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16. Abstract

With much of the highway network system completed, pavement management becomes more and more important. The complex nature of highway pavements suggests that this management should be carried out by considering the total pavement system at the statewide program level. A Pavement Management System (PMS) methodology is described herein which may assist the Texas State Department of Highways and Public Transportation (SDHPT) in effectively allocating pavement budgets. The framework and essential characteristics of an ideal PMS and subsystems are reviewed, and the stochastic decision process to be applied in Texas is discussed.

The material reported herein primarily documents efforts made to develop the program level PMS using a method that will lead to a more realistic and efficient way of making decisions concerning pavement rehabilitation at the program level. The methodology presented is based on the Markovian decision process which has been applied in Arizona, and involves a set of performance variables, such as roughness, cracking, and rutting. The development and practical application of this stochastic decision process using a policy-iteration algorithm is discussed, together with the results obtained. It is believed that the method which uses a probability concept may provide a better way to make decisions, based on the probability concept.

17. Key Words

Pavement Management System, pavement evaluation, rehabilitation and maintenance, stochastic decision process, Markovian Decision Process, algorithm

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DEVELOPMENT OF A PROGRAM LEVEL PAVEMENT MANAGEMENT SYSTEM FOR TEXAS

by

Hosin Lee
W. Ronald Hudson

Research Report Number 307-3

Implementation of a Pavement Management System for Texas
Research Project 3-8-81-307

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

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Bureau of Engineering Research
The University of Texas at Austin

December 1984

PREFACE

This is the third report forthcoming from Research Study 3-8-81-307, "Implementation of a Pavement Management System for Texas." The long-range goal of this project is to assist the Texas State Department of Highways and Public Transportation in developing a rational pavement management system (PMS) for all pavement types and to provide for updating the system with continued input of the latest research findings.

This report summarizes PMS development and implementation to date in Texas. Many people have contributed significantly to this work, and the authors are deeply grateful to them all. In particular, we would like to thank the members of the SDHPT PMS Task Force, the staff of the Center for Transportation Research, and, especially, Dr. Chhote Saraf, Lyn Gabbert, and Art Frakes, for their valuable assistance.

Hosin Lee
W. Ronald Hudson

LIST OF REPORTS

Report No. 307-1, "Development of an Initial Pavement Management System for Texas," by W. Ronald Hudson, R. D. Pedigo, and E. G. Fernando, describes current PMS experience, presents a recommended structure for the Texas PMS Release 1.0, and suggests areas for future improvement.

Report No. 307-2, "Development of a Prioritization Procedure for the Network Level Pavement Management System," by E. G. Fernando and W. R. Hudson, describes existing methods for formulating a prioritization index, documents the development of the rational factorial rating method as an alternative procedure for formulating an index, and presents a prioritization procedure established through application of the rational factorial rating method.

Report No. 307-3, "Development of a Program Level Pavement Management System for Texas," by Hosin Lee and W. Ronald Hudson, describes the Texas PMS experience and presents the stochastic decision process as applied to pavement rehabilitation at the program level.

ABSTRACT

With much of the highway network system completed, pavement management becomes more and more important. The complex nature of highway pavements suggests that this management should be carried out by considering the total pavement system at the statewide program level. A Pavement Management System (PMS) methodology is described herein which may assist the Texas State Deprtment of Highways and Public Transportation (SDHPT) in effectively allocating pavement budgets. The framework and essential characteristics of an ideal PMS and subsystems are reviewed, and the stochastic decision process to be applied in Texas is discussed.

The material reported herein primarily documents efforts made to develop the program level PMS using a method that will lead to a more realistic and efficient way of making decisions concerning pavement rehabilitation at the program level. The methodology presented is based on the Markovian decision process which has been applied in Arizona, and involves a set of performance variables, such as roughness, cracking, and rutting. The development and practical application of this stochastic decision process using a policy-iteration algorithm is discussed, together with the results obtained. It is believed that the method which uses a probability concept may provide a better way to make decisions, based on the probability concept.

KEYWORDS: Pavement Management System, pavement management, pavement evaluation, rehabilitation and maintenance, stochastic decision process, Markovian Decision Process, Markov Processes, policy-iteration algorithm.

SUMMARY

Pavement management is a broadly based process which encompasses all the activities required to provide and maintain pavements. The process of pavement management has been developed to respond to certain needs and issues. At the program level,

(1) pavements represent a substantial investment in transportation,
(2) substantial annual expenditures are required to preserve and maintain this investment, and
(3) funds available for investments in pavements, and for maintenance, are generally limited.

There is a strong need for an objective procedure for distributing rehabilitation and maintenance funds efficiently and for measuring the effectiveness of the money spent on the overall highway network. The establishment of this procedure is essential to the development of a valid program level PMS. In connection with this need, a stochastic decision model is worthy of studying as a program level PMS in Texas. The objective of this model is to determine a statewide rehabilitation policy that achieves and maintains specified performance standards for the entire highway network with minimum cost.

This stochastic decision model is based on the Markovian decision process, and involves the following decision variables: (1) roughness, (2) cracking, (3) rutting, (4) traffic, and (5) environmental factors. The practical application of this stochastic decision model to determine a near optimal policy of pavement rehabilitation is presented. Numerous pavement engineers were consulted in the development of this method. A computer program has been developed using a policy-iteration algorithm to solve a practical situation. The computer output is included in this report and the

results are discussed. It is recommended that this procedure be tested using field pavement data collected within a long-term pavement monitoring system using the guidelines given in this report.

IMPLEMENTATION STATEMENT

This report describes the development of a program level pavement management system which can be used to determine the optimal statewide rehabilitation policy in Texas. A computer program has been developed to accept the engineering inputs and to generate the optimal solution to practical pavement rehabilitation problems. A trial implementation of the program level PMS is recommended.

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CHAPTER 1. INTRODUCTION

A Pavement Management System (PMS) is an organized procedure intended to assist decision-makers in determining optimum strategies for providing and maintaining pavements in a serviceable condition over a given life or time period. It involves an integrated and coordinated treatment of many phases of pavement related activities and is a dynamic process which incorporates feedback regarding the various attributes, criteria, and constraints involved in the optimization or prioritization procedure. In Research Report 307-1 (Ref 8), recommendations were made using the result of a PMS workshop held with the Texas State Department of Highways and Public Transportation (SDHPT) in February 1981 and two PMS task force meetings involving field and central office personnel in 1981-82. A significant outcome of the February 1981 workshop was the identification of the benefits and needs of a pavement management system in the State of Texas.

There was general agreement that a PMS could help the Department get more funds for the preservation of pavements and roads in the state highway network. In addition, it was recommended that the initial working system be kept as simple and flexible as possible in order to allow for the incorporation of suitable improvements in the future. Finally, it was emphasized that a PMS is a tool to assist decision makers in the management of the roads under their jurisdiction. The recommendations resulting from the 1981 workshop formed the basis of the discussions for the PMS task force meetings which then led to the implementation of the existing Pavement Evaluation System (PES) for the state. Minor modifications were originally needed to make the PES compatible with the stated requirements of the Texas State Department of Highways and Public Transportation. These included (1) the removal of skid in the calculation of the overall pavement performance score; (2) revision of the PES to accommodate statistical sampling; and (3) addition of analysis techniques for identifying consequences of different funding levels.

Subsequently the PES has been expanded to its second year but no major efforts have yet been made to upgrade the PES to fulfill the broader PMS needs of the Texas State Department of Highway and Public Transportation (SDHPT). The purpose of this report is to examine the current situation and to recommend a course of action for continued improvement.

BACKGROUND

Roads and highways are the primary assets of the Texas State Department of Highways and Public Transportation (SDHPT) and are major assets of the state of Texas, with an estimated current worth of $20-50 billion. The pavements form a key portion of these existing assets. The complex nature of highway pavements and the ever-increasing demands placed on them in the face of inflating costs and shrinking purchasing power make efficient, rational management of these assets a necessity. Good pavement management requires careful analysis of the many factors involved, including examination of the total pavement network using systems analysis techniques. These concepts were first applied to pavements through NCHRP Project 1-10, in 1966 (Ref 1), although the application of general systems methods is widespread in industry and the military.

