow - THD pavement design system.

CHAPTER 6. IMPLEMENTATION OF THE PAVEMENT DESIGN SYSTEM

The ultimate value of research is its implementation into the daily operations of the Highway Department. The objective of this chapter is to recommend guidelines for infusing the pavement design system into the organizational operations in the easiest way. Although the objectives of Project 123 are to develop a complete pavement design system, at the present time only the Flexible Pavement System has progressed to a point where implementation is feasible. Therefore, this report pertains primarily to the immediate application of the Flexible Pavement System, but the concepts are also applicable to a rigid pavement system as it develops. It is felt that the approach described here will provide the following:

(1) a sound engineering documentation of pavement design and a method for evaluating its performance,

(2) a pattern of uniform procedures that gives a designer the best information from which to select the optimum pavement structure,

(3) a rational computer-oriented design procedure that allows the Highway Design Division to function in a consulting capacity with the districts,

(4) an immediate application of the best pavement design system that can be developed from the current state-of-the-art, and

(5) in connection with point 1, documentation for submission of pavement structure designs to the Bureau of Public Roads.

The ultimate objective of the project is to develop a complete design system that encompasses all the parameters and variables in the conceptual system (Fig 1). To attain this will require time and effort. If the Texas Highway Department waits until the complete system is developed at some distant future time, then the payoff of the research investment will be postponed until that future time. Furthermore, its full achievement is not possible without applied usage since the feedback loop discussed in Chapter 5 (Fig 14) is necessary for ascertaining if the system simulates the real design problem adequately. Only through a step function of continual improvement can the ideal system be developed. The implementation of the procedures is discussed here in the context of continual improvement.

As explained previously, the pavement design system consists of several subsystems such as software, information, hardware, research management, and organization. The organizational subsystem must provide the manpower and framework for operating the software and hardware systems. In order for the pavement design system to operate, it is necessary that each of the subsystems be implemented, since a breakdown in any one of these subsystems may impair implementation of the whole system. In this chapter, a possible method for implementing each of the subsystems, except organization, is discussed. Organization is discussed in Chapter 5.

Implementation of Software

At the present time, the staff of Project 123 has developed three related computer programs that may be used for pavement design. These have been designated as IG, the AASHO Interim Guides, FPS-IG, the Flexible Pavement System with the Interim Guides, and FPS-D, the Flexible Pavement System Using a Deflection Procedure. A recommended sequential application is presented in Fig 16. The authors feel this sequence will provide for continual improvement of the design system and will be most compatible with the operational activities of the Texas Highway Department. In Fig 16 the dash lines represent improvement which will be made as the project progresses. Each of the three computer programs is discussed in terms of its specific improvement with reference to the advantages of its position in the sequential application.

IG - Interim Guides. The IG program is a limited system that covers only the top part of the ideal system as shown in Fig 1. The decision criteria represented in the lower part of the figure, are not considered. Basically, this step consists of programming the AASHO Interim Guides for Flexible Pavements along with the improvements recommended in the NCHRP 1-11 Final Report (Ref 16).

At the present time, the Highway Design Division periodically uses the Interim Guides to document pavement structure submissions to the Bureau of Public Roads. The procedure is not smooth: the Planning Survey Division must furnish traffic data to the Automation Division for conversion to a total equivalent wheel load application; the equivalent wheel load data are returned to the Planning Survey Division and subsequently are submitted to the Highway Design Division, where the plan reviewer uses the guides to develop the

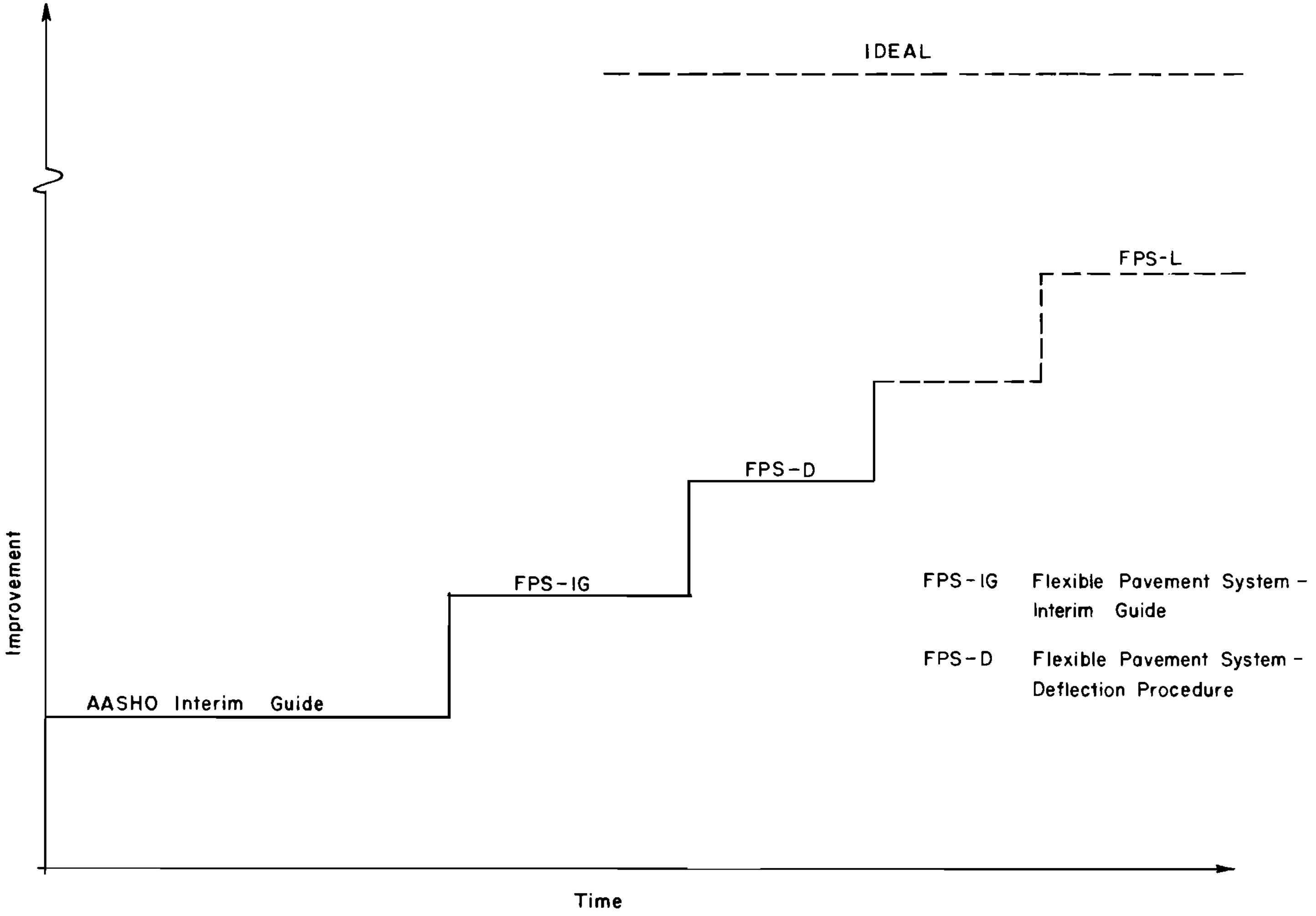


Fig 16. Sequential schedule for implementing software in Texas Highway Department.

required design documentation. With the computer program, all the input information required will be submitted directly to the computer, and the design will be obtained in one computational step. Thus, calendar time may be saved through reduction of correspondence, and either plan review time will be reduced or more design conditions may be examined for the same number of manhours. Furthermore, the computer-based solutions will eliminate some of the errors inherent in the simplified hand computation procedures presently used. For more detailed information as to the nature of these errors, see Ref 16.

There are several advantages in applying the Interim Guides program as the initial step in addition to the improvements discussed above. First, this step can be implemented with a minimum of effort or organizational change, since only the Automation Division is directly involved, and no change in laboratory test procedures by the Texas Highway Department is required. Another inherent advantage is that the step gives the designer an opportunity to confidently make a transition through a computer-oriented design procedure, since he may personally check the results by using the nomograph from the Design Guide.

FPS-IG - Flexible Pavement System with the Interim Guides. Some of the major details of this program are described in Appendix B, but basically it is the combination of the Interim Guides program with the decision criteria from FPS (Fig 1). Thus, the designer is achieving an improved analysis procedure which also provides a basis for a more realistic and comprehensive design decision. In addition to the improvements, this sequential step provides the designer with an opportunity to evaluate the effect of additional factors, since he will be adding to the experience previously acquired with the Interim Guides program described above. The application of this program will not require any change in the current test procedures, but considerably more input data will be required, such as unit costs, seal coat schedule, constraints, and traffic control inputs (Table 2).

FPS-D - Flexible Pavement System Using a Deflection Procedure. The details of this program and its development are described in Chapter 4. It has been checked against various pavements in Texas (Ref 9). The basic difference between this program and the FPS-IG is that the performance model in FPS-IG is based on a structural number concept. The improvement represented in applying this program is that the structural layer coefficient for the materials is based on as-built field measurements rather than laboratory tests of materials that may or may not be representative of the as-constructed condition. Thus, construction variables are considered with more accuracy. Through the use of the FPS-IG program, the designer will achieve a knowledge of the effect of the additional system variables, and in this step will be developing an understanding of the deflection-based coefficient and adding it to previous experience.

Implementation of the Information System

The application of the software systems necessitates the implementation of an information system such as that in Fig 13 in order to provide the necessary input information. In Table 3 the information required for the Interim Guides program is listed with the source of this information relative to the subdivisions of the Texas Highway Department, i.e., District or Division. Only the Highway Design Division, the District, and the Planning Survey Division are directly involved in this program. Table 4 gives the information sources for the two flexible pavement system programs. For these programs, the information sources involved are the district, the Highway Design Division, the Planning Survey Division, and the Maintenance Division. In both tables the District and the Highway Design Division are occasionally checked as information sources where Texas Highway Department policy decisions are involved. To make this information system operational, the necessary communication lines must be established between the appropriate Texas Highway Department subdivisions.

Implementation of Hardware

The development of information for the software system will require certain specialized equipment. Table 5 summarizes the equipment needs for each of the implementation steps. The Interim Guides program should be placed on line by the Automation Division for production use. The triaxial equipment is the same as equipment presently being used by the Department. The application of the FPS-IG program will not require any additional equipment, but utilization of the roughness measuring equipment developed in Project 73 (Ref 17) is recommended to supply the designer with better information on initial

TABLE 3. INFORMATION SOURCES FOR APPLYING INTERIM GUIDES

VARIABLE	Highway Design	District	Planning Survey	Maintenance
Initial Serviceability Index	x	x		
Terminal Serviceability Index	x	x		
Regional Factor	x	x		
Texas Triaxial Class		x		
Lane Distribution Factor		x		
Direction Distribution Factor		x	x	
Annual Growth Rate of Traffic			x	
Length of Analysis Period	x	x		
Load Groups			x	
Number of Axle Applications of Group			x	
Layer Coefficients		x		

TABLE 4. INFORMATION SOURCES FOR APPLYING FLEXIBLE PAVEMENT SYSTEM

	Highway Design	District	Planning Survey	Maintenance
Material cost/cubic yards		x		
Material strength coefficient		x		
Material minimum depth	x	x		
Material maximum depth	x	x		
Material salvage percentage		x		
Number material input types		x		
Maximum funds available/square yards	x	x		
Length analysis period	x	x		
Interest rate	x	x		
Asphalt concrete production rate		x		
Asphalt concrete compacted density		x		
Maximum allowable thickness	x	x		
District temperature constant		x		
Serviceability index, initial		x		
Serviceability index, after overlay		x		
Minimum serviceability index	x	x		
Swelling clay parameters		x		
One-direction ADT (Beginning)			x	
One-direction ADT (End)			x	
One-direction accumulated 18-kip axles			x	
Minimum time to first overlay		x		
Minimum time between overlays		x		
Time to first seal coat		x		
Time between seal coats		x		
Open lanes in restricted zone in the overlay direction (O.D.)		x		
Open lanes in restricted zone in the non-overlay direction (N.O.D.)		x		
Center line distance traffic slowed (O.D.)		x		
Center line distance traffic slowed (N.O.D.)		x		
Proportion ADT arriving/hour		x		
Overlay construction time		x		
Proportion vehicles stopped (O.D.)		x		
Proportion vehicles stopped (N.O.D.)		x		
Average time stopped (O.D.)		x		
Average time stopped (N.O.D.)		x		
Average approach speed to overlay zone		x		
Average speed through overlay zone (O.D.)		x		
Average speed through overlay zone (N.O.D.)		x		
Traffic Model		x		
First year maintenance cost		x		x
Increment increase in maintenance cost		x		x
Cost of seal coat		x		
Width of each lane		x		
Minimum overlay thickness	x	x		
Accumulated maximum depth of all overlays	x	x		

TABLE 5. EQUIPMENT REQUIRED IN IMPLEMENTING PAVEMENT DESIGN SYSTEM

AASHO Interim Guides	FPS Interim Guides	FPS Deflection Based
Triaxial equipment	Triaxial equipment	Computer
Computer	Computer	Profilometer
	Profilometer	Dynaflect

serviceability after construction and terminal serviceabilities prior to overlays. The application of the FPS-D program will require extensive use of the Dynaflect to measure the material stiffness coefficients, and, therefore, arrangements to assign the Dynaflect (Ref 15) will be required.

Schedule of Implementation

Basically, the schedule for the pavement design system implementation is determined by the software implementation since the hardware (equipment) is currently available and the information system can be developed only as the need arises. It is felt that the two basic factors, extent of application and timing, should be considered in the scheduling.

Extent. Primarily the Interim Guides program would be used by the Highway Design Division to document designs submitted to the Bureau of Public Roads. Therefore, it could be implemented simultaneously in all Districts with a minimum of conflict since the procedures are presently being utilized on a hand computation basis. In contrast the FPS systems should be introduced on a more gradual basis as time and personnel allow, involving only a few Districts at a time, primarily those showing a greater interest. As the interest in the system develops, its use could be increased appropriately. This gradual approach would provide time to firm up the procedures and also allow for immediate modifications of the system based on feedback from the initial applications.

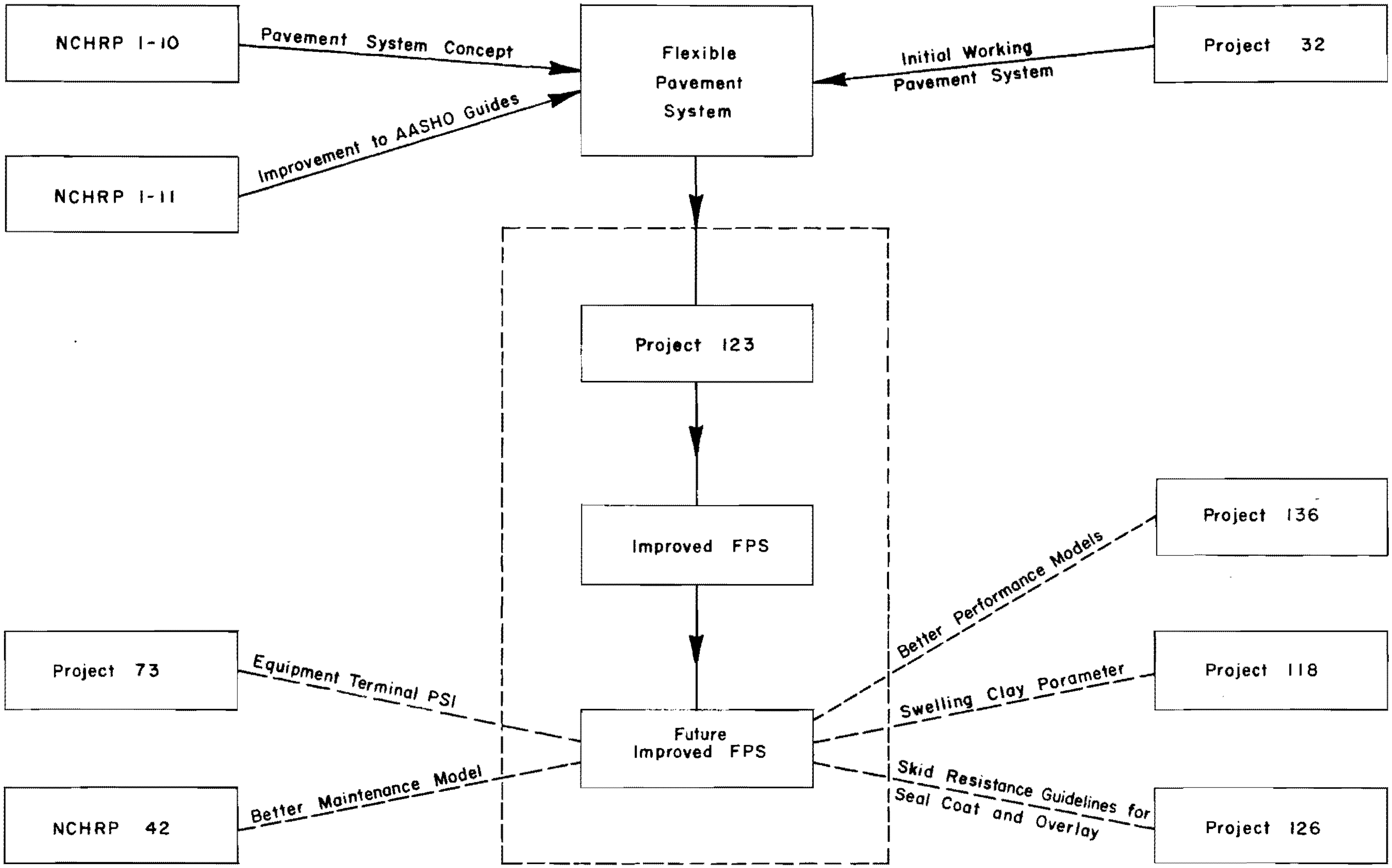


Fig 17. Past and future implementation of research management by Project 123.

Time. The Interim Guides program has been prepared and checked out and could be utilized immediately by the Department. The FPS programs are ready and could be implemented on a limited basis within several months and extensively when confidence is obtained with the system.

Implementation of Research Management Phase

Figure 17 illustrates the implementation of research findings from other departmental projects and national research projects. Project 32 and NCHRP Project 1-10 provided the pavement systems concepts and the initial working pavement system. The recommendations from NCHRP Project 1-11 provided improvements for the FPS-IG system and the Interim Guides program. Since its early start, the Flexible Pavement System program has been considerably improved. These improvements are represented by solid lines in Fig 17, and improvements which are expected from other research projects in the near future are represented by the dashed lines. For example, it is felt that Project 118, "Study of Expansive Clays in Roadway Structural Systems," will supply better information for quantifying the swelling clay parameter and Project 126, "A Laboratory and Field Evaluation of the Polishing Characteristics of Texas Aggregates," will provide skid resistance guidelines for seal coats and overlays. Project 73, "A System for High Speed Measurement of Pavement Roughness," has developed roughness measuring equipment which may be used to quantify more precisely the initial and terminal serviceability indices of in-service pavements on the Texas Highway Department system. NCHRP Report 42 (Ref 18) will provide information for inserting a better maintenance model than that currently used in the FPS program. The use of FPS will also point out areas of needed research which must be added to the research program.

It can be seen from these examples how various research efforts supported by the Texas Highway Department and Bureau of Public Roads through HPR funds and NCHRP can be put to immediate effective use.

CHAPTER 7. EVALUATING THE UTILITY OF A SYSTEMS BASED DESIGN

The design system model and organization have been discussed in previous chapters. Attention was concentrated on the use of systems engineering concepts to achieve a working pavement design system for the Texas Highway Department. It is implied that this is feasible, but it is also necessary at this point to discuss the utility or value in applying the systems approach. Such evaluation involves two major questions:

(1) Will the working systems model as developed be more comprehensive and efficient than present design methodology?

(2) Can the approach be implemented within the administrative framework of the Texas Highway Department?

Evaluation Guidelines

In order to evaluate the utility of the approach, it is necessary to establish guidelines or criteria. The authors felt that the four factors, operationality, rationality, acceptability, and revisability, were excellent for comparison. If these factors are satisfied then the pavement design system concept is useful to the Texas Highway Department in its normal operations.

Operational Criterion. It was shown in Chapter 4 that a comprehensive working systems model was possible and one has been developed. The rationality of the model is discussed below. The organizational and equipment requirements for the system were discussed in Chapter 5. The necessary organization is not now present within the Highway Department, but the operational channels are and the required organization could be established within the present framework of the Department. The initial hardware items required by the systems design method are a computer and a Dynaflect. The Highway Department presently has both pieces of equipment. No additional major equipment would be required at the present time or in the immediate future. Another operational guideline is that the cost of utilizing the system must be within reason. The application of the pavement design system approach to the Texas Highway Department operations will require more computational and working man-hours than are presently used by the Department in pavement design. It is felt that these additional expenditures would represent an excellent investment. The cost of a pavement structure represents approximately 50 percent of the total construction and maintenance costs (Ref 20) but the amount of engineering man-hours being utilized in pavement design at the present time is not proportionate. This is no reflection on past practices because current techniques were not previously available to design personnel. The additional expenditures required to apply the systems design approach may realize considerable savings in construction and maintenance cost, and a better engineered project will be obtained. In summary, after considering the organization, equipment, and design cost, the application of the pavement design system meets the operational criteria.

Rationality. From a rational standpoint, the pavement design system considers a large number of the variables known to influence pavement design. It is not implied that all important variables are considered; however, the method certainly considers more variables than existing design techniques. Another question of rationality is whether or not the pavement design system simulates the performance of the in-place or real-world system. This is a question that can be answered only by time and by observing the performance of in-service pavements. The system does meet a limited test of reasonableness in that most of the mathematical models were developed from observations of real-world pavements and hence have a sound basis for prediction. Furthermore, the sensitivity analysis, which is discussed later in the chapter, indicated that the pavement design system is rational from a mathematical standpoint.

Acceptability. The third test is whether or not the pavement design system is acceptable to the personnel of the Texas Highway Department. Basically, this is a very difficult question and can be fully answered only after it is implemented within the system as described in Chapter 6. Certainly, if the tests of operationality and rationality are met, then acceptability is much more probable than if they are not met. Considering the user, the system has a much higher probability of acceptance if many of the procedures, tests, and equipment presently being utilized by the Department are encompassed in the design method. The pavement design system and sequential implementation procedure proposed in Chapter 6 utilize the present factors where possible and practical. In many cases, however, new factors must be initiated, since more variables are being considered, and hence must be evaluated. The methods of handling traffic, measuring soil shear strength, and so forth are exactly the same as the procedures currently being utilized.

Revisability. The fourth criterion is that the pavement design system must be capable of being revised on the basis of additional research findings. This system has been designed in such a manner that new concepts may be inserted in the procedures when they are developed. This capability was illustrated in the section on research management in Chapter 6.

In summary, the pavement design system meets the tests of operationality, rationality, acceptability, and revisability, and the implementation of the pavement design systems approach within the Texas Highway Department is feasible.

Sensitivity Analyses

In order to ascertain the rationality of the computer program and also to evaluate the relative effect of the numerous variables, a sensitivity analysis was performed on FPS programs. A similar study was performed on Interim Guides procedure in connection with NCHRP 1-11 and these results were used in this study. The sensitivity analysis was designed with the following objectives:

(1) to establish the "reasonableness" of the solutions under a wide range of input conditions,

(2) to establish the relative importance in cost sensitivity of the different variables involved in the system, and

(3) to assist the user in decisions concerning the amount of computation time needed.

Due to the complexity of the program, it was impossible to solve a full factorial of all 45 variables involved in the pavement design system. Such a solution is impossible from both the cost standpoint and the physical ability to solve all the problems required. (For three levels of each variable, over one million solutions would be required.) With this in mind, an experiment was selected which would isolate the effects of an individual variable by varying it while the rest were held constant. The experiment was designed by giving each variable a low, average, and high value. Three basic solutions were obtained, keeping all the variables at these three levels, and the variations were studied by changing one variable to each of its other two levels in turn while holding all other variables constant. For example, in the average case two problems were studied for every variable. These problems involved all variables held at the average level except the one under study, which was given its low and high values in turn for the two problems. Similarly, for the low level, each variable was studied at average and high levels in turn, with all other variables kept at low levels.

The results of the sensitivity analysis indicated that the FPS program provided reasonable solutions under a wide variety of input conditions. The results of the sensitivity analysis provided information for removing several abnormalities in the program and for preparation of a User's Manual. The analysis also shows, as would be expected, that the variables have differing degrees of importance. Based on the sensitivity analysis, the variables were placed in five groups, according to their effect on the cost of the optimum designs (Table 6). In this table variables found to have the greatest impact on cost were placed in Group I, those having the next greatest impact were placed in Group II, etc. (A more detailed presentation of this material will be given in a future report.) The rating gives the designer guidance as to which should be most carefully quantified for design and which would require the least consideration. In addition, these relative ratings give an indication of possible priorities for research needs or performance evaluation studies (e.g., those in Groups I and II may warrant top priority).

Operational Suitability

Operational suitability testing of the FPS computer program and the attendant hardware was begun during the spring and summer of 1969, when the first real design problem was undertaken. Personnel from the Texarkana Residency, the District Design office in Atlanta, and the Research Section of the Highway Design Division collaborated to develop the inputs and solve a complete design problem. The particular section of roadway chosen for design was an upgrading of U. S. 59 in District 19. Some considerations used in selecting this project included the following: (1) Principal Investigator James L. Brown was familiar with the particular strip of road, having participated in the original design and construction in 1959, (2) District 19

TABLE 6. RATING OF EFFECT OF VARIABLES AT THE AVERAGE LEVEL

			Group		
	I	II	III	IV	V
Material cost/cubic yards		x			
Material strength coefficient		x			
Material minimum depth				x	
Material maximum depth					x
Material salvage percentage			x		
Number output pages					x
Number input material types					x
Maximum funds available/square yards			x		
Length analysis period		x			
Interest rate				x	
Asphalt concrete production rate			x		
Asphalt concrete compacted density			x		
Maximum allowable thickness					x
District temperature constant			x		
Serviceability index, initial		x			
Serviceability index, after overlay		x			
Minimum serviceability index		x			
Swelling clay parameters		x			
One-direction ADT (Initial)	x				
One-direction ADT (End)				x	
One-direction accumulated 18-kip axles			x		
Minimum time to first overlay			x		
Minimum time between overlays				x	
Minimum time to first seal coat				x	
Minimum time between seal coats				x	
Number open lanes in restricted zone (O.D.)					x
Number open lanes in restricted zone (N.O.D.)					x
Center line distance traffic slowed (O.D.)				x	
Center line distance traffic slowed (N.O.D.)				x	
Proportion ADT arriving/hour			x		
Overlay construction time					x
Proportion vehicles stopped (O.D.)				x	
Proportion vehicles stopped (N.O.D.)				x	
Average time stopped (O.D.)				x	
Average time stopped (N.O.D.)				x	
Average approach speed to overlay zone			x		
Average speed through overlay zone (O.D.)				x	
Average speed through overlay zone (N.O.D.)			x		
Traffic model					x
First year maintenance cost				x	
Incremental increase in maintenance cost				x	
Cost of seal coat				x	
Width of each lane					x
Minimum overlay thickness					x
Accumulated maximum depth of all overlays					x

expressed the desire to participate, and (3) It was a chance to investigate the use of FPS in an evaluation job in an effort to reveal revisions needed to make it applicable to such a situation. It is apparent that for the pavement design there is generally little difference between the basic problem of upgrading an existing pavement as opposed to constructing one on a new location.