During the period 1968-1975, a comprehensive flexible pavement design system (FPS) was developed for use by the Texas State Department of Highways and Public Transportation (SDHPT) (Ref 2). This system has been implemented and used by the Design Division and in some Districts for individual project level, pavement design decision making. Additional work has been done in Texas, by Lytton et al on rehabilitation (RAMS) (Ref 3). More recently, the Texas State Department of Highways and Public Transportation (SDHPT) has embarked on development of a PMS to assist in evaluating pavement information for planning and making investment decisions covering the highway network which emphasize rehabilitation and maintenance.

OBJECTIVES AND SCOPE

A PMS task group within the Texas State Department of Highways and Public Transportation (SDHPT) has outlined several general objectives for activities concerning the development of such a PMS. The purpose of this report is to describe how certain aspects of those general objectives have been fulfilled, to clarify other objectives, and to recommend modifications or revisions of existing programs and procedures that could be implemented in the near future.

The original list of objectives considered is as follows:

(1) To establish the framework and essential characteristics for an ideal PMS.

(2) To review the current state-of-the-art concerning PMS development in Texas and throughout the United States.

(3) To identify the needs and benefits associated with the development of such a PMS for Texas highways and to investigate the cost of implementing a suitable PMS in relation to the resources currently available within the Texas State Department of Highways and Public Transportation (SDHPT).

(4) To recommend a simplified, skeleton PMS suitable for use in the Texas State Department of Highways and Public Transportation (SDHPT) and to establish how RAMS (a candidate system being developed at TTI) would fit such a system.

(5) To recommend a schedule for the implementation of PMS by the Texas State Department of Highways and Public Transportation (SDHPT).

SPECIFIC GOALS AND OBJECTIVES

The long-range goal of this project is to assist the Texas State Department of Highways and Public Transportation (SDHPT) in developing a rational pavement management system for all pavement types and, further, to provide for updating the system with continued input of the latest research developments and findings.

Accordingly, the objective of this report is to further outline the development of a PMS methodology that will assist the Texas State Department of Highways and Public Transportation (SDHPT) in allocating its resources for the maintenance, rehabilitation, and design of pavements in an efficient manner.

The early work on a network level PMS in the Texas State Department of Highways and Public Transportation (SDHPT) and in this project outlined a plan of attack for pavement management centered on the Pavement Evaluation System (PES) approach. The following goals for such activities were outlined in Ref 8:

(1) accelerate implementation of a PMS in a logical progression within the Department;
(2) develop a single system for managing the pavement resources for
    (a) legislative requirements,
    (b) administrative and Commission requirements,
    (c) maintenance activities,
    (d) RRR activities,
    (e) design criteria for the necessary feedback data system, and
    (f) pavement materials evaluation;
(3) maximize utilization of previous research efforts;
(4) maximize utilization of existing data bases in SDHPT;
(5) integrate with the SDHPT Transportation Network Data Base;
(6) place primary emphasis on a network level PMS; and
(7) promote cooperative efforts of research agencies.

While these remain important objectives, the experience gained in the past two years suggests some needed revisions in the concepts. The PES has been accepted as a first phase routine PMS and is now being implemented in a second annual phase by the Maintenance Division and District personnel. This second round will include the evaluation of the entire Interstate mileage in

Texas and an evaluation of one third of the remaining mileage on the Texas network.

Extensive work has been done to include rigid pavement evaluation techniques in the basic PES method and close coordination is being maintained between projects in rigid pavement evaluation at The University of Texas Center for Transportation Research and the Pavement Management Unit of the Maintenance Division of the Texas State Department of Highways and Public Transportation (SDHPT).

The sheer size of the Texas network has limited the possibility of applying one complete overriding PMS concept for all purposes. Based on numerous efforts, meetings, and discussions in the past two years the following modified objectives are recommended as the most feasible next step in improving pavement management in the Texas State Department of Highways and Public Transportation (SDHPT).

(1) Intensify coordination of pavement management between the pavement group in D-18 and the pavement design group in D-8. This can perhaps best be accomplished by moving the D-18 group to the LaCosta office complex.

(2) Establish a formalized data collection and retention activity for the wide variety of research and experimental sections which have been constructed and observed on the Texas highway system during the past 10 to 20 years. This activity can be carried out through the Center for Transportation Research and the Texas Transportation Institute, as research arms of the Texas State Department of Highways and Public Transportation (SDHPT).

(3) In conjunction with the activities outlined in item 2 above establish a statistically sound sampling activity to permit collection of data and information on a factorial of Texas highways covering a wide range of design, materials, environmental, and traffic variables. This data base will provide Texas State Department of Highways and Public Transportation (SDHPT) with

information which can be used to produce a wide variety of essential models.

(4) Continue on-going research activities so that the data obtained above will be available for use in improving models, design methods, maintenance cost estimates, rehabilitation benefits and other related input needs for future PMS improvements.

(5) Establish a framework for continued input from Texas State Department of Highways and Public Transportation (SDHPT) field and central office personnel. This should be accomplished by renewing the semiannual meetings of the PMS Task Force or by establishing a new subgroup under the auspices of the Design Division or the Pavement Research Advisory Committee.

(6) Continue research on an improved network optimization concept for PMS use at the true network level in Texas State Department of Highways and Public Transportation (SDHPT).

CHAPTER 2. APPLICATIONS OF PAVEMENT MANAGEMENT

BACKGROUND

The process of pavement management has been developed to respond to several needs and issues:

(1) pavements represent a substantial investment in transportation, and any investment of this magnitude deserves good management,

(2) substantial expenditures are required each year to preserve and maintain this investment, and, because this involves a large number of technical and economic factors, good management is needed to efficiently coordinate and carry out the work and at the same time ensure economical results, and

(3) available funds for investments in pavements, and for maintenance, are generally limited, and good management is essential to obtain maximum value for these limited dollars.

Pavement management is a broadly based process which incorporates the set of all activities required to provide and maintain pavements. These activities range from the initial planning and programming of investments to design, construction, in-service monitoring, evaluation, maintenance, and research. The basic objective of pavement management is to obtain the best value possible for public funds expended on pavements. This can be accomplished by systematic coordination of methods and procedures and using existing technology as efficiently as possible (Refs 4 and 8).

This chapter addresses (1) the historical development of pavement management (2) some of the critical issues and questions which still face us, and (3) the definition of pavement management as a logical and sequential process within which further developments and improvements can be accomplished.

PMS DOES NOT MAKE DECISIONS -- ADMINISTRATORS DO

It will never be possible to use quantitative criteria exclusively in applying decision rules to engineering projects, including pavements. It will always be necessary to use qualitative judgement in systems involving human input, and, thus, it is emphasized that the system or the computer used on the system does not make decisions but, rather, processes information for use by the administrator or decision-making team.

In the 1970's it became more apparent that other aspects of pavement management were at least as important as improved pavement design. While consideration of budgeting and cost benefit analyses at the project level were important, it became clear to many people that greater savings were to be gained by applying a type of pavement management at the network level. This involves consideration of the relative importance of pavement investments, not on a specific project but among a variety of projects, to see that funds are applied in the most beneficial way in order to gain the greatest benefits for the taxpayers and highway users.

CRITICAL ISSUES AND QUESTIONS

Pavement management has now progressed to a working process. In addition, many agencies are implementing their own pavement management systems. Some are already well underway in Idaho, Arizona, Washington, and other states.

However, because pavement management is still in a state of development and considerable implementation experience is still required, a number of critical issues and questions exist. These differ in focus and scope, depending on the government, the agency (i.e., Federal, State, City, or County), or the management level involved. These questions and issues can be conveniently categorized in terms of three basic levels of interest: legislative, administrative, and technical, as illustrated in Fig 2.1. The following paragraphs provide examples under these three categories.

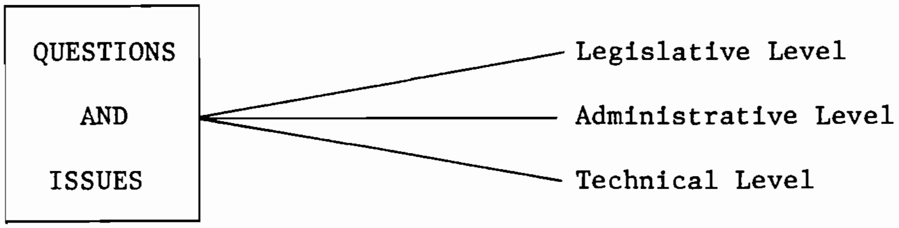


Fig 2.1. A categorization of pavement management issues and questions.