It is not desirable to review the development of design inputs for this problem in detail here. The problem is briefly defined, the inputs are developed, and the solutions are reviewed in another document (Ref 21).

In summary, the first attempt at application of the Flexible Pavement Design system to practice was considered successful. Several revisions to the computer program to make it more flexible were suggested. Additionally, this trial application led to the writing of "A Recommended Texas Highway Department Pavement Design System User's Manual" (Ref 15), which ties together the FPS program and attendant hardware and coding forms. It is believed that the system will be accepted by operating engineers as fast as they can be trained in its use.

System Flexibility

In order for the pavement design system to be feasible, it certainly must be flexible. The information flow, the computer programs, and the implementation procedure must all be subject to easy revision. The information flow chart has been changed several times prior to being presented herein. The FPS computer program which is based on a deflection-performance model was readily revisable when the Texas Transportation Institute developed it for Research Project 32. The first version of the FPS program did not include the important parameters for swelling or expansive soils.

Flexibility in Revision

Subsequent FPS programs have received many revisions, basically because they are flexible. Some of the technical changes made in the FPS computer program are

(1) the addition of several variables associated with initial construction cost,

(2) the addition of minimum overlay thickness,

(3) the addition of maximum accumulated thickness of all overlays,

(4) the addition of a provision to allow an interest rate equal to zero, and

(5) the exclusion of the one-year exemption period for seal cost costs.

A major modification was made in the original version of FPS when the AASHO Interim Design Guides for Flexible Pavement Structures equation (FPS-IG) was used instead of the deflection performance model developed by Scrivner (FPS-D).

Future revisions expected in FPS include the addition of an aggregate polishing criteria to require seal coats based on loss of skid resistance, as well as improved maintenance models.

Flexibility in Application

In addition to having flexibility for change, the FPS programs have wide applicability. The obvious application is to the analysis and design of new pavements which have previously been discussed. The second major use was illustrated by the analysis of an existing pavement for upgrading discussed earlier in this chapter. The Highway Department now has available a tool for realistic analysis of possible stage construction. A third important application of the program involves pavement maintenance management. Given an existing pavement, the FPS system can analyze an optimum maintenance policy to help conserve program maintenance funds and/or to help make the best possible use of any limited available funds. Ultimately the FPS can be applied to an entire pavement network to help administrators program available funds to optimize use of available pavement investments. Therefore, uses plus variations indicate the wide flexibility of FPS as a tool for highway engineers.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Conclusions

Many engineers feel that pavement design decisions should be based on a coordinated and systematic consideration of all the important variables, rather than being made in the piecemeal fashion of most past practice. This report presents a method for achieving this goal and considers its feasibility. The general conclusion, based on the past year's studies, is that systems engineering methodology is applicable to pavement design. Furthermore, a working systems model has been developed and presented in the report as proof of such feasibility. More specifically, this feasibility is demonstrated by the following:

(1) The computer programs developed (Chapter 4) realistically simulate pavement behavior. They currently consider 45 variables in generating an optimum design and the scope of the analysis can be increased to include more, if shown to be warranted by future studies.

(2) A field application of the FPS method in District 19 showed the approach to be operationally feasible (Chapter 7).

(3) A sensitivity analysis over a wide range of variables (Chapter 7) showed that the FPS program produces rational designs.

(4) FPS gives a more realistic analysis because it considers not only the initial design but also subsequent reevaluation and stage construction.

(5) The systems approach provides a framework for utilizing performance evaluation of in-service pavements as feedback for continually upgrading the design procedures (Chapters 5 and 6).

(6) The pavement design system also provides a framework for managing research, thereby utilizing available funds to their maximum (Chapter 6).

The pavement design system may appear to be more complex than past procedures but it allows the designer considerable flexibility and scope in exploring a wide variety of options. He is therefore more likely to obtain the best possible design. The importance of expending time and effort in achieving this is supported by the fact that about 50 cents of each current highway dollar goes into pavement construction and maintenance.

Another unique feature of this approach is that it considers the taxpayer in maintenance operations quantitatively for the first time. Preliminary analyses with FPS indicate user cost due to delays for maintenance operations is excessive on highways with high traffic volume, thus justifying heavier designs during initial construction or special traffic handling. In contrast, low traffic volume roads may require an entirely different design scheme, such as stage construction. The systems analysis does not take away any prerogative of the administrator and gives a wider range of possible satisfactory designs, ranked on the basis of total cost, for use in making design decisions.

In order for the pavement design system to function properly, the Texas Highway Department should provide an organizational structure similar to that described in Chapter 5. With such a framework, the pavement design system could be implemented rapidly and the Texas Highway Department could realize immediate benefits from research expenditures.

Recommendations

Based on the findings in the project thus far it is recommended that an appropriate implementation procedure be initiated by the Texas Highway Department in the near future to assist in putting FPS into practice. It is only through use of the system for design and construction that the necessary feedback information can be developed to complete the cycle and begin subsequent improvements. It is also recommended that Texas Highway Department engineers be encouraged to support the project with their time, effort, and facilities when called upon through the proper administrative procedures of the Highway Department.

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APPENDICES

APPENDIX A

INPUT AND OUTPUT FORMATS OF COMPUTER PROGRAM FPS-3

GUIDE FOR DATA INPUT FOR FPS-3

FPS3 GUIDE FOR DATA INPUT

IDENTIFICATION OF PROGRAM

NPROB	Description of problem
A5	Alphanumeric 16A4

1 5 10 74 80

PARAMETERS AND DESIGN VARIABLES

NMB	MATYPE	CMAX	CL	RATE	ACPR	ACCD	TCKMAX
I10	I10	F10.2	F10.2	F10.2	F10.2	F10.2	F10.2

1 10 20 30 40 50 60 70 80

NMB	Format design variable for summary table.
MATYPE	Number of material types or classes.
CMAX	Maximum dollars/sq yd available for construction.
CL	Length of analysis period (years).
RATE	Interest rate or time value of money (percent).
ACPR	Asphaltic concrete production rate (tons per hour).
ACCD	Asphaltic concrete compacted density (tons per compacted cubic yard).
TCKMAX	Maximum total thickness of initial construction (inches).

PERFORMANCE VARIABLES

ALPHA	PSI	P1	P2	P2P	BONE
F10.2	F10.2	F10.2	F10.2	F10.2	F10.4

1 10 20 30 40 50 60 80

ALPHA	District or regional temperature constant.
PSI	Serviceable index of the initial structure.
P1	Serviceability index after an overlay.
P2	Minimum allowed value of serviceability index.
P2P	The no-traffic lower bound on the serviceability index.
BONE	Swelling clay parameter.

TRAFFIC VARIABLES (One Card)

RO	RC	XNC
F10.0	F10.0	F10.0

1 10 20 30

RO	One-direction ADT at beginning of analysis period.
RC	One-direction ADT at end of analysis period.
XNC	One-direction accumulated traffic after CL years.

MINIMUM TIME VARIABLES AND NUMBER OF OPEN LANES IN RESTRICTED AREA (One Card)

XTTO	XTBO	TTSC	TBSC	NLRO	NLRN
F10.0	F10.0	F10.1	F10.1	110	110

1 10 20 30 40 50 60

XTTO	Minimum time to the first overlay (years).
XTBO	Minimum time between overlays (years).
TTSC	Time to the first seal coat (years).
TBSC	Time between seal coats (years).
NLRO	Number of open lanes in the overlay direction in the restricted zone.
NLRN	Number of open lanes in the non-overlay direction in the restricted zone.

VARIABLES FOR OVERLAY, ROUTINE MAINTENANCE AND SEAL COAT CONSIDERATIONS (One Card)

XLSO	XLSN	XLSD	PROP	HPD	ITYPE
F10.2	F10.2	F10.2	F10.2	F10.2	I 10

1 10 20 30 40 50 60

XLSO	Center line distance in the overlay direction over which traffic is slowed (miles).
XLSN	Center line distance in the non-overlay direction over which traffic is slowed (miles).
XLSD	Detoured distance around the overlay zone (input zero unless MODEL 5 is used).
PROP	Avg. percent of ADT passing through the overlay zone during each hour of overlay.
HPD	Average number of hours/day that overlay takes place.
ITYPE	Type of road consideration (input 1 for rural or 2 for urban road).

USER COST VARIABLES (One Card)

PPO2	PPN2	DDO2	DDN2	AAS	ASO	ASN	MODEL
F10.2	F10.2	F10.4	F10.4	F10.2	F10.2	F10.2	I 10

1 10 20 30 40 50 60 70 80

PPO2	Percent of vehicles stopped in overlay zone (overlay direction) due to equipment.
PPN2	Percent of vehicles stopped in overlay zone (non-overlay direction) due to equipment.
DDO2	Average delay/vehicle stopped in overlay zone (overlay direction) due to equipment (hours).
DDN2	Average delay/vehicle stopped in overlay zone (non-overlay direction) due to equipment (hours).
AAS	Average approach speed (miles per hour).
ASO	Average thru speed in overlay direction (miles per hour).
ASN	Average thru speed in non-overlay direction (miles per hour).
MODEL	Model number describing the traffic situation.

ROUTINE MAINTENANCE AND SEAL COAT COSTS (One Card)

CM1	CM2	SC	XLW	OVMIN	OVMAX
F10.2	F10.2	F10.2	F10.2	F10.2	F10.2

1 10 20 30 40 50 60

CM1	Cost per lane mile for routine maintenance during the first year after initial or overlay construction.
CM2	Annual incremental increase in cost per lane mine for routine maintenance.
SC	Cost per lane mile of a seal coat.
XLW	Width of each lane (feet).
OVMIN	Minimum thickness of an individual overlay (inches).
OVMAX	Accumulated maximum thickness of all overlays (inches).

NUMBER OF MATERIALS (One Card, MATYPE values)

NMBMAT(1)	NMBMAT(2)	NMBMAT(3)	NMBMAT(4)	NMBMAT(5)	NMBMAT(6)	NMBMAT(7)	NMBMAT(8)
I10	I10	I10	I10	I10	I10	I10	I10

1 10 20 30 40 50 60 70 80

NMBMAT(J)	Number of materials of type J that are available.

PARAMETERS OF THE MATERIALS (NMP cards)

MATERIAL	COST/C.Y.	ST. COEFF.	MIN. DEPTH	MAX. DEPTH	SALVAGE
6A3	F10.2	F10.2	F10.2	F10.2	F10.2

3 20 30 40 50 60 70

COST/C.Y.	In-place cost per compacted cubic yard.
ST. COEFF.	Strength coefficient.
MIN. DEPTH	Minimum thickness allowable in initial construction (inches).
MAX. DEPTH	Maximum thickness allowable in initial construction (inches).
SALVAGE	Salvage value percentage of the material.

LISTING OF INPUT DATA FOR EXAMPLE PROBLEM

IDENTIFICATION A SAMPLE PROBLEM CODED BY DLP DATE 23DEC69 PAGE 1 OF 1

```
   1                A SAMPLE PROBLEM
         3         3     5.00     20.00      5.00     75.00      1.80     36.00
    30.00      4.20      3.80      3.00      1.50      0.08
   12000.    18000.  2000000.
     2.00      5.00      5.00      3.00          1         2
     0.50      0.50      0.00      6.00     10.00          1
     2.00      0.00      0.10      0.10     60.00     40.00     55.00          3
    50.00     20.00   1500.00     12.00      0.50      8.00
         1         1         1
  ASPHALTIC CONCRETE    10.00      0.82      1.00     10.00     45.00
  CR. LIMESTONE-1        5.00      0.55      6.00     16.00     75.00
  GRAVEL-1               3.00      0.35      6.00     16.00    100.00
  SUBGRADE                         0.22
```

COMPUTED RESULTS FOR EXAMPLE PROBLEM

```
PROB     1                  A SAMPLE PROBLEM

        THE CONSTRUCTION MATERIALS UNDER CONSIDERATION ARE

   MATERIAL          COST/C.Y.  ST.COEF. MIN.DEPTH MAX.DEPTH SALV.PCT.
ASPHALTIC CONCRETE     10.00       .82      1.00     10.00     45.00
CR. LIMESTONE-1         5.00       .55      6.00     16.00     75.00
GRAVEL-1                3.00       .35      6.00     16.00    100.00
SUBGRADE                0.00       .22      0.00      0.00      0.00

  NUMBER OF OUTPUT PAGES DESIRED(8 DESIGNS/PAGE)                            3
  NUMBER OF INPUT MATERIAL TYPES                                            3
  MAX FUNDS AVAILABLE PER SQ.YD. FOR INITIAL DESIGN (DOLLARS)            5.00
  LENGTH OF THE ANALYSIS PERIOD (YEARS)                                  20.0
  INTEREST RATE OR TIME VALUE OF MONEY (PERCENT)                          5.0
  ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR)                         75.0
  ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/C.Y.)                       1.80
  MAXIMUM ALLOWED THICKNESS OF INITIAL CONSTRUCTION (INCHES)             36.0

  DISTRICT TEMPERATURE CONSTANT                                          30.0
  SERVICEABILITY INDEX OF THE INITIAL STRUCTURE                           4.2
  SERVICEABILITY INDEX P1 AFTER AN OVERLAY                                3.8
  MINIMUM SERVICEABILITY INDEX P2                                         3.0
  SWELLING CLAY PARAMETERS -- P2 PRIME                                   1.50
                             B1                                         .0800

  ONE-DIRECTION ADT AT BEGINNING OF ANALYSIS PERIOD (VEHICLES/DAY)      12000
  ONE-DIRECTION ADT AT END OF ANALYSIS PERIOD (VEHICLES/DAY)            18000
  ONE-DIRECTION  20-YR ACCUMULATED NO. OF EQUIVALENT 18-KIP AXLES     2000000

  MINIMUM TIME TO FIRST OVERLAY (YEARS)                                   2.0
  MINIMUM TIME BETWEEN OVERLAYS (YEARS)                                   5.0
  MIN TIME TO FIRST SEAL COAT AFTER OVERLAY OR INITIAL CONST.(YEARS)      5.0
  MINIMUM TIME BETWEEN SEAL COATS (YEARS)                                 3.0
  NUMBER OF OPEN LANES IN RESTRICTED ZONE IN O.D.                           1
  NUMBER OF OPEN LANES IN RESTRICTED ZONE IN N.O.D.                         2

  C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE O.D. (MILES)          .50
  C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE N.O.D. (MILES)        .50
  PROPORTION OF ADT ARRIVING EACH HOUR OF CONSTRUCTION (PERCENT)          6.0
  OVERLAY CONSTRUCTION TIME (HOURS/DAY)                                  10.0
  THE ROAD IS IN A RURAL AREA.

  PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN O.D. (PERCENT)      2.0
  PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN N.O.D. (PERCENT)    0.0
  AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN O.D. (HOURS)                 .100
  AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN N.O.D. (HOURS)               .100
  AVERAGE APPROACH SPEED TO THE OVERLAY ZONE (MPH)                       60.0
  AVERAGE SPEED THROUGH OVERLAY ZONE IN O.D. (MPH)                       40.0
  AVERAGE SPEED THROUGH OVERLAY ZONE IN N.O.D. (MPH)                     55.0
  TRAFFIC MODEL USED IN THE ANALYSIS                                        3

  FIRST YEAR COST OF ROUTINE MAINTENANCE (DOLLARS/LANE MILE)            50.00
  INCREMENTAL INCREASE IN MAINT. COST PER YEAR (DOLLARS/LANE MILE)      20.00
  COST OF A SEAL COAT (DOLLARS/LANE MILE)                             1500.00
  WIDTH OF EACH LANE (FEET)                                             12.00
  MINIMUM OVERLAY THICKNESS (INCHES)                                       .5
  ACCUMULATED MAXIMUM DEPTH OF ALL OVERLAYS (INCHES)                      8.0
```

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  PROB      1                  A SAMPLE PROBLEM

FOR THE 1 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

     MATERIAL          COST/C.Y.  ST.COEF. MIN.DEPTH MAX.DEPTH SALV.PCT.
ASPHALTIC CONCRETE      10.00        .82      1.00     10.00     45.00
SUBGRADE                 0.00        .22      0.00      0.00      0.00

 1   THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--
      FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE
             ASPHALTIC CONCRETE    8.50 INCHES

      THE SCI OF THE INITIAL STRUCTURE  =   .542
      THE LIFE OF THE INITIAL STRUCTURE =  4.75 YEARS
      THE OVERLAY SCHEDULE IS
              2.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER  4.75 YEARS.
              1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 10.30 YEARS.
              1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 17.33 YEARS.
             TOTAL LIFE =      26.04 YEARS

      SEAL COATS SHOULD OCCUR AFTER
             (1)   9.75 YEARS
             (2)  15.30 YEARS

      THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE
             INITIAL CONSTRUCTION COST            2.361
             TOTAL ROUTINE MAINTENANCE COST        .170
             TOTAL OVERLAY CONSTRUCTION COST       .982
             TOTAL USER COST DURING
                       OVERLAY CONSTRUCTION        .224
             TOTAL SEAL COAT COST                  .233
             SALVAGE VALUE                        -.518
             TOTAL OVERALL COST                   3.452


      NUMBER OF FEASIBLE SESIGNS EXAMINED FOR THIS SET --       8


        AT THE OPTIMAL SOLUTION,THE FOLLOWING
        BOUNDARY RESTRICTIONS ARE ACTIVE--
                   1. THE MINIMUM TIME BETWEEN OVERLAYS
```

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  PROB      1                  A SAMPLE PROBLEM

FOR THE 2 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

     MATERIAL         COST/C.Y.  ST.COEF. MIN.DEPTH MAX.DEPTH SALV.PCT.
ASPHALTIC CONCRETE      10.00       .82       1.00      10.00     45.00
CR. LIMESTONE-1          5.00       .55       6.00      16.00     75.00
SUBGRADE                 0.00       .22       0.00       0.00      0.00

 2   THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--
       FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE
              ASPHALTIC CONCRETE    1.00 INCHES
              CR. LIMESTONE-1      12.00 INCHES

       THE SCI OF THE INITIAL STRUCTURE  =   .516
       THE LIFE OF THE INITIAL STRUCTURE =  4.97 YEARS
       THE OVERLAY SCHEDULE IS
              2.00 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER  4.97 YEARS.
              1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 10.01 YEARS.
              1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 16.34 YEARS.
              TOTAL LIFE =      24.03 YEARS

       SEAL COATS SHOULD OCCUR AFTER
              (1)   9.97 YEARS
              (2)  15.01 YEARS

       THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE
              INITIAL CONSTRUCTION COST            1.944
              TOTAL ROUTINE MAINTENANCE COST        .166
              TOTAL OVERLAY CONSTRUCTION COST       .882
              TOTAL USER COST DURING
                        OVERLAY CONSTRUCTION        .203
              TOTAL SEAL COAT COST                  .233
              SALVAGE VALUE                        -.612
              TOTAL OVERALL COST                   2.816


       NUMBER OF FEASIBLE SESIGNS EXAMINED FOR THIS SET --       52


         AT THE OPTIMAL SOLUTION,THE FOLLOWING
         BOUNDARY RESTRICTIONS ARE ACTIVE--
                    1. THE MINIMUM DEPTH OF LAYER  1
                    2. THE MINIMUM TIME BETWEEN OVERLAYS
```

```
  PROB      1                  A SAMPLE PROBLEM

FOR THE 3 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

     MATERIAL           COST/C.Y.  ST.COEF. MIN.DEPTH MAX.DEPTH SALV.PCT.
ASPHALTIC CONCRETE        10.00        .82       1.00     10.00     45.00
CR. LIMESTONE-1            5.00        .55       6.00     16.00     75.00
GRAVEL-1                   3.00        .35       6.00     16.00    100.00
SUBGRADE                   0.00        .22       0.00      0.00      0.00

 3   THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--
      FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE
             ASPHALTIC CONCRETE    1.00 INCHES
             CR. LIMESTONE-1       8.50 INCHES
             GRAVEL-1              6.50 INCHES

      THE SCI OF THE INITIAL STRUCTURE  =   .521
      THE LIFE OF THE INITIAL STRUCTURE =  4.91 YEARS
      THE OVERLAY SCHEDULE IS
              2.00 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER  4.91 YEARS.
              1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER  9.95 YEARS.
              1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 16.20 YEARS.
             TOTAL LIFE =       23.81 YEARS

      SEAL COATS SHOULD OCCUR AFTER
             (1)   9.91 YEARS
             (2)  14.95 YEARS

      THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE
             INITIAL CONSTRUCTION COST             2.000
             TOTAL ROUTINE MAINTENANCE COST         .166
             TOTAL OVERLAY CONSTRUCTION COST        .882
             TOTAL USER COST DURING
                        OVERLAY CONSTRUCTION        .203
             TOTAL SEAL COAT COST                   .233
             SALVAGE VALUE                         -.679
             TOTAL OVERALL COST                    2.804


      NUMBER OF FEASIBLE SESIGNS EXAMINED FOR THIS SET --      145


        AT THE OPTIMAL SOLUTION,THE FOLLOWING
        BOUNDARY RESTRICTIONS ARE ACTIVE--
                   1. THE MINIMUM DEPTH OF LAYER  1
                   2. THE MINIMUM TIME BETWEEN OVERLAYS
```

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PROB      1                    A SAMPLE PROBLEM



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

       DESIGN NUMBER    TOTAL COST
             3             2.804
             2             2.816
             1             3.452

 ALL MATERIAL COMBINATIONS HAVE AT LEAST ONE FEASIBLE DESIGN.
```

```
 PROB      1                  A SAMPLE PROBLEM

                              SUMMARY OF THE MOST OPTIMAL DESIGNS
                               IN ORDER OF INCREASING TOTAL COST

                                 1       2       3       4       5       6       7       8
**************************************************************************************
DESIGN NUMBER                    3       3       2       3       3       2       2       3
INIT. CONST. COST              2.000   2.278   1.944   2.306   2.347   2.222   2.292   2.375
OVERLAY CONST. COST             .882    .543    .882    .532    .517    .543    .517    .517
USER COST                       .203    .125    .203    .123    .120    .125    .120    .121
SEAL COAT COST                  .233    .384    .233    .380    .374    .384    .374    .374
ROUTINE MAINT. COST             .166    .190    .166    .190    .192    .190    .192    .192
SALVAGE VALUE                  -.679   -.711   -.612   -.715   -.730   -.644   -.663   -.734
**************************************************************************************
**************************************************************************************
TOTAL COST                     2.804   2.810   2.816   2.816   2.821   2.821   2.832   2.845
**************************************************************************************
**************************************************************************************
NUMBER OF LAYERS                 3       3       2       3       3       2       2       3
**************************************************************************************
LAYER DEPTH (INCHES)
     D( 1)                      1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
     D( 2)                      8.5    10.5    12.0    11.0    11.0    14.0    14.5    11.5
     D( 3)                      6.5     6.5     0.0     6.0     6.5     0.0     0.0     6.0
**************************************************************************************
**************************************************************************************
NO.OF PERF.PERIODS               4       3       4       3       3       3       3       3
**************************************************************************************
PERF. TIME (YEARS)
     T( 1)                     4.906   6.250   4.969   6.406   6.531   6.281   6.563   6.656
     T( 2)                     9.945  12.383  10.008  12.773  13.094  12.453  13.164  13.453
     T( 3)                    16.195  20.039  16.336  20.703  21.336  20.148  21.445  21.969
     T( 4)                    23.812   0.000  24.031   0.000   0.000   0.000   0.000   0.000
**************************************************************************************
OVERLAY POLICY(INCH)
(EXCLUDING LEVEL-UP)
     O( 1)                      1.0      .5     1.0      .5      .5      .5      .5      .5
     O( 2)                       .5      .5      .5      .5      .5      .5      .5      .5
     O( 3)                       .5     0.0      .5     0.0     0.0     0.0     0.0     0.0
**************************************************************************************
NUMBER OF SEAL COATS             2       3       2       3       3       3       3       3
**************************************************************************************
SEAL COAT SCHEDULE
   (YEARS)
   SC( 1)                      9.906   5.000   9.969   5.000   5.000   5.000   5.000   5.000
   SC( 2)                     14.945  11.250  15.008  11.406  11.531  11.281  11.563  11.656
   SC( 3)                      0.000  17.383   0.000  17.773  18.094  17.453  18.164  18.453
**************************************************************************************
```

```
  PROB      1                A SAMPLE PROBLEM

                                    SUMMARY OF THE MOST OPTIMAL DESIGNS
                                     IN ORDER OF INCREASING TOTAL COST

                          9      10      11      12      13      14      15      16
******************************************************************************
DESIGN NUMBER             3      3       3       3       2       3       2       2
INIT. CONST. COST       2.417  2.208   1.931   2.556   2.361   2.236   2.153   1.875
OVERLAY CONST. COST      .507   .647    .991    .497    .507    .636    .647    .991
USER COST                .119   .147    .225    .118    .119    .145    .147    .225
SEAL COAT COST           .370   .384    .233    .286    .370    .380    .384    .233
ROUTINE MAINT. COST      .194   .190    .166    .198    .194    .190    .190    .166
SALVAGE VALUE           -.750  -.715   -.683   -.789   -.683   -.718   -.648   -.616
******************************************************************************
******************************************************************************
TOTAL COST              2.856  2.862   2.862   2.864   2.867   2.868   2.873   2.873
******************************************************************************
******************************************************************************
NUMBER OF LAYERS          3      3       3       3       2       3       2       2
******************************************************************************
LAYER DEPTH (INCHES)
     D( 1)              1.0    1.0     1.0     1.0     1.0     1.0     1.0     1.0
     D( 2)             11.5   10.0     8.0    12.5    15.0    10.5    13.5    11.5
     D( 3)              6.5    6.5     6.5     6.5     0.0     6.0     0.0     0.0
******************************************************************************
******************************************************************************
NO.OF PERF.PERIODS        3      3       4       3       3       3       3       4
******************************************************************************
PERF. TIME (YEARS)
     T( 1)              6.781  5.938   4.531   7.250   6.813   6.094   5.969   4.594
     T( 2)             13.773 12.266   9.727  15.023  13.844  12.617  12.297   9.828
     T( 3)             22.602 20.234  16.289  24.984  22.711  20.898  20.344  16.430
     T( 4)              0.000  0.000  24.336   0.000   0.000   0.000   0.000  24.555
******************************************************************************
OVERLAY POLICY(INCH)
(EXCLUDING LEVEL-UP)
     O( 1)               .5    1.0     1.5      .5      .5     1.0     1.0     1.5
     O( 2)               .5     .5      .5      .5      .5      .5      .5      .5
     O( 3)              0.0    0.0      .5     0.0     0.0     0.0     0.0      .5
******************************************************************************
NUMBER OF SEAL COATS      3      3       2       2       3       3       3       2
******************************************************************************
SEAL COAT SCHEDULE
   (YEARS)
   SC( 1)               5.000  5.000   9.531   5.000   5.000   5.000   5.000   9.594
   SC( 2)              11.781 10.938  14.727  12.250  11.812  11.094  10.969  14.828
   SC( 3)              18.773 17.266   0.000   0.000  18.844  17.617  17.297   0.000
******************************************************************************
```