Legislative Level

The issues and questions at the legislative level are fairly broad in scope but have to be recognized by the administrative and technical levels. They include the following:

(1) Justification of Budget Requests. Legislators are faced with a variety of competing demands and those that "make the case" in a clear, properly supported manner are likely to receive more favorable consideration.

(2) Effects of Less Capital and/or Maintenance Funding. Legislators may well ask what the short and long-term effects are of less funds, perhaps of even a zero capital budget, and should be able to get answers as to deterioration of serviceability, extra maintenance costs, eventual replacement costs, effects on users, etc.

(3) Effects of Deferring Work or Lowering Standards. The question related to lower funding is that of deferring maintenance and rehabilitation, or lowering the standards. Again, the same answer as that above should be available from a good pavement management system.

(4) Effect of Budget Request on Future Status of the Network. Even if a funding level matching the budget request is approved, a key question relates to the effect that will have on the status of the network. Will the average serviceability or condition of the pavement worsen, improve, or stay the same? Alternatively, there may be a question as to the level of funding required to keep the network in its present state.

(5) Effects of Increased Load Limits. This is an example of the type of issue facing many legislative bodies. Obviously a good pavement management system should be able to supply the technical and economic answers.

Administrative Level

The administrative and planning people responsible for developing capital spending and maintenance programs (i.e., state highway administrators, division heads for planning, maintenance, etc.) need to recognize explicitly and respond to legislative level issues, and they require certain answers from the technical level, in addition to facing questions at their own level. In other words, there is overlap in both directions at this level. Some issues and questions, for example, are

(1) An objectively based priority program to provide justification for budget requests.
(2) A summary assessment of the current status of the network, in graphical and tabular forms, based on inventory measurements.
(3) The means for quantitatively determining the effects of the lower budget levels and/or the budget level required to keep the network in its present state.
(4) The means for quantitatively demonstrating the effects of deferring maintenance or rehabilitation.
(5) Estimates of the future status of the network (in terms of average serviceability, condition, safety, etc.) for the expected funding.
(6) Benefits of a pavement management system, its major features or "deliverables", etc.
(7) Costs of pavement management implementation, including (1) inventory, (2) assignment of responsibility, (3) manpower requirements, and (4) implementation staging and scheduling, etc.
(8) Implementation experience of others; documentation of such experience.
(9) Relationship between pavement management and any existing maintenance management system.
(10) Interfacing a pavement management system with highway management in general.

Technical Level

From a technical perspective, pavement management involves a large number of issues and questions. In addition, the questions and issues faced at the administrative and legislative levels must be appreciated if technical activities are to be meaningful.

The following is a listing of some of the key questions for this level, involving both network and project considerations:

(1) Inventory data base design and operation.
(2) Methods for and adequacy of inventory data base.
(3) Models for predicting traffic, performance, distress, skid, etc. -- their reliability, consistency, reasonableness, deficiencies, etc.
(4) Criteria for minimum serviceability, minimum skid, maximum distress, minimum structural adequacy -- reasonableness, effects of changes in criteria, etc.
(5) Models for priority analysis and/or network optimization.
(6) Verification of models.
(7) Relating project optimization or sub-optimization to network optimization.
(8) Methods for characterizing materials and using results.
(9) Sensitivity of model analysis results to variations in factors.
(10) Relationships between vehicle operating costs and pavement characteristics.
(11) Construction quality control.
(12) Effects of construction and maintenance on pavement performance.
(13) Communication between design, construction and maintenance, within existing administrative structure.
(14) Guidelines for pavement management implementation.
(15) Relating pavement management to maintenance management.
(16) Improving the technology of pavement management and making use of implementation projects for this purpose.

CHAPTER 3. REORGANIZING THE PMS CONCEPT

INTRODUCTION

The Texas State Department of Highways and Public Transportation (SDHPT) has been developing parts of a good pavement management system (PMS) since 1970 and currently has the evaluation portion of a working system, called Pavement Evaluation System (PES). The recent discussions within the SDHPT administration in December 1983 reflected continued interest in pavement management and support for continued development and implementation. A strong commitment by Texas SDHPT top management is necessary for the successful development of an improved pavement management system (PMS).

The objectives of this review are to assist the Texas SDHPT in identifying the current problem areas and existing weaknesses in pavement management practices and to promote the improvement of pavement management practices in Texas. First, in this report, we will discuss an ideal PMS and compare it with the current status of PMS in the Texas SDHPT. Then we will discuss overall direction with specific recommendations for improving and implementing an improved system department-wide as various elements became operational.

THE IDEAL PMS

A system can be defined among other ways as "a collection of mutually interacting components that are affected by some exogenous inputs." In a pavement system the mutually interacting components are usually a surface layer, including a traffic lane and shoulder, a base layer, a subbase layer, and a subgrade. The outside inputs which affect the pavement characteristics are environment, traffic, and maintenance. The maintenance inputs keep the pavement system from deteriorating from the negative impacts of traffic and environmental inputs to the pavement. Such a pavement system is shown in Fig 3.1.

The pavement management system (Fig 3.2) consists of such mutually interacting components as planning, design, construction, and maintenance. Some of the exogenous inputs affecting a pavement management system's characteristics are budgets, necessary data or information, and non-quantifiable administrative policies. Figures 3.1 and 3.2 are structured according to the definition of the system, but emphasize differences between a pavement system and a pavement management system.

An ideal pavement management system yields the best possible value for the available funds while providing and operating smooth, safe, and economical pavements. The minimum requirements of such a system include (1) adaptability, (2) systematic operation, (3) practical application, (4) quantitative decision making, and (5) feedback information. It may be obvious, but no single PMS is best for all agencies. Every agency presents a unique situation and has specific needs. Therefore the Texas SDHPT must define very carefully what it wants from a pavement management system.

INFLUENCE LEVELS OF PMS SUBSYSTEMS

In conventional terms, four subsystems (planning, design, construction, and maintenance including rehabilitation) have equal shares in the total PMS. In some cases, the planning subsystem may be emphasized more than the others in terms of the "level-of-influence" concept which shows how the effect on the total life-cycle cost of a project decreases as the project evolves. This concept is not new and has been used in sectors of industry, such as manufacturing and heavy-industrial construction (Ref 14).

Figure 3.3 illustrates essential features of the "level-of-influence" concept. The lower portion of the figure presents a simplified picture of the life of a pavement in a bar chart for four subsystem activities. The upper portion includes plots of increasing expenditures and decreasing influence. The bar chart and both curves are plotted against the same abscissa: time or traffic as related to the pavement life. Expenditures