```
  PROB      1                    A SAMPLE PROBLEM

                              SUMMARY OF THE MOST OPTIMAL DESIGNS
                               IN ORDER OF INCREASING TOTAL COST

                              17      18      19      20      21      22      23      24
*************************************************************************************
DESIGN NUMBER                  2       3       3       3       3       3       2       3
INIT. CONST. COST            2.500   1.958   2.444   2.583   2.486   2.139   2.431   2.514
OVERLAY CONST. COST           .497    .982    .507    .497    .507    .750    .507    .497
USER COST                     .118    .224    .119    .118    .120    .168    .120    .117
SEAL COAT COST                .286    .233    .370    .286    .370    .384    .370    .366
ROUTINE MAINT. COST           .198    .170    .194    .198    .194    .190    .194    .198
SALVAGE VALUE                -.722   -.687   -.754   -.793   -.769   -.718   -.703   -.773
*************************************************************************************
*************************************************************************************
TOTAL COST                   2.875   2.880   2.880   2.888   2.906   2.914   2.918   2.918
*************************************************************************************
*************************************************************************************
NUMBER OF LAYERS               2       3       3       3       3       3       2       3
*************************************************************************************
LAYER DEPTH (INCHES)
     D( 1)                    1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
     D( 2)                   16.0     8.5    12.0    13.0    12.0     9.5    15.5    12.5
     D( 3)                    0.0     6.0     6.0     6.0     6.5     6.5     0.0     6.0
*************************************************************************************
*************************************************************************************
NO.OF PERF.PERIODS             3       4       3       3       3       3       3       3
*************************************************************************************
PERF. TIME (YEARS)
     T( 1)                   7.250   4.719   6.906   7.344   7.031   5.625   7.063   7.156
     T( 2)                  15.062  10.109  14.094  15.313  14.453  12.109  14.484  14.734
     T( 3)                  25.102  16.945  23.234  25.625  23.867  20.430  23.937  24.422
     T( 4)                   0.000  25.344   0.000   0.000   0.000   0.000   0.000   0.000
*************************************************************************************
OVERLAY POLICY(INCH)
(EXCLUDING LEVEL-UP)
     O( 1)                     .5     1.5      .5      .5      .5     1.5      .5      .5
     O( 2)                     .5      .5      .5      .5      .5      .5      .5      .5
     O( 3)                    0.0      .5     0.0     0.0     0.0     0.0     0.0     0.0
*************************************************************************************
NUMBER OF SEAL COATS           2       2       3       2       3       3       3       3
*************************************************************************************
SEAL COAT SCHEDULE
   (YEARS)
   SC( 1)                    5.000   9.719   5.000   5.000   5.000   5.000   5.000   5.000
   SC( 2)                   12.250  15.109  11.906  12.344  12.031  10.625  12.062  12.156
   SC( 3)                    0.000   0.000  19.094   0.000  19.453  17.109  19.484  19.734
*************************************************************************************


        THE TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED WAS        205
```

APPENDIX B

MATHEMATICAL MODELS USED IN THE FLEXIBLE PAVEMENT DESIGN SYSTEMS INVESTIGATED TO DATE

APPENDIX B. MATHEMATICAL MODELS USED IN THE FLEXIBLE PAVEMENT DESIGN SYSTEMS INVESTIGATED TO DATE

An effort is made here to describe briefly the latest modification (FPS-3) of the deflection-based system developed in Project 32, and the later system (FPS-4) based on the AASHO Road Test equation. Since it is assumed that Project 32 research reports describing FPS-1 (Refs 9, 10, 12, and 14) are available to the reader, only changes from that system are treated in any detail.

Physical Factors Considered

The physical factors considered in FPS-3 and FPS-4 can be conveniently grouped in five categories: pavement performance, traffic loading, pavement strength, regional effects, and swelling clays.

Pavement Performance. In both FPS-3 and FPS-4, the performance of a pavement is defined, or described, by its serviceability history (the curve of serviceability index plotted against time), as it was in FPS-1 (page 2 of Ref 9, page 10 of Ref 12).

Traffic Loading. In both FPS-3 and FPS-4, the traffic stream is reduced to an equivalent number of 18-kip single axle loads, as in FPS-1 (page 8 of 12).

Pavement Strength. Pavement strength in FPS-3 is characterized by the "surface curvature index", as in FPS-1 (page 41 of 9, page 6 of 12). In FPS-4, on the other hand, pavement strength characterized by the "structural number" of the materials above the foundation, together with the "soil support value" of the foundation material, as described in the foreword of the "AASHO Interim Guide for the Design of Flexible Pavement Structures" (Ref 4).

Certain material coefficients are used in FPS-4 in computing the structural number. These, which are supplied by the program user, should not be confused with the stiffness coefficients used in computing the surface curvature index in FPS-3.

The soil support value used in FPS-4 is computed from the Texas Triaxial Class of the subgrade material, also supplied by the program user.

Regional Effects. In FPS-3, regional effects are accounted for as in FPS-1, that is, an ambient temperature statistic is considered (page 15 of Ref 12) and the stiffness coefficients of the proposed materials are estimated from deflection tests made on existing pavements composed of similar materials in the general vicinity of the proposed project (pages 32-37 of Ref 12). In FPS-4, provision is made for a "regional factor" that modifies the traffic loading, but means for estimating its value have not yet been developed.

Swelling Clays. In both FPS-3 and FPS-4, the effect of swelling clays in the foundation material is accounted for in the same manner as in FPS-1 (pages 10-13 and page 38 of Ref 12).

Performance Equations

The performance equation of FPS-1, which states the assumed relationship between pavement performance, traffic loading, pavement strength, regional effects, and swelling clay effects (page 27 of Ref 12) was carried over without change into FPS-3.

On the other hand, the performance equation of FPS-4 is borrowed, in part, from a preliminary draft (as yet unpublished) of the final report of NCHRP Project 1-11 (Eq 13, page 97 of Ref 16). This equation, modified to include a term representing the effect of swelling clays, is

$$g = g' + g'' \tag{1}$$

where

$$g = \frac{P_1 - P_2}{P_1 - 1.5} \tag{2}$$

$$g' = \left[\frac{1.051[R(W_k - W_{k-1})]^{.1068}}{(SN+1) \times 10^{.03973(SS-3)}}\right]^{(B/.1068)} \tag{3}$$

$$B = 0.4 + \frac{.081(19)^{3.23}}{(SN+1)^{5.19}} \tag{4}$$

$$SN = b_1D_1 + b_2D_2 + \ldots + b_nD_n \tag{5}$$

$$SS = 11.899 - 0.6716\ T^{3/2} \tag{6}$$

$$g'' = \frac{M^2 + 2M\sqrt{5-P_1}}{P_1 - 1.5} \tag{7}$$

$$M = (\sqrt{5-P_2} - \sqrt{5-P_1})[1-e^{-b_k(t_k-t_{k-1})}] \tag{8}$$

The following are definitions of the symbols appearing in Eqs 1 through 8.

g = a measure of the total loss in serviceability occuring during a performance period; which is defined in FPS-1 (page 10 of Ref 12),

g' = that portion of g that is attributed to the effect of traffic,

g'' = that portion of g that is attributed to the effect of foundation movements,

P_1, P_2 = values of the serviceability index at the beginning and end of a performance period, as in FPS-1 (page 10 of Ref 12),

R = the regional factor, as in the AASHO Design Guide (Appendix C of Ref 4),

W_k = the accumulated equivalent number of 18-kip single axle loads at the end of the K^{th} performance period,

B = a function of SN (Eq 4), equivalent to the function β in the AASHO Road Test Flexible Pavement Performance equation (Eq 17, page 40 of Ref 1),

SN = the structural number, similar to the thickness index in the Road Test equation (Eq 16, page 36 of Ref 1),

$b_1, b_2, \ldots, b_n$ = the material coefficients of the first, second, ..., n^{th} layers in the pavement. These coefficients, similar to those determined at the AASHO Road Test (Eq 19, page 40 of Ref 1), should not be confused with the stiffness coefficients used in FPS-1 (Chapter 4 of Ref 12),

$D_1, D_2, \ldots, D_n$ = thicknesses of the first, second, ..., n^{th} layers in the pavement,

SS = the soil support value, as in the foreword of the AASHO guide (Ref 4),

T = the Texas Triaxial Class of the foundation material (Ref 22),

P_2', b_k = swelling clay parameters, as in FPS-1 (page 10 and Chapter 5 of Ref 12),

t_k = time at the end of the k^{th} performance period, measured in years from the date of completion of initial construction, as in FPS-1 (page 11 of Ref 12).

Certain Features of FPS-4 Performance Equation

The following features of Eq 1 are of interest:

Equation 1 represents Design Chart 400-1 of the AASHO Guide (page 24 of Ref 4) if the following numerical values are substituted where appropriate in Eqs 1-8:

(a) $P_1 = 4.2$,
(b) $P_2 = 2.0$,
(c) $b_k = 0$ (or $g'' = 0$).

Equation 1 reduces to the AASHO Road Test flexible pavement performance equation (Eq 12, page 36; Eqs 17, 18, and 19, page 40 of Ref 1), if the following substitutions are made:

(a) $P_1 = 4.2$,
(b) $R = 1$,
(c) $T = 5.6$ (or SS=3),
(d) $n = 3$,

(e) $b_1 = .44$, $b_2 = 14$, $b_3 = .11$,
(f) $b_k = 0$ (or $g'' = 0$).

If W_k and W_{k-1} in Eq 3 are each set to zero to represent the complete absence of traffic, and if the traffic term in the pavement performance equation used in FPS-3 is also set to zero (Eq 3, page 27 of Ref 12), then these two equations reduce to the same equation. Thus, when it is assumed that only foundation movements affect the serviceability index, the serviceability history predicted by FPS-4 is (as it should be) the same as that predicted by FPS-3, provided, of course, that identical values of P_2' and b_k are used in the two systems.

Economic Models (FPS-3 and FPS-4)

The economic models in FPS-3 and FPS-4 are the same, and in most instances are identical with those in FPS-1 (pages 39-74 of Ref 12). The following discussion outlines the content of these models and lists the changes made in FPS-1 to form FPS-3 and FPS-4. For a more detailed discussion one should refer to the previously published report on FPS-1. All costs are calculated for one square yard of pavement, the unit used for comparison of the cost of alternative designs.

Initial Construction Cost. The initial construction cost per square yard for each pavement design is calculated in FPS-3 and FPS-4 as the sum of the products of the depths (in inches) of the pavement layers and their respective costs (per square yard per inch), as in FPS-1.

Routine Maintenance Cost. The routine maintenance cost, calculated for each year of the analysis period, is assumed to be a constant amount per square yard per year (a program input) during the first year after initial construction and after each overlay. This annual cost is further assumed to increase by a constant amount per year (also a program input), starting at the previously mentioned amount after initial construction and overlays. The model also assumes that all costs for a year are incurred at the beginning of the year. Maintenance costs are computed in FPS-3 and FPS-4 in the same manner as in FPS-1.

Seal Coat Costs. The model for application of seal coats assumes that the design engineer will provide as program inputs (1) the cost per lane-mile of applying a seal coat; (2) the time, in years, after initial construction or overlay, before a seal coat will be applied; and (3) the time, in years, between seal coats. Given these inputs and the times at which overlays are to occur (calculated internally by the program) the program calculates the times at which seal coats are expected to be applied and their cost per square yard. In FPS-1, it was assumed that no seal coat would be applied within the year prior to each overlay; this restriction, which appeared in some cases to lead to illogical results, has been removed from FPS-3 and FPS-4.

Overlay Construction Cost. It is assumed that overlays will be constructed of asphaltic concrete in multiples of one-half-inch thickness. It is also assumed that each time an overlay is constructed there is an additional charge, the "level-up cost", equal to the cost of one inch of overlay.

The number of overlays, their times of occurrence, and their thicknesses are calculated internally by the computer program. The overlay cost per square yard is obtained by multiplying the overlay thickness in inches (including the level-up inch) by the cost of asphaltic concrete per square yard per inch.

The methods for computing overlay construction costs in FPS-3 and FPS-4 are the same as in FPS-1.

Cost of Traffic Delays During Overlay Construction. The calculation of the cost of traffic delays during overlay construction in FPS-3 and FPS-4 are basically the same as in FPS-1, except for the changes discussed below. In FPS-1, the program user provided as a program input the time he estimated it would take to make an overlay pass of a certain length and depth. From this input the computer program estimated the amount of time it would take to do each overlay. This method of calculating construction time is not used in FPS-3 and FPS-4. Instead, the program user provides as inputs the production rate of asphalt in tons per hour, and the density of the overlay in tons per cubic yard. The traffic or user cost per square yard, TUCSY, is

$$\mathrm{TUCSY} = \frac{DT\,(HUC)}{P} \qquad (9)$$

where

D is the density of the asphaltic concrete, in tons per cubic yard;

T is the thickness of the asphaltic concrete overlay, plus one inch (the equivalent thickness of asphaltic concrete used in leveling up), the total expressed in yards;

HUC is the traffic, or user, cost per hour of overlay construction, computed from Eq 10; and

P is the production rate of asphaltic concrete in tons per hour.

In the above equation, the quotient DT/P is the portion of an hour which it takes to overlay one square yard of thickness T ; this quotient, multiplied by the user cost per hour HUC gives TUCSY.

Thus, in FPS-3 and FPS-4 the constraint determining the length of time in overlay construction is the production rate of the asphalt plant, whereas in FPS-1 the constraint was the speed of the asphalt spreading and rolling operation. It is believed that the method used in FPS-3 and FPS-4 conforms more closely to field practices.

The formula used for computing the hourly user (traffic) cost HUC for the overlay operation (prior to discounting to obtain the present value) is

$$\begin{aligned} HUC = \; & Q[PO_1(CO_1 + CO_2 + CO_3) + (1 - PO_1)(CO_3 + CO_4) \\ & + PO_2(CO_5) + PN_1 \, (CN_1 + CN_2 + CN_3) + (1 - PN_1) \, (CN_3 + CN_4) \\ & + PN_2(CN_5)] \end{aligned} \tag{10}$$

where the variables with an "0" refer to the overlay direction and with an "N" refer to the non-overlay direction, and

where

Q is the number of vehicles arriving at the overlay area per hour from each direction,

PO_1 and PN_1 are the proportions of traffic stopped due to the capacity of the overlay section being less than the demand for it, i.e., the proportions stopped because of congestion,

PO_2 and PN_2 are the proportions of traffic stopped due to the movement of overlay personnel and equipment in the restricted area,

CO_1 and CN_1 are the excess costs per vehicle of stopping from the speed at which the vehicles approach the restricted area,

CO_2 and CN_2 are the costs per vehicle of idle time which stopped at the entrance to the restricted area,

CO_3 and CN_3 are the excess costs per vehicle of travelling through the restricted area at a reduced speed,

CO_4 and CN_4 are the excess costs per vehicle of slowing from their approach speed to the speed at which they travel through the restricted area, and of returning to their approach speed, and

CO_5 and CN_5 are the excess costs per vehicle of stopping from the through speed, plus the cost of idling while stopped due to the movement of overlay personnel and equipment.

The variable HUC, computed by means of Eq 10 in FPS-3 and FPS-4, replaces the variable TUC (total user cost associated with the entire overlay) used in FPS-1. The need for the variable TUC was eliminated by the introduction of Eq 9.