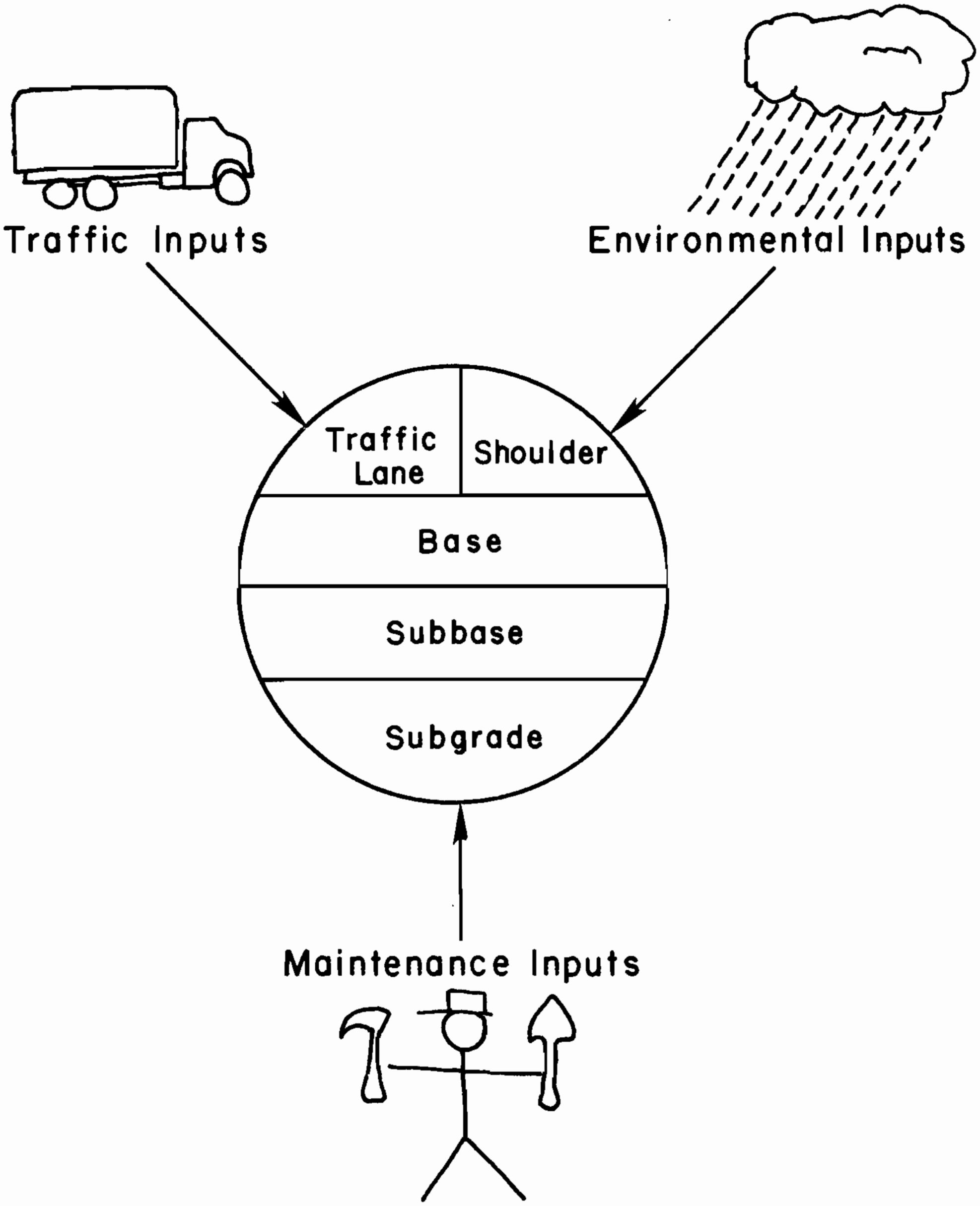


Fig 3.1. Pavement system.

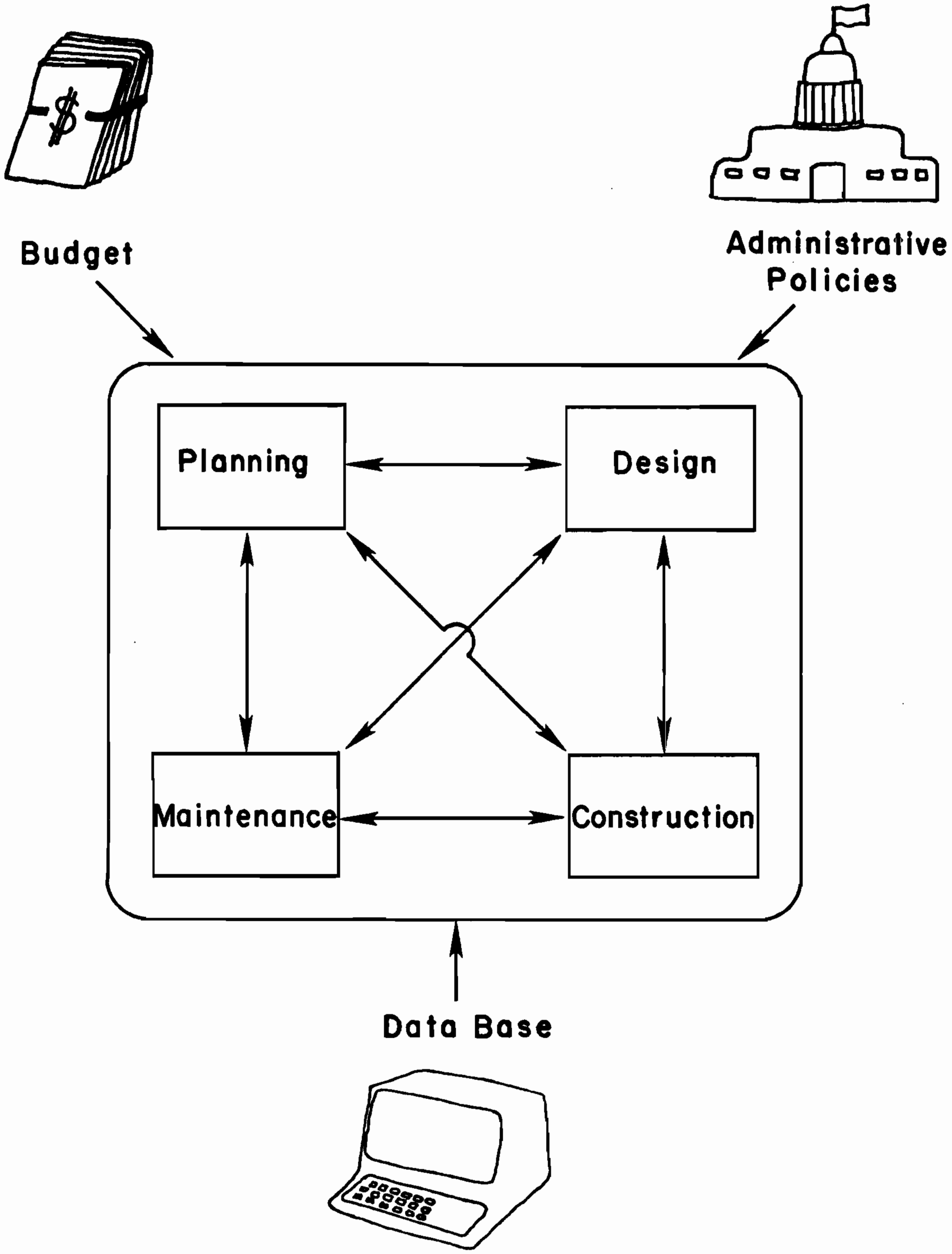


Fig 3.2. Pavement Management System.

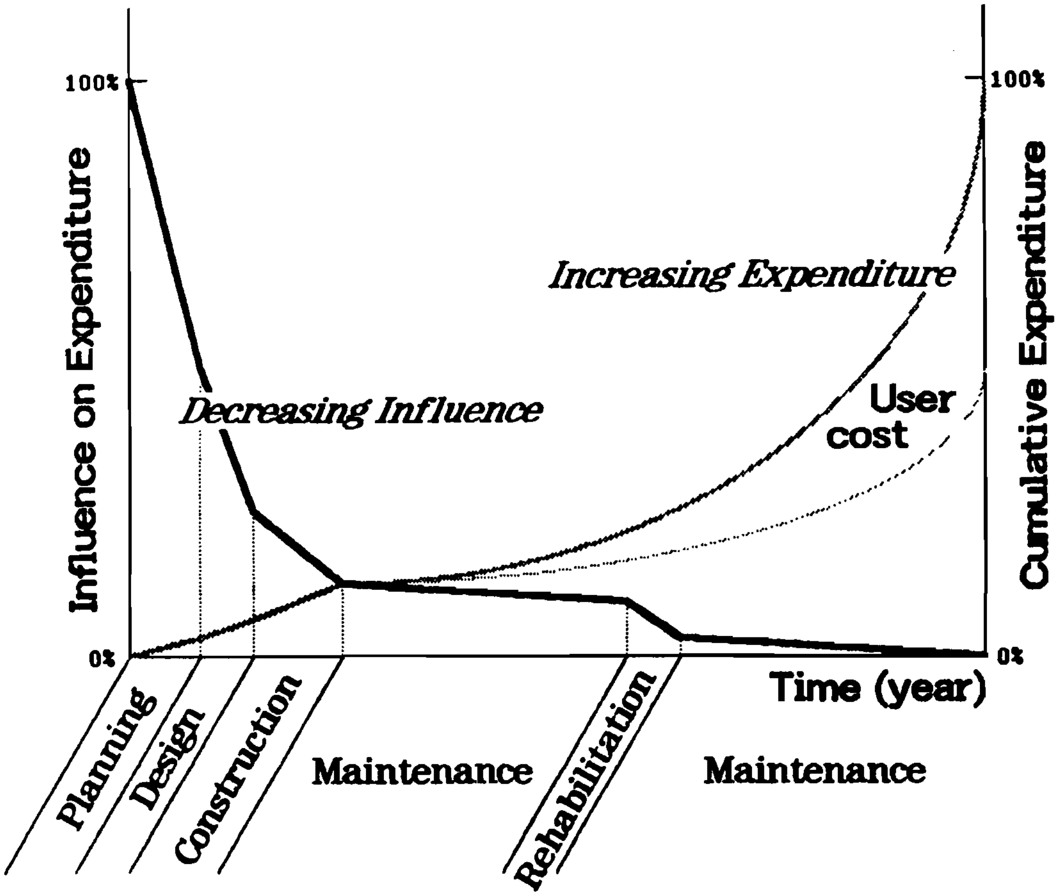


Fig 3.3. Influence level of four PMS subsystem on the total cost.

during the planning phase are relatively small compared with the total cost. Similarly, the capital costs for construction are but a fraction of the operating and maintenance costs associated with a pavement life cycle. However, the decisions and commitments made during the early phases of a project have far greater relative influence on later required expenditures than some of the later activities.

At the beginning of a project, a highway agency controls all (100 percent influence) factors in determining future expenditures. The question is: To build or not to build? A decision not to build requires no future expenditure for the project. A decision to build requires more decision making, but initially at a very broad level. For example, shall they build a flexible pavement or a rigid pavement, and, if rigid, with joints or continuously reinforced? How thick should they make it and with what kind of materials? Once decisions are firm and commitments are made, the further level of influence of future actions on the future project costs will decrease.

In the same manner, decisions made during construction, even within the remaining level of influence, can greatly impact the costs of maintaining or rehabilitating the pavement. Lack of quality control in the construction phase or substitution of inferior materials may save a few dollars in construction costs, but costs resulting from the extra maintenance that will be required, and from the traffic delays to users due to more frequent maintenance activities, will consume those savings many times over.

With construction of the highway completed, attention is now given to maintaining the existing pavement at a satisfactory level to satisfy the public. The level-of-influence concept can also be applied to the subsystems of a maintenance management system (MMS). Expenditures during the planning phase of rehabilitation are relatively small compared to the total maintenance cost. However, the decisions and commitments made during early phases of a rehabilitation project have far greater relative influence on what other maintenance expenditures and user costs will be required later.

PMS DECISION LEVELS

Conventionally, the decision making process of the pavement management system is divided into two levels: (1) the network level and (2) the project level. The network level traditionally includes programming, budgeting, and planning activities, while the project level includes design, construction, and maintenance activities. The so-called network level should be further divided into two levels, (1) the project selection level and (2) the program level. The project selection level involves a prioritization procedure concerning one or more groups of projects. The program level involves an overall budgeting process and general fund allocations over an entire network.

This three-level concept is not new, but the two levels mentioned earlier have been used interchangeably in many papers and reports. For example, in some papers when "project level", is mentioned, the "project selection level" actually may be meant. In other cases when the "network" level is mentioned, what it actually meant is the "program" level.

Decisions at three different levels must interface with one another. A total PMS functions at all decision levels from the project level to the program level. For example, the interaction between project selection level and program level is evident if one considers that, a good estimate of the budget to be used at the program level requires information on the candidate projects for rehabilitation. The decisions at the project selection level are influenced by the decisions at the program and project level, and vice versa.

This three-level concept is illustrated in Fig 3.4. The lower-left triangle is an unreliable area because too little information is available for models at the project level, and the upper-right triangle is an area infeasible for modelling due to the size and complexity of the required models. As the size of the model increases, the detail of information should decrease and vice versa. Three levels of PMS are shown in the diagram, according to the previous definition. The boundaries of the three levels are not clearly delineated of course and need not be at this point.

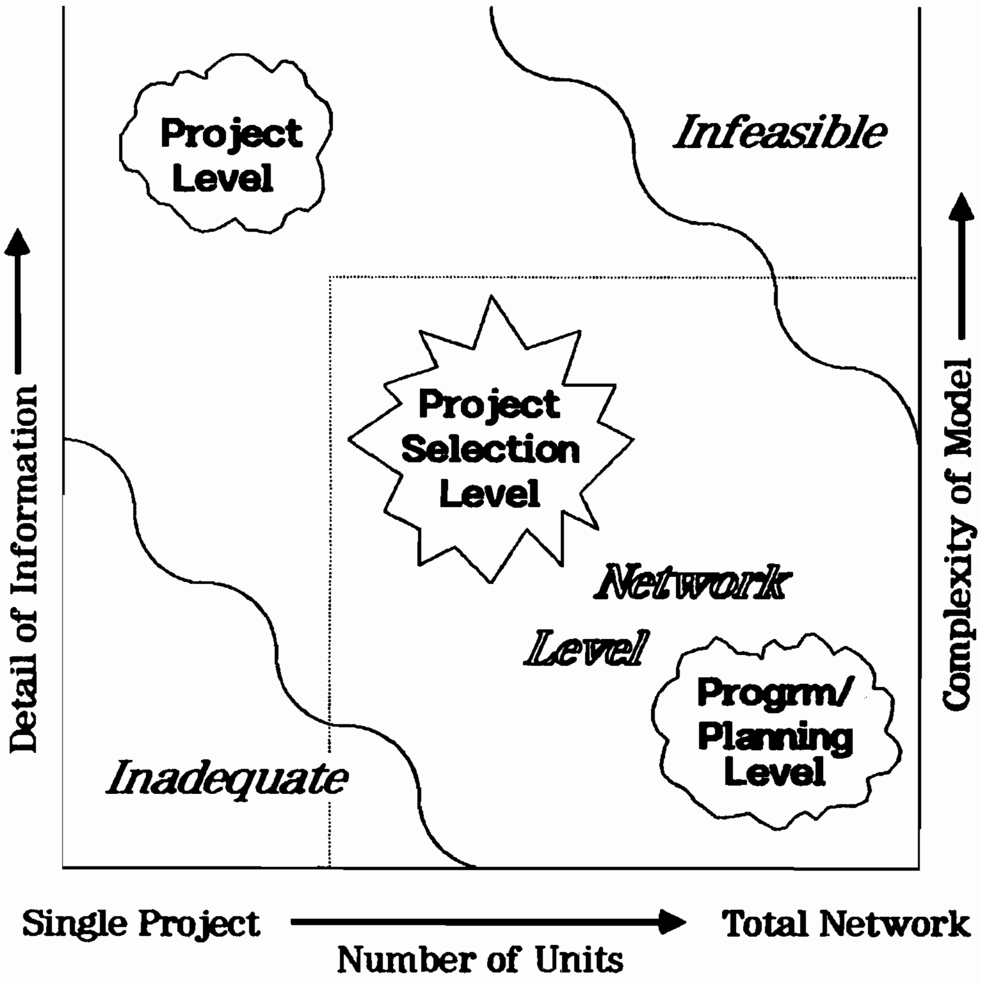


Fig 3.4. Level of PMS models.

PMS MODELS AT THREE DECISION LEVELS

In the previous section, the PMS process was divided into three decision making levels: (1) project level, (2) project selection level, and (3) program level. Several computer programs are currently available for use at one or more of the PMS decision levels. Some that are closely associated with the Texas State Department of Highways and Public Transportation (SDHPT) are discussed here:

Project Level

The PMS models at the project level deal with technical management concerns, such as detailed design decisions, regarding an individual project. The models require detailed information on an individual section of pavement, as described in Fig 3.4.

The inputs for project level models include load, environmental factors, materials characteristics, construction and maintenance variables, and costs. The specific information needed varies depending on the models in the system. The typical output from the models would be a set of design strategies that minimize total costs, including construction, maintenance, and user costs, while satisfying physical and administrative constraints, such as performance requirements and fund availability.

Example pavement design models include: Flexible Pavement Design System (FPS) (Ref 18) is one of the first major working PMS models developed at the project level. This FPS computer program may or may not be the best available PMS model, but it was the first available fully automated pavement design system. Rigid Pavement Design System (RPS) (Ref 16) was the first and may be the only currently available working PMS model relating to rigid pavements at the project level. System Analysis Method for Pavements (SAMP) (Ref 1) has a broader application than most existing working pavement system at the project level. It is widely applicable and relatively simple to apply. The SAMP series illustrates how a simple working system, once developed, can be extended and improved. Any of these three system models will be useful guides to setting up a pavement management system at the project level.