In FPS-3 and FPS-4, as in FPS-1, the program user must stipulate for both directions of travel (1) the speeds at which vehicles approach and travel through the restricted area, (2) the proportion of vehicles which will be stopped in the restricted area due to the movement of overlay personnel and equipment, (3) the average length of time that such vehicles will remain stopped, and (4) the length of the area over which vehicles will travel at reduced speeds. If vehicles are required to detour around the overlay area, the program user must stipulate the expected length of the detour route. This input, which did not appear in FPS-1, has been added to account for additional distances travelled in detouring around overlay operations.

The excess costs for slowing and stopping from different speeds, for idling and for travelling at uniform speeds, are incorporated in the computer program (and are given in pages 53-56 of Ref 12). These costs include time costs and vehicle operating costs.

The proportions of vehicles stopped because of congestion in the area restricted because of overlay are calculated in the computer program using the same formulas as were reported for FPS-1 (pages 61-67 of Ref 12).

The program user must stipulate which of five possible methods he expects to be used to handle traffic near the overlay area. These five methods for FPS-3 and FPS-4 are basically the same as those used with FPS-1 but differ in some respects. Figures B.1 through B.5 illustrate these traffic-handling situations. In these figures LO designates the length of the overlay operation and LSO and LSN designate the distances (measured along the centerline of the original traveled way), in the overlay and nonoverlay directions, respectively, over which vehicles travel at a reduced speed. In FPS-3 and FPS-4, LSO and LSN need not be equal whereas in FPS-1 they were assumed to be equal and were designated simply as LS. In Fig B.5, LSD represents the length of the detour around the overlay area previously mentioned as a new input to FPS-3 and FPS-4.

Further explanation of each of these five methods of handling traffic, and of the formulas used to calculate numbers of stops and hours of delay due to congestions, will not be given here since it is available in pages 57-67 of Ref 12.

Salvage Value. In FPS-1, the salvage value of a pavement was assumed to be a certain percentage of the total of initial construction cost and cost of overlays (not including the cost of asphaltic concrete used for level-up). The program user had to provide this percentage figure as an input. In FPS-3 and FPS-4, this method of calculation has been changed so that the program user can designate a different percentage for each material used. That is, prior to discounting, salvage value per square yard of pavement SV is calculated in FPS-3 and FPS-4 using

$$SV = \sum_{j=1}^{n} P_j D_j C_j \tag{11}$$

where

n is the number of layers in the initial construction,

P_j is the proportion (i.e., percentage/100) that salvage value for layer j is of the cost of layer j,

D_j is the depth in inches of the j layer, and in the case of the top layer is the initial asphaltic concrete depth plus the depth of all asphaltic concrete overlays, excluding that used for level-up, and

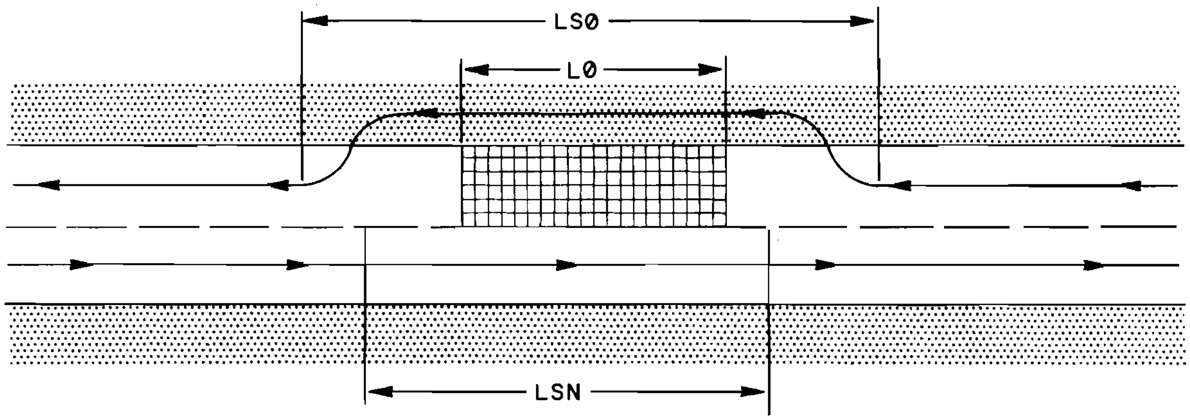

Fig B.1. Method I: traffic routed to shoulder.

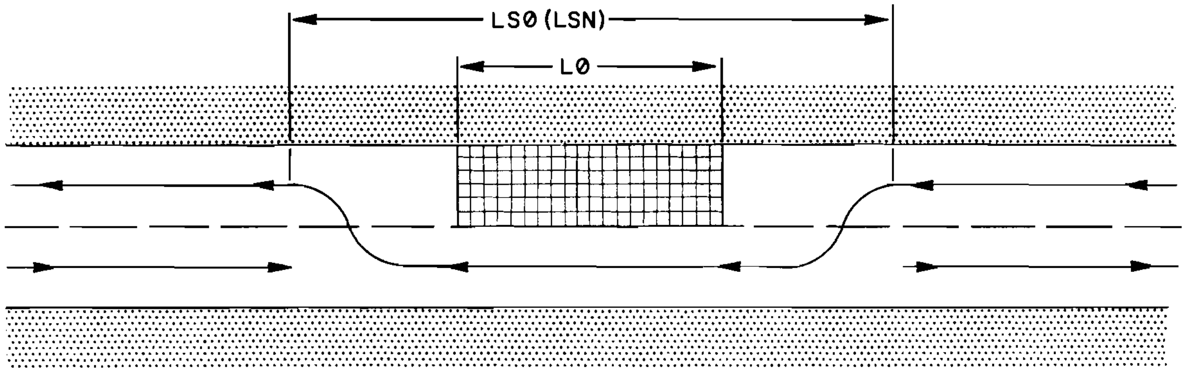

Fig B.2. Method II: alternating traffic in one lane.

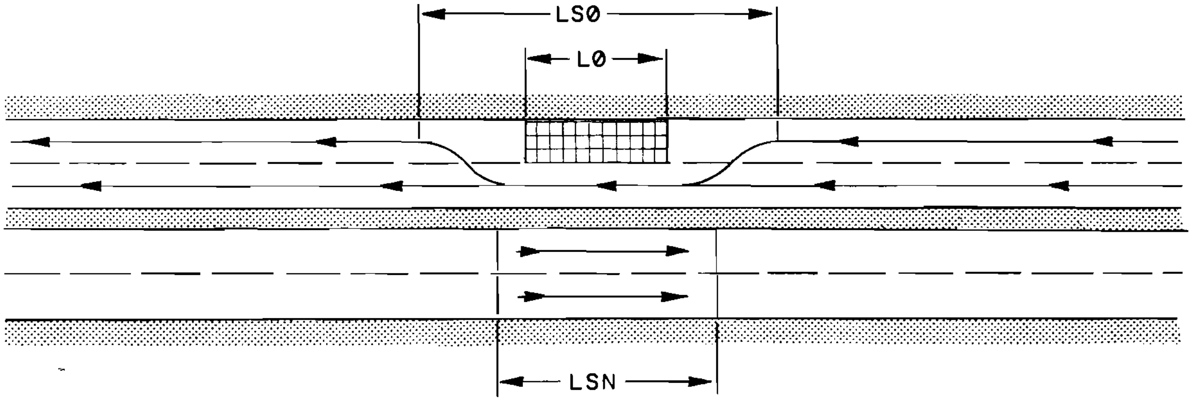

Fig B.3. Method III: two lanes merge, nonoverlay direction not affected.

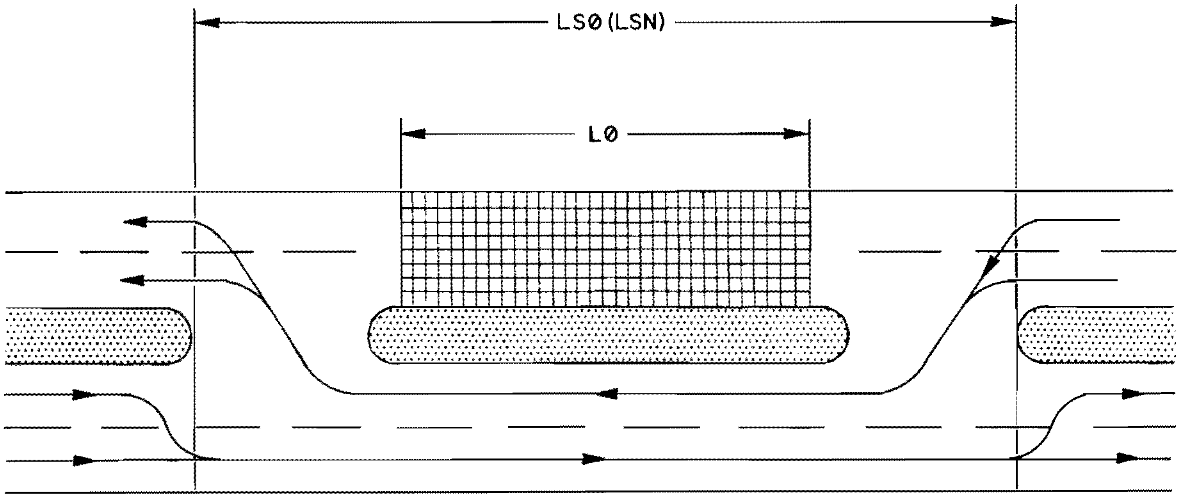

Fig B.4. Method IV: overlay direction traffic routed to nonoverlay lanes.

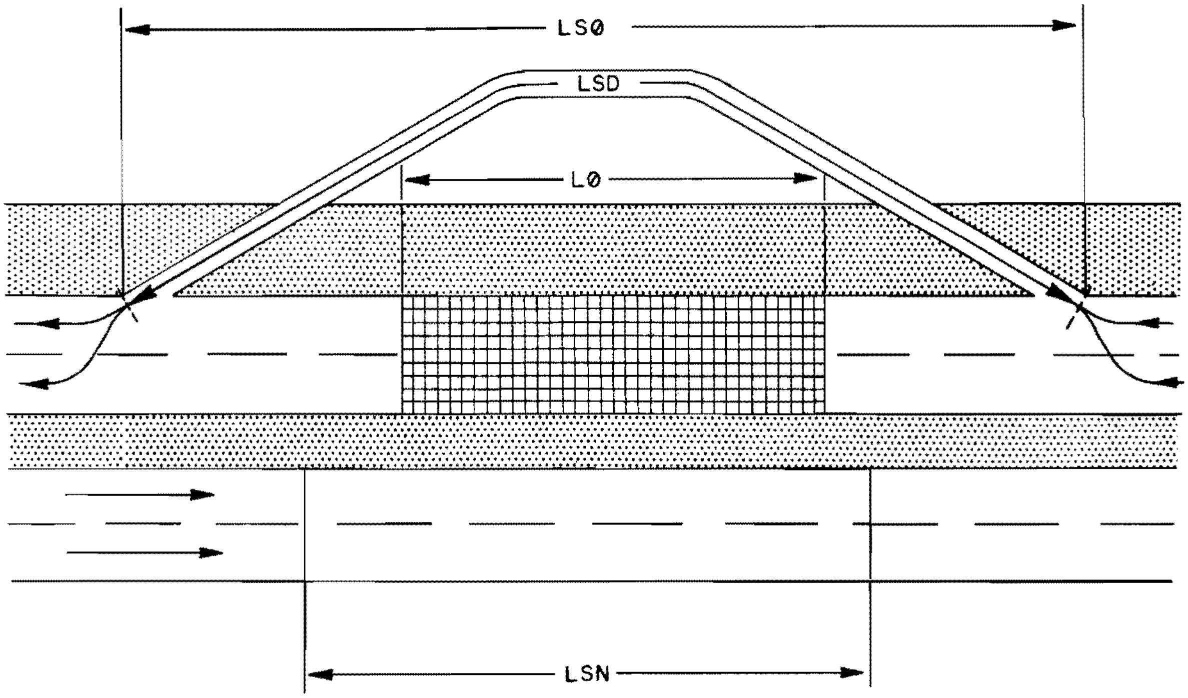

Fig B.5. Method V: overlay direction traffic routed to frontage road or other parallel route.

C_j is the cost per square yard per inch of the material in the j layer.

The new method of computing salvage value adds flexibility to the program, since it permits the assignment of different percentages to the various materials. Such a capability was necessary, for example, to properly account for the tendency of asphaltic concrete to depreciate in value more rapidly, as a rule, than underlying materials. This fact was not recognized in FPS-1.

Total Overall Cost (Present Value). The total cost of each pavement alternative considered is the sum of the present worths of initial construction costs, traffic (user's) costs due to traffic delays during overlay, seal coat costs, and routine maintenance costs, less the present worth of the pavement's salvage value. These costs are considered over an analysis period provided by the program user as a program input. The present worth of the future costs (all costs except initial construction cost) and the salvage value are calculated by discounting to the present using an interest rate which also is a program input.

The method used in FPS-3 and FPS-4 in computing the present worth of total overall cost is the same as that used in FPS-1.

Constraints

The computer programs for FPS-3 and FPS-4 consider all possible construction designs, both initial and overlay. Many of these designs would be considered both impractical and undesirable. To provide for the exclusion of such designs, the designer may specify a number of physical restrictions which will be used by the computer program to filter out these unrealistic designs. The following is a complete list of these physical restrictions:

(1) minimum and maximum initial construction depths for each type of material, as in FPS-1;

(2) maximum total depth of initial construction, as in FPS-1;

(3) maximum funds available per square yard for initial construction, as in FPS-1;

(4) minimum time to the first overlay after initial construction and the minimum allowed time between subsequent overlays;

(5) minimum overlay thickness allowed and the accumulated maximum depth of all overlays. These restraints were not included in FPS-1. Their addition is believed to make the program more practical.

In addition to these physical restrictions, FPS-4 further utilizes a special act of initial construction restrictions on the structural numbers of the materials above each layer as well as the subgrade. The purpose of these restrictions, as was first reported in NCHRP Report 1-11 (Ref 16) is to insure that each layer has the proper structural strength above it. For example, it would be undesirable to construct a pavement that has a very strong base with a very weak surface above it. Such contingencies are avoided in FPS-4 by requiring that a feasible initial design with, say, three layers above the subgrade must satisfy the following:

$$b_1D_1 \geq SN_2$$

$$b_1D_1 + b_2D_2 \geq SN_3$$

$$b_1D_1 + b_2D_2 + b_3D_3 \geq SN_4$$

where SN_2 is the structural number required above a hypothetical subgrade composed of material No. 2, SN_3 is the structural number required above a hypothetical subgrade composed of material No. 3, and SN_4 is the structural number required above the actual subgrade. The structural number SN_1 is computed from Eq 1 with the associated soil support value being computed from the triaxial class value of the material in the ith layer (Eq 8).

Optimization Algorithms

The total cost of a design strategy is used as the criterion for selecting the most economical design from the set of all possible designs. The computer programs for FPS-3 and FPS-4 obtain not only this design but several alternative designs, each with a higher total cost.

The overall optimization plan is very similar to that of FPS-1; that is, it is divided into two stages: (1) optimization with respect to initial design and (2) optimization with respect to overlay construction policies. For this reason, these procedures will be described only briefly. More detail can be obtained by referring to Report 32-11 (Ref 12).

It is assumed that a number of materials are available for initial construction. Each material has an associated strength coefficient along with a cost per compacted cubic yard, restrictions on the initial construction depth (if the material is used), and a salvage value percentage. In addition, FPS-4 requires the triaxial class of each material. It is also assumed that all materials are typed into a hierarchy which indicates the layer in which each material may be used. Thus, designs with only one layer above the subgrade are constructed from Type I materials (only one material may be used at a time). Designs with two layers above the subgrade may be formed by using various combinations of Type I and Type II materials. Again only one material of each type may be used in a single design. Three layer designs are constructed from material Types I, II, and III, etc. This method of classifying materials according to their position in the structure represents a change from FPS-1, adopted because it gives the program user more control over the combinations of materials to be constructed.

First Stage of Optimization. For each combination of materials considered in FPS-3 (as in FPS-1), the computer program utilizes the deflection equation (Ref 10), along with the cost and thickness restrictions, to generate various initial designs. Thus, each design is characterized in FPS-3 (and in FPS-1) by the individual layer depths and the surface curvature index of the structure. The FPS-3 performance equation (Ref 9) and the traffic equation (Ref 12) can next be solved simultaneously to determine the length of time required before the serviceability index is reduced to its lower limit of P_2. This length of time t_1 has been previously defined to be the first performance period.

In a similar manner, each design in FPS-4 is characterized by the individual depths and the structural number of the materials above the subgrade. This structural number, along with the FPS-4 performance equation (Eq 1) and the traffic equation (Ref 12) are combined to determine the time of the first performance period.

Second Stage of Optimization. The second stage of the optimization is concerned with determining the optimal overlay policy for each of the initial designs. As in FPS-1 the procedure is to evaluate each overlay alternative in terms of total cost. This is done by combining the costs, discussed earlier in this chapter, for

(1) initial construction,
(2) routine maintenance,
(3) seal coats,
(4) overlay construction,
(5) traffic delays during overlay construction,
(6) salvage.

Only in this way can the complete cost of a design strategy be evaluated.

Not only does the computer program determine the optimal design strategy for each combination of materials but it also accumulates a predesignated number (usually 24) of the most economical design strategies. These are summarized and tabulated upon the completion of the problem in a form giving the complete information of

(1) the initial construction design,
(2) the optimal overlay and seal coat policies,
(3) the individual cost components for each design strategy.

APPENDIX C

DEFINITIONS OF TERMS

APPENDIX C. DEFINITIONS OF TERMS

(1) Performance is a measure of the accumulated service provided by a facility; i.e., the adequacy with which a pavement fulfills its purpose. Performance is often specified with a performance index, as suggested by Carey and Irick. As such, it is a direct function of the present serviceability history of the pavement.

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

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

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

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

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

(7) Distortion is 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.

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

(9) 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 (Ref 23).

(10) System failure may be expressed as a condition where the distress from the system output has exceeded an acceptable level based on the decision criteria.

(11) Hardware in the design system is the physical equipment required, such as the computer and the Lane Wells Dynaflect.

(12) Software is the set of computer programs which are used for the solutions made in the design system.

(13) Model is a system of postulates, data, and inferences presented as a mathematical description of a conceptual reality.

(14) Feedback is the reversion of the pavement distress or limiting response data to the data bank for use as new design input.

APPENDIX D

APPLYING SYSTEMS ENGINEERING TO PAVEMENT STRUCTURAL BEHAVIOR

APPENDIX D. APPLYING SYSTEMS ENGINEERING TO PAVEMENT STRUCTURAL BEHAVIOR

Since the pavement is a complex structure subjected to many diverse combinations of loading and must perform under a variety of environments, it seems appropriate to utilize the concepts of systems engineering, which have evolved in recent years in the electronic communications and aerospace industries, to examine the design of pavement structures. Accordingly, in this section, a systems approach will be used to formulate the pavement design problem.

The words "system" and "systems engineering" mean many things to many people. Systems engineering grew up primarily in association with the complex electronic, mechanical, and nuclear systems associated with the aerospace industry, the communication industry, and the space program. From the point of view of understanding what is happening, it is probably better to talk about a systems approach or the "concepts of systems engineering" rather than to talk about systems engineering itself.

Ellis and Ludwig (Ref 23) give a reasonably concise definition for a system which 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 (Ref 24) 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" describes an approach which 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.

To provide a starting point for discussion of the various facets of systems engineering, a set of concepts set forth by J. A. Morton (Ref 27) is helpful. He brings out the basis for systems engineering in the following:

> The systems engineering method recognizes each system as an integrated whole even though composed of diverse specialized structures and subfunctions. It further recognizes that any system has a number of objectives and that the balance between them may differ widely from system to system. The methods seek to optimize the overall system functions according to the weighted objectives and to achieve maximum compatibility of its parts.

The systems approach is dedicated to emphasizing the ideas and factors which are common to the successful operation of somewhat independent parts in an integrated whole. Furthermore, the successful operation of the whole is the primary objective of the system; thus, 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 overall system requirements for the entire period of interest.

It is also important to remember that any particular system under consideration may serve as a part of a larger system. By the same token the various subsystems making up a system may be evaluated by systems techniques. Thus, the highway system may form a part of a transportation system; in turn, the highway system consists in part of the pavement structure system, which can be treated in the same systems fashion. Although the requirements placed on these different systems are not the same, the general methods used in arriving at the systems solution are similar.

The problem of attacking the design of a large-scale system is overwhelming if it is done all at once. Yet, if the attack is made piecemeal, it is highly unlikely to be successful. It is necessary to subdivide the problem in a number of ways both conceptionally and organizationally. However, in order to be able to subdivide the problem one must first be able to formulate the problem in its whole. This idea is at once an anomaly and a truth, because it is certainly true that one must formulate the problem in general terms before one can attack it; on the other hand, one must often delve deeply into the problem and approach its solution in steps before the ultimate solution can finally be developed. Nevertheless, if an initial attempt to define the overall problem is not made, it is highly impractical to attack the problem from a system point of view. It is also important in systems engineering to divide the problem into subsystems for analysis. An important aid to formulating the problem is the development of appropriate models, mathematical or physical, for the overall 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 make the model and its solutions more satisfactory.

Any system has a number of characteristics. These characteristics can be related to the objectives of the individual subfunctions within the system which may be an objective of the whole system or merely a contribution to the operation of the whole system. These characteristics may be such things as simplicity, ease of maintenance, low cost, long life, good performance and/or other factors, all of which may be required to be present simultaneously or at different times. Thus, 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 quality of performance and cost is relegated to a minor role. Some 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, it is necessary that each system be considered on its own basis and the relative merits of the different objectives be considered in their proper order of importance. Establishing this order is the engineer's function.

Applications of the Systems Approach

The system can be considered as a black box (Fig D.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's behavior; (2) response variables, which represent those aspects of system's behavior that are of interest to the investigator; and (3) intermediate variables, those which are neither excitation nor response variables. Then, one step further, rather than referring to the system as the "black box," it is possible merely to say that the system is some physical object which transforms the input variables or excitation variables in some as-of-yet mysterious fashion to the response or output variables.

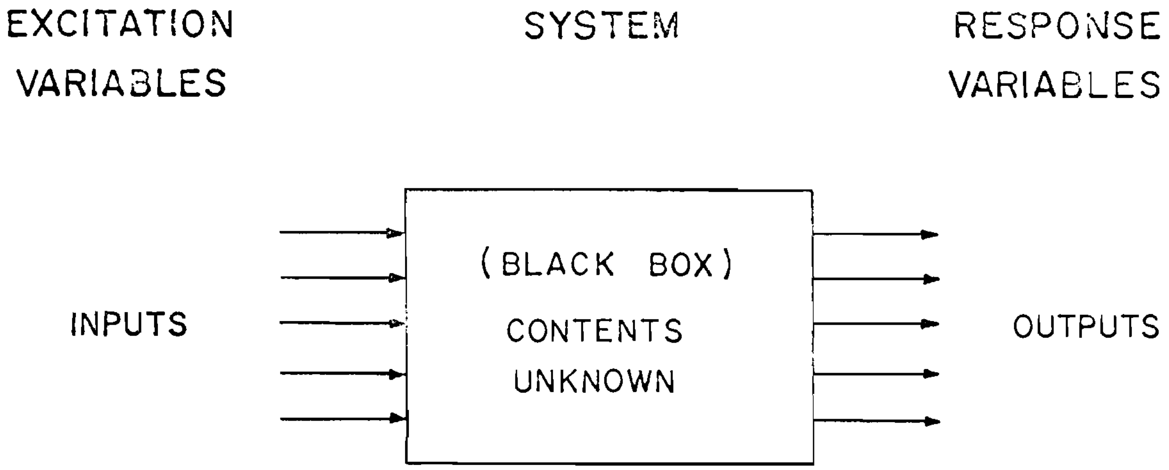

Fig D.1. Black box system.

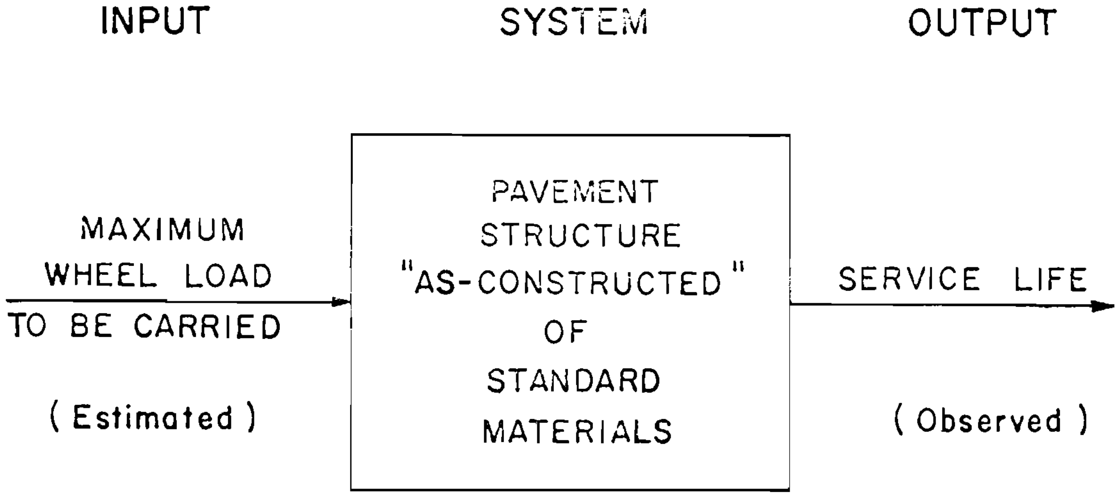

Fig D.2. System diagram of early pavement design methods.

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 illustrated in Fig D.1, he would be happy from an operational point of view. Many road test evaluations fall into this class for which no attempt is made to evaluate the contents or component parts of the system but merely to observe its performance.

This does not preclude the need of many people to know what is happening inside the system or the "black box." Unfortunately, most of the system problems facing civil engineers, particularly those of transportation engineering, will not yield to solution without some understanding of 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 the mathematical model, and (4) the physical realization of a mathematical design. Thus, it is essential that systems engineers 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 so that the necessary outputs can be observed. Looking at it in another way, the designer must determine the transfer functions of the system or those expressions which relate the desired outputs to the excitation inputs or disturbances of the system.

Because of different backgrounds, experience, training, and materials available, different designers arrive at different solutions to satisfy the same specified need. Although the desired result may be approximately the same for the various methods, a number of the intermediate results may differ, and the values of the various judgment factors for determining the worth of the system may not be the same for each. An important systems engineering precept is that a number of these alternate methods should be considered and that the method actually used should be one that can be shown to meet most adequately the known needs of the system.

Phase Development in a System

It would be naive to say that no one has ever looked at a highway system or a pavement structural system as a whole entity. Phases in systems

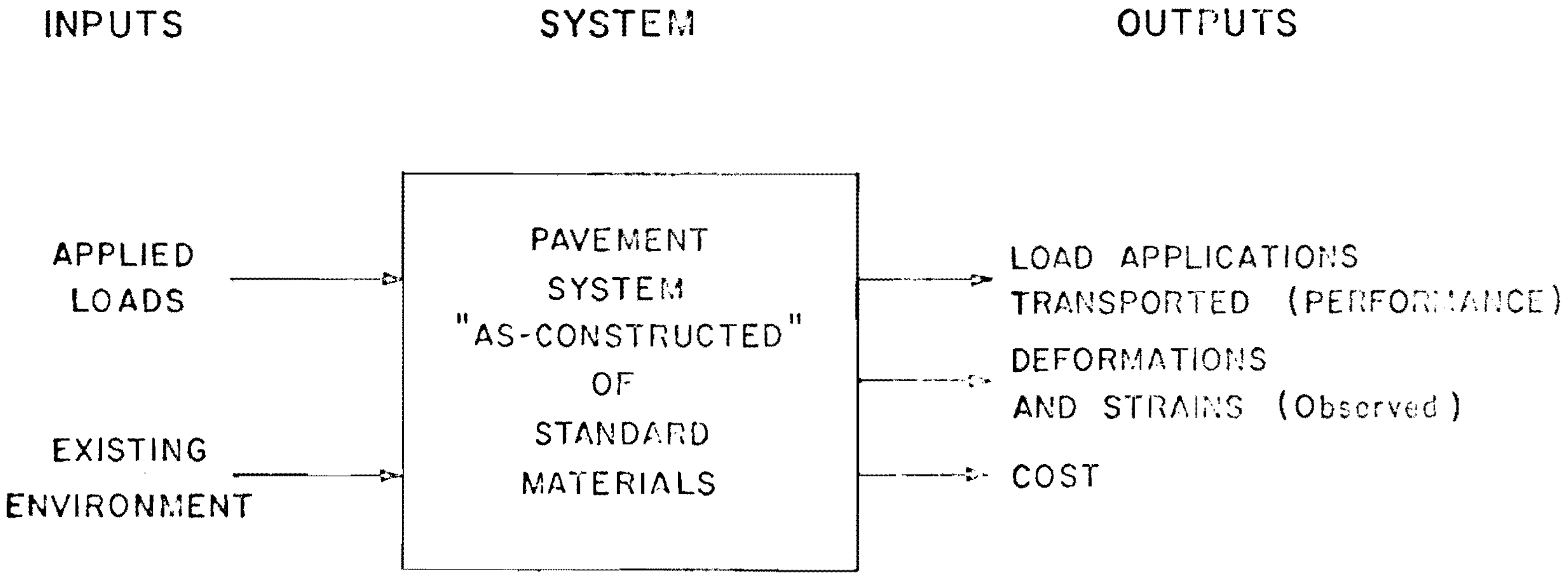

Fig D.3. Second generation pavement system description.

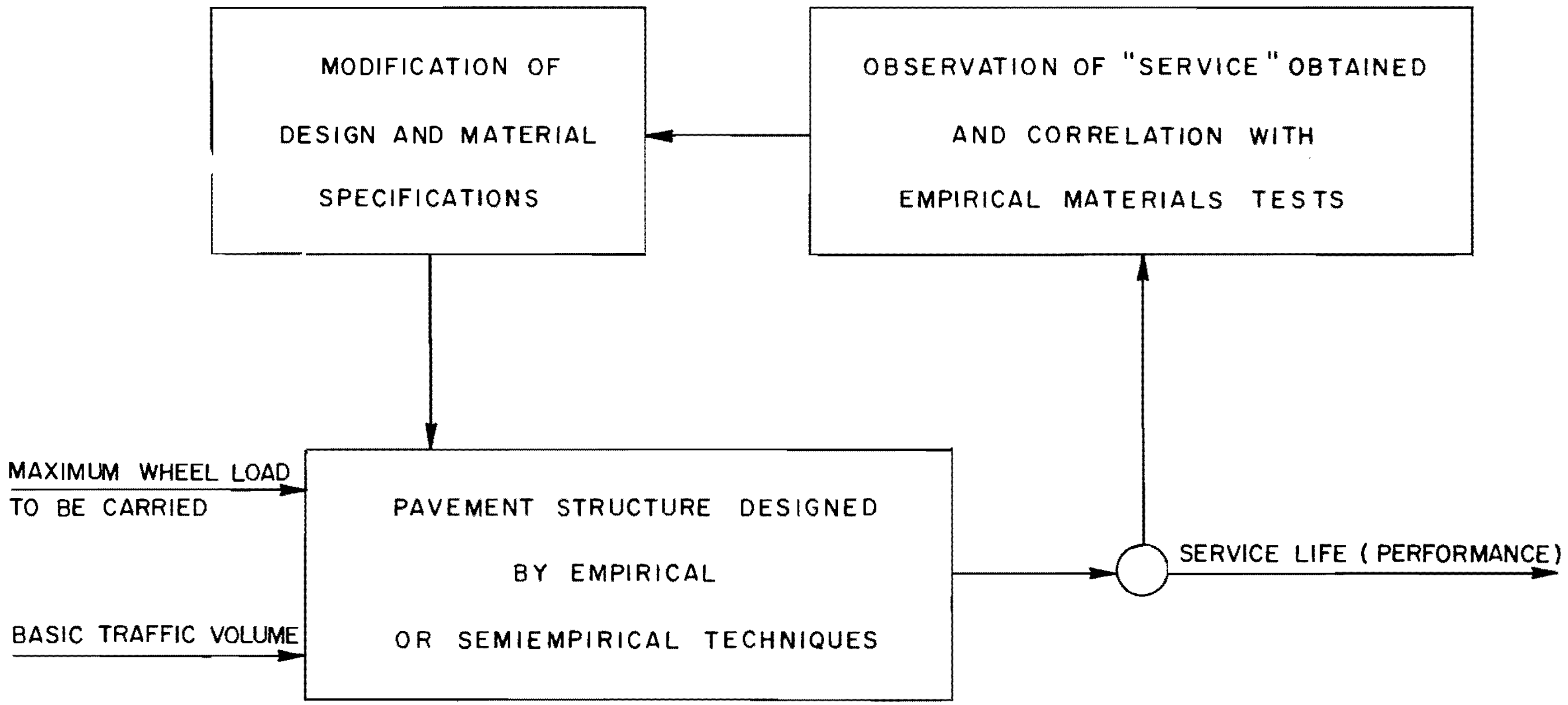

Fig D.4. Block diagram of current pavement design techniques.

development as they succeed one another repeat themselves. 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 D.2 is a simple example of such early trial pavement systems.

The pavement engineer observes the performance of the pavements so designed and repeats the construction of those which perform well. Those which 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. A second iteration pavement "system" might be illustrated in Fig D.3, which adds consideration of environment as an input and cost and deformations of the section under load as outputs.

Figure D.4 shows a block diagram of the evolution of many existing pavement design techniques. These methods have evolved primarily through observations of pavement behavior and the use of these observations 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).

It appears, however, that the next iteration in the process requires a much more thorough evaluation of the complexity of the problem with better specification and definition of such factors as performance, serviceability, and material properties; more attention must be given to the necessary input and output variables for the system. More specific criteria for selection and decisions must also be developed. The need for these improvements will be intensified as traffic demands and costs increase, and as the complexity and variety of materials used in pavement construction continue to increase.

Description of the Pavement System

Having discussed the generalities of current pavement design methods in a systems context, one may now turn to the development of a more complete description of the pavement system. As discussed, it is often convenient to regard the pavement system as the "black box" in Fig D.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) Approximate 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) The 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.

In order to treat these ideas quantitatively, it will be necessary to define terms and operations more precisely. The <u>input</u> to the system consists of traffic, environment, and maintenance. The effect of traffic is to impress, through wheel loads, certain stresses on the pavement surface. The spatial distribution and time variations (both dynamic and cyclic) are ascribable functions. The <u>environmental</u> input consists, among other things, of diffusion of heat and moisture into the system. Once again, these inputs are characterized as functions of space and time. In certain instances a chemical input may occur; e.g., with the use of deicing salts. The <u>response</u> of the system consists of the generation of a mechanical state, identified by <u>deformation</u> and internal stress. For our purposes, the mechanical state is most readily described in terms of strain and stress.

The pavement system itself is characterized by properties of the individual constituents, their arrangement and to some extent the method by which the system is constructed. <u>The system function is defined as the operator which describes the manner in which the pavement accepts an input and converts it into a response</u>. The system function is evidently an intrinsic property of the pavement system. Furthermore, it is apparent that the system function may be affected by aging and may be altered by the input itself, particularly in case of "overloading" the input; furthermore, the environmental input may influence strongly the response to traffic input.

At this point it is well to observe that for a particular system, it is possible, although perhaps not practical, to inquire 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 responses measured. Perhaps a number of alternative "boxes" may be used and their responses compared. Based upon observations of response, it is possible to set up a measure of the performance of the system. Performance is in some sense a measure of the quality of the response; e.g., does breakdown (cracking or disintegration) of the system result during the response, or does excessive permanent deformation occur? Further, is good performance 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. In order 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 this type of experiment is that it is not predictive. That is, changes of input variables or changes in the system function falling outside of the range covered in the experiment must be examined by extrapolation rather than interpolation. Furthermore, the sheer number of variables involved in the system (input, response, system function) magnifies the experimental task enormously. Consequently, it is highly desirable to place as much of the system description as possible 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.

Value of Systems Approach

A great deal of important research has been carried on in pavement design during recent years and yet there seems to be a lack of coordination and relation between the many parts of the problem. This is evident in a thorough study of the literature and in general discussions with engineers and researchers in the field. Something is needed to provide a coordinated framework for solution of the overall problems. A systems approach to the problem offers several advantages:

(1) A good description of the problem is required in a systems approach. The development of such a description will provide a new insight and perspective into the complexity and breadth of the problem, including the complex feedback and interactions involved.

(2) A systems approach and description will provide a background and structure for coordinating and utilizing research from many sources.

(3) A systems description will rapidly point out the areas of weakness and consequently areas of urgently needed research.

(4) A systems approach provides a method of attacking the problem on two levels; (a) the general description will lend itself to development of optimum overall solutions and (b) immediate methods involving the current "state-of-the-art" can be "plugged" into the system to function until better techniques can be developed.

(5) The systems approach emphasizes the need for a coordinated solution to the problem and requires the development of mathematical models and theories which can be solved in order to define and optimize the system. It also recognizes the importance of judgment criteria and weighting functions which are so often taken for granted and forgotten.

(6) Developing techniques in optimization and operations research are greatly improving our ability to choose optimum solutions in the face of complex judgment criteria. Proper formulation of the pavement or roadway structure problem will permit the use of these techniques to help solve our complex problems.

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