Project Selection Level

The project selection level involves programming decisions or selecting sections for funding from groups of projects as opposed to the program level which involves information and general budget allocation decisions for an entire highway network. The models employed at the project selection level are geared to less detailed data for a set of projects under consideration than ones at the project level, as described in Fig 3.4. The models at the project selection level can be categorized into two groups: prioritization models and optimization models. Currently most highway agencies are mainly interested in models at the project selection level. The two types of model formulations at the project selection level are discussed in the following paragraphs with concentration on their differences.

Prioritization Models. A prioritization model is used to select candidate projects for action (maintenance or rehabilitation) by the ranking method. In order to select projects for pavement rehabilitation several highway agencies have developed pavement rating systems to quantify the condition of each segment separately. Using these quantifiable attributes of pavement condition, prioritization models (or prioritization indices) are developed without consideration of maintenance (rehabilitation) strategies. In Texas, the deduct point system has been used to derive a utility function for calculating pavement scores in order to prioritize the candidate projects in the Pavement Evaluation System (PES) (Ref 7).

Optimization Models. Optimization is maximization or minimization of an objective function subject to a set of constraints. Optimization models are popularly used for analyzing complex systems problems in industry or government. An optimization model in the context of pavement management is a mathematical description or algorithm designed to compare alternative strategies and to identify the relative merits of each maintenance strategy according to assigned decision criteria, such as safety, cost, etc. Optimization models at the project selection level deal with a selected set of pavement sections instead of the entire highway network. In Texas, the Rehabilitation and Maintenance System (RAMS) (Ref 6) has been developed as an optimization model at the project selection level. The RAMS model is now being reviewed by the Texas State Department of Highways and Public Transportation (SDHPT) for possible use as a project selection level model.

Program Level

The program level involves making policy decisions regarding pavement rehabilitation for the entire highway network as a whole. At the program level allocation of budgets is the major concern, and the models should be designed to optimize the use of funds allocated to pavement rehabilitation. At the program level, the entire network should be considered, rather than individual projects.

Data is needed to determine the existing condition of the network as a whole. This includes traffic data and other condition data such as cracking and roughness, and the processing of the data, all directed toward providing the basic foundation for conducting the program level analysis. These data will be used to select rehabilitation policies such as the goals and standards for different classes of roads in the network. The initial program can be set up based on the random sample data over the entire network as a start to know what the current condition of the network is.

As described in Fig 3.4, due to the size of the network and the complexity of the modelling process, two approaches can be used at the program level. One is to set up a program using random sample data over the entire network as an estimate of the current condition of the network. Obviously such data cannot be used to define each section individually but accurate estimates of the network are possible. The other approach is to categorize all pavements in the network into different strata using simple, and quantifiable pavement attributes such as functional class, serviceability, or cracking. Optimization models then use the strata, which are less than the number of individual sections in the network, to develop a systematic or near optimal rehabilitation policy. These policies will achieve desired performance standards on various classes of roads in the network with near minimum cost.

An optimization model has been developed and applied in the State of Arizona for use in a program level PMS (Ref 5). It is based on the formulation of the problem as a Markovian decision process and a linear programming technique was used to solve the problem. The objective of that model is to determine the rehabilitation policy that achieves and maintains specified performance standards for the statewide highway network within minimum cost. The model was developed based on an overall proportion of the total network instead of specific individual pavement sections. Based on these general results, individual projects must be selected at the project selection level.

THE CURRENT STATUS OF THE TEXAS PMS

The Texas SDHPT currently has in service a pavement evaluation system (PES) as its first network level PMS. The primary objectives of PES are to monitor, obtain, and use pavement condition data on a consistent basis to determine the statewide "current" condition of the pavement network. A first round of evaluation of a portion of the Texas pavement network for ride quality and pavement distress for flexible pavements was begun in October 1982 and completed in January 1983.

A second round of pavement evaluation was begun in October 1983 and is now complete. As of 1 March 1984, in the second round of evaluation, the Texas SDHPT reviewed the pavement distresses used in the analysis process and simplified the surveys by eliminating ravelling and flushing data from PES. They also evaluated sampling techniques and changed the sampling procedures and amount. While there were a few problems in the segmentation of the system data collection and data processing, the first round of implementation was considered highly successful by the SDHPT. Currently the SDHPT is adapting an evaluation system for rigid pavements into the PES program.

The Rehabilitation and Maintenance System (RAMS) developed by Texas Transportation Institute (Ref 6) is now being tested as a method for optimizing the effectiveness of rehabilitation activities subject to given resource constraints. The RAMS-District Optimization (DO-1) model is being reviewed for implementation. This model provides an estimate of rehabilitation needs for a one-year planning horizon. Efforts are being made to improve and expand PES into a pavement management system. Directions and specific recommendations for improving the PES are addressed in the next chapter.

CHAPTER 4. IMPROVING PAVEMENT MANAGEMENT IN TEXAS

ORGANIZATION

The Texas SDHPT is interested in developing an improved pavement management system, as evidenced by the meetings held in December 1983 to assure the highway administration's support for continued PMS development.

What are the pavement management related responsibilities, and which Divisions or Sections are charged with these responsibilities? Does the Texas SDHPT establish a formal pavement coordinating group or a special pavement management office? Figure 4.1 is a chart of the Texas SDHPT organization as of December 1984 with a special pavement management office added under the Safety and Maintenance Operation Division. Pavement Management is such a broad concept that it can be related to most sections of the Department.

The Texas SDHPT established a PMS Task Force but it has not been active since 1983. Does this committee provide direction to the development of an improved PMS in a straightforward, and logical fashion? In view of Texas SDHPT activities to date a few recommendations need to be addressed.

(1) Strong input from the PMS Task Force and strong leadership are needed in order that the current PES activities can continue toward the development and implementation of an improved PMS.

(2) As shown in Fig 4.1, a special pavement management office has been established under the Safety and Maintenance Operation Division, in order to speed up PMS activities. This office will concentrate on leading the PMS process effectively, through vertical and horizontal communications among all the related groups.

(3) The responsibilities of individuals or groups related to PMS activities need to be spelled out for clear understanding.

(4) The establishment of the pavement management office will facilitate the flow of information among district engineers on a horizontal

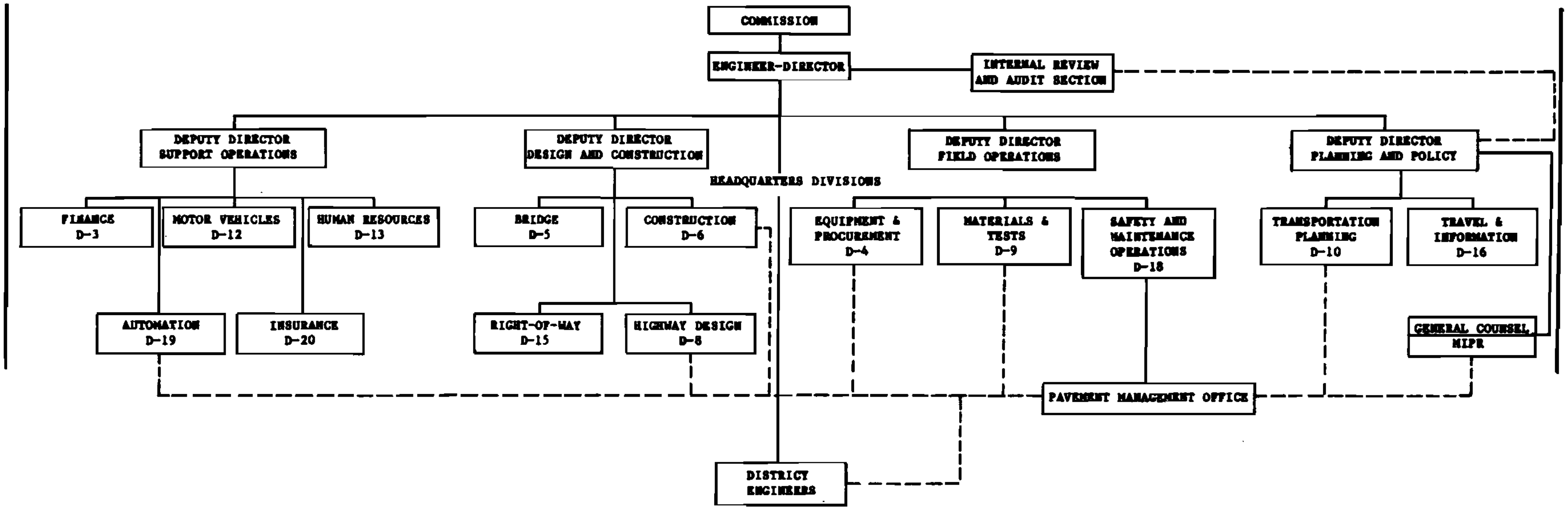


Fig 4.1. Texas State Department of Highways and Public Transportation (SDHPT) organizational chart (December 1984), with a pavement management office added under the Safety and Maintenance Operations Division.

level. This office will help the SDHPT headquarters to interact with district personnel more effectively as the pavement management system is being developed and improved.

PAVEMENT EVALUATION SYSTEM (PES)

As mentioned in previous sections, the Texas SDHPT currently has in service a Pavement Evaluation system (PES) as its first network level PMS. Two rounds of pavement evaluation have been completed. Even though the first implementation of the PES is considered successful by the SDHPT, there are still a number of problems and limitations in the segmentation of the highway system, training, data consistency, etc.

The PES is still in the early stage of development and use; the first output reports were available in February 1983. [In order to improve the current PES, first, there should be continuous interaction between SDHPT headquarters and Districts to ensure that the PES inputs are collected and that the PES outputs are used effectively.< Second, further improvements to the computer programs and the models, such as the utility functions, will help alleviate current problems. Third, a method is needed that identifies a rehabilitation strategy to correct the pavement deficiencies and estimates rehabilitation costs to determine the minimum budget levels required to maintain alternative levels of pavement condition. Recommendations to improve the PES are further discussed below.

(1) The PES should not only provide pavement condition trends by geographical area, broad-based highway system, and functional class, but it should also indicate trends of individual pavement condition for a given section of highway. The trend of each pavement section's performance history is a useful tool for predicting the future behavior and life of the pavement. In 1984-85, the SDHPT is collecting condition data in Texas for all the interstate highway mileage, 50 percent of U.S. and State highways,

20 percent of FM roads. Under these constraints we might have to wait several years to get adequate trend information about pavement performance of primary and secondary roads. However, it is important to know how rapidly each type of individual pavement section deteriorates in terms of ride quality and distress under different levels or categories of traffic and environmental conditions. In order to accomplish this, data must be collected from the same pavement sections every year.

(2) With the current records of PES data, it is impossible to know what kinds of rehabilitation actions have been taken on the pavement between any two rounds of evaluation. However, pavement performance history data are also very useful in measuring the effectiveness of different rehabilitation actions. Therefore it is recommended that rehabilitation action data be added to the ride quality and that distress evaluation be recorded upon completion of a rehabilitation. However, justification of data collection and storage cost may be made more difficult in light of the fact that most pavement rehabilitation efforts will mask visual distress data for some period of time; perhaps six months or more should elapse prior to collection. Transfering construction files including ride data upon completion of construction to the PES should be an automated process.

(3) Detailed physical maintenance and cost data are not now recorded in a usable format. Maintenance costs are available only by major category of work and are not tied to or recorded in accordance with the mile post system. As a result, the utility functions used in PES neglect operational maintenance cost. It is recommended that SDHPT begin collecting maintenance cost data for a number of the PES pavement sections in order to obtain a history of relative project related maintenance costs. It should be recommended to the administration.

PREDICTION AS PART OF THE TEXAS PMS ACTIVITIES

Management is important to mankind. It is concerned with the beneficial employment of scarce resources to achieve objectives — the means by which ends are achieved in all social organizations. Prediction is likely to be more effective if it is regarded as a means for achieving an organization's objectives rather than as an end in itself. As illustrated in Fig 4.2, pavement performance predictions need to be tailored so that they serve an SDHPT pavement management system effectively. Pavement performance predictions play an important role in the total PMS, contributing to better planning and design activities.

Much confusion can result from the failure to distinguish between predicting and planning. The two are described as follows:

(1) Predicting tells an engineer what he can achieve if policy remains unchanged.

(2) Planning enables an engineer to take action to change a prediction.

The distinction between predicting and planning can be explained with a pavement example. The pavement may deteriorate more rapidly than predicted under higher traffic volumes and more severe weather conditions than estimated. This has implications for the use of past pavement condition data for predicting future pavement performance since such predictions may be misleading if the effects of traffic changes and weather conditions are not included in the historical data.

Budgets are frequently a prediction based on past performance. Indeed, most highway agencies base their budget plans for pavement rehabilitation on an extrapolation of past trends without considering pavement condition changes.

Figure 4.3 amplifies the relationship between prediction and decision-making. A distinction is made in the figure between policy variables, such as minimum performance requirements, which are generally under the control of SDHPT, and external variables, such as environmental and traffic changes,

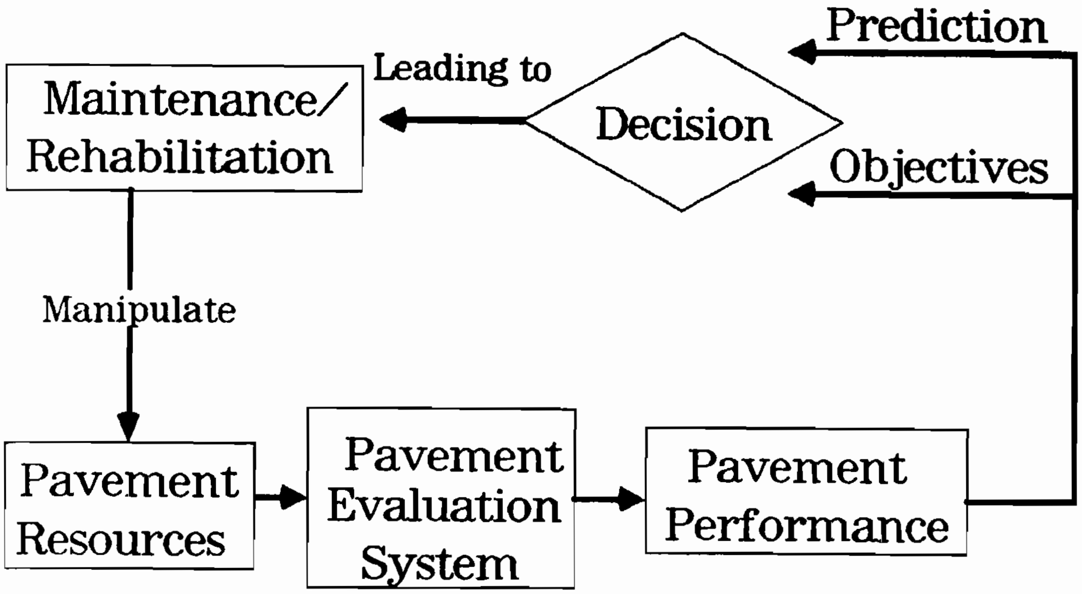


Fig 4.2. Prediction as part of Texas PMS activities.

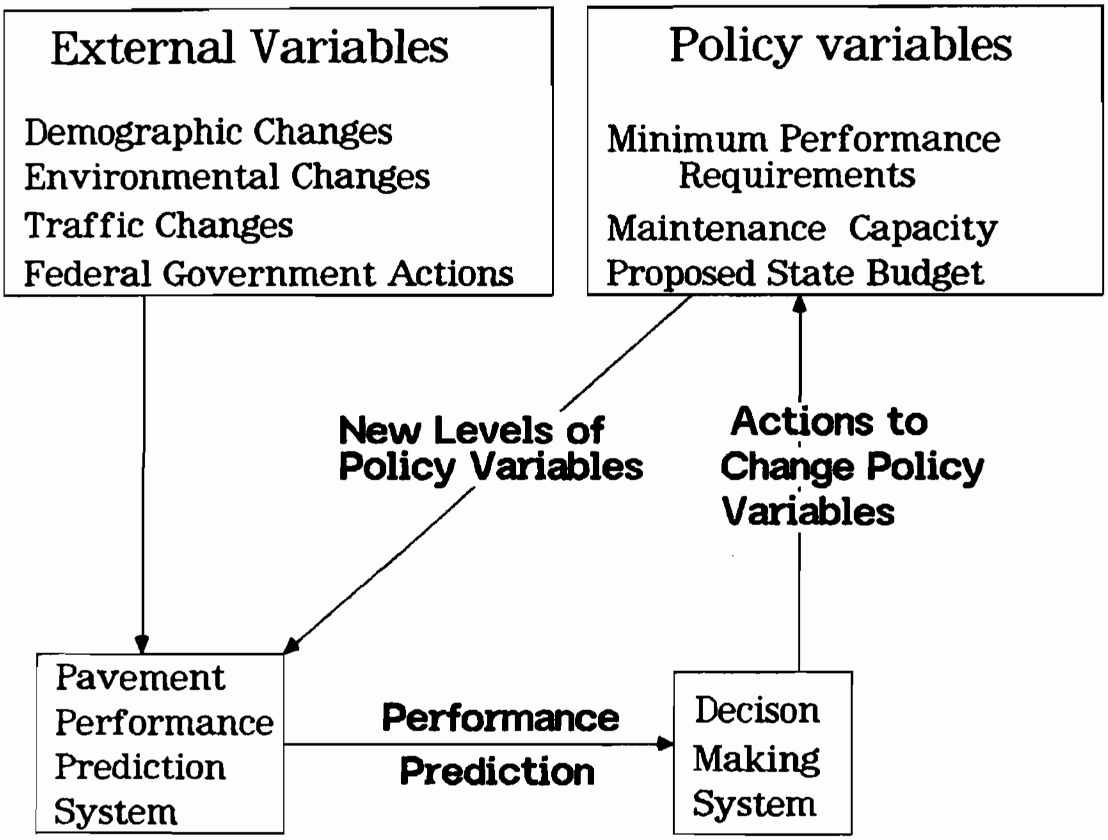


Fig 4.3. Role of Pavement Performance Prediction System in decision making.

which also influence the variables being predicted but are not under the control of the SDHPT.

The following are some guidelines for the development and use of a prediction system (Ref 10):

(1) Define predictions needed to serve the decision making system.
(2) Develop a conceptual model describing mechanisms influencing predictions.
(3) Develop a method for generating predictions.
(4) Conduct experiments to assess the accuracy of predictions and the methods.
(5) Determine how judgements are to be incorporated into predictions.
(6) Implement the prediction system.
(7) Appraise its effectiveness.

Figure 4.4 shows how a pavement performance prediction system could be implemented in an overall pavement management organization in the SDHPT.

NEED FOR HISTORICAL DATA

Each highway agency needs to develop a long-term history of pavement performance data oriented toward pavement management objectives. Long-term and continuous monitoring of roadway deterioration is needed to determine the relative damage attributable to traffic and environmental factors and to predict pavement performance behavior. The National Highway Cost Allocation Study (completed in 1982) examined the data available for determining causal relationships among traffic use, the environment, and maintenance costs. The FHWA Long-Term Monitoring Program (LTM) was established in an attempt to assess the problems of building a national data base that can develop improved pavement damage relationships (Ref 17).

The purpose for developing this historical data base in Texas is to monitor pavement performance closely in order to develop for Texas a wide variety of models and relationships which can be used to improve our ability

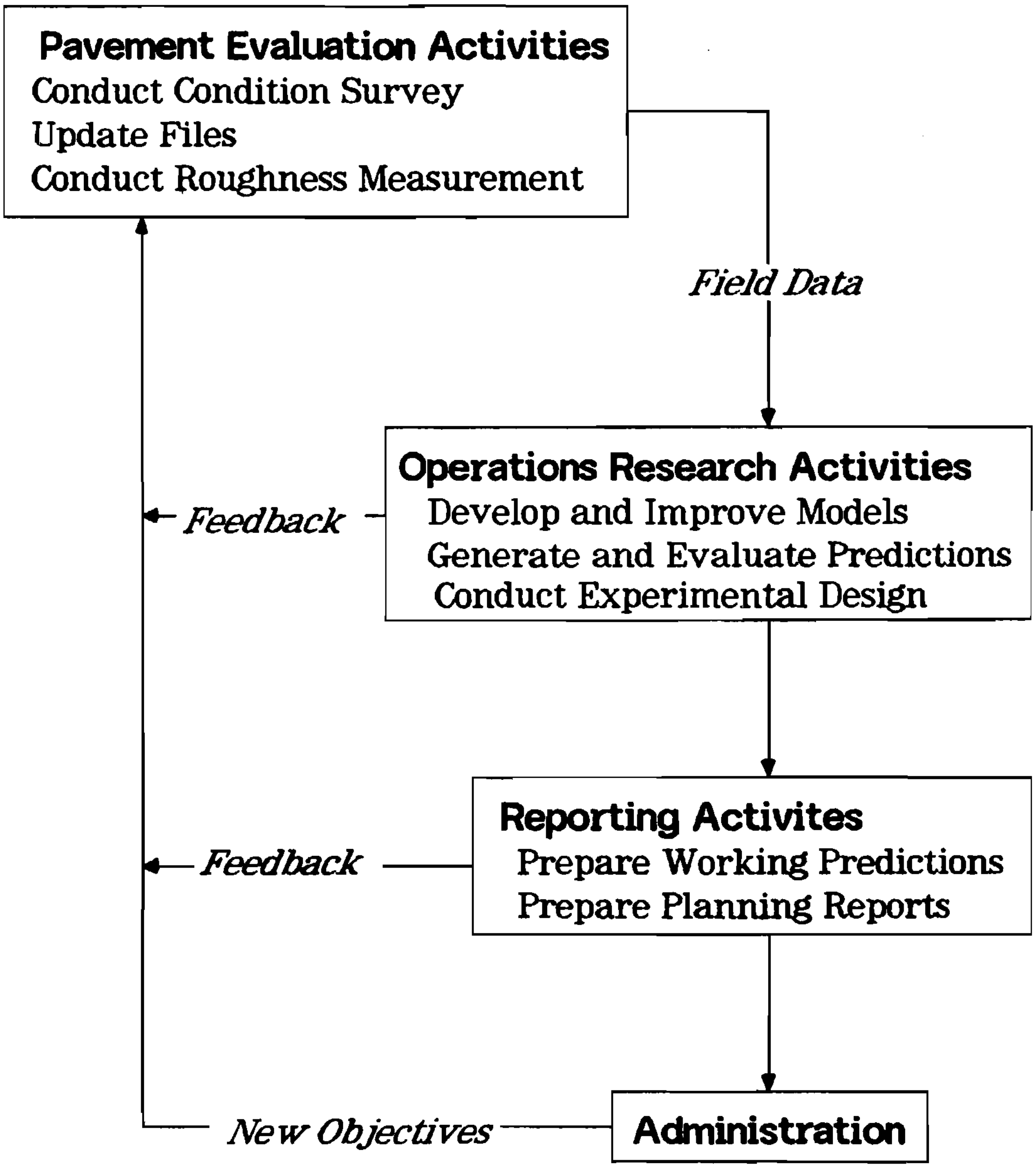


Fig 4.4. Activities of the pavement management for the SDHPT.

to design, maintain, and manage our pavement resources. The scope of this study is concentrated on the state of Texas in order to produce meaningful long-term observation. The data base will be used to verify current prediction models and develop improved pavement performance models including maintenance cost relationships with pavement conditions.

A detailed study of data and sampling concepts should be made before any long-term data collection is started. The data should include, as a minimum; (1) test section identifications and (2) pavement type and highway functional class. It will also be beneficial to reconstruct and record the past history of the pavement section before the monitoring starts. This past history should include

(1) estimated accumulated past traffic and axle-load data,
(2) estimated total accumulated cost and details of construction and maintenance to date, and
(3) pavement condition and serviceability index to date.

The data are required before beginning the monitoring period for any existing pavement.

Routine monitoring data should include

(1) condition surveys,
(2) roughness measurements,
(3) deflection measurements,
(4) traffic and axle load data,
(5) detailed environmental factors, including inches of rainfall and number of cycles of freezing and thawing or temperature,
(6) routine maintenance actions and expenditures, and
(7) rehabilitation actions and expenditures.

These data may be collected on a regular basis, annually seasonally, or monthly, and after major rehabilitation and maintenance activities in order to capture any major costs and changes in condition. The sampling plans for test sections will be based on available budgets and cooperation from the local Districts. This historical data base will be used for developing relationships among (1) distress, (2) roughness, (3) deflection, (4) traffic, (5) axle loads, (6) age, (7) environment, (8) maintenance cost, and (9) rehabilitation cost.

An appropriate sampling base should be selected (1) among available rigid, flexible, and composite pavements, (2) at various functional classes, (3) under various environmental and geographic conditions, and (4) for varied traffic conditions. Figure 4.5 is a simplified diagram which illustrates the hierarchical data base structure for a long-term pavement performance monitoring system.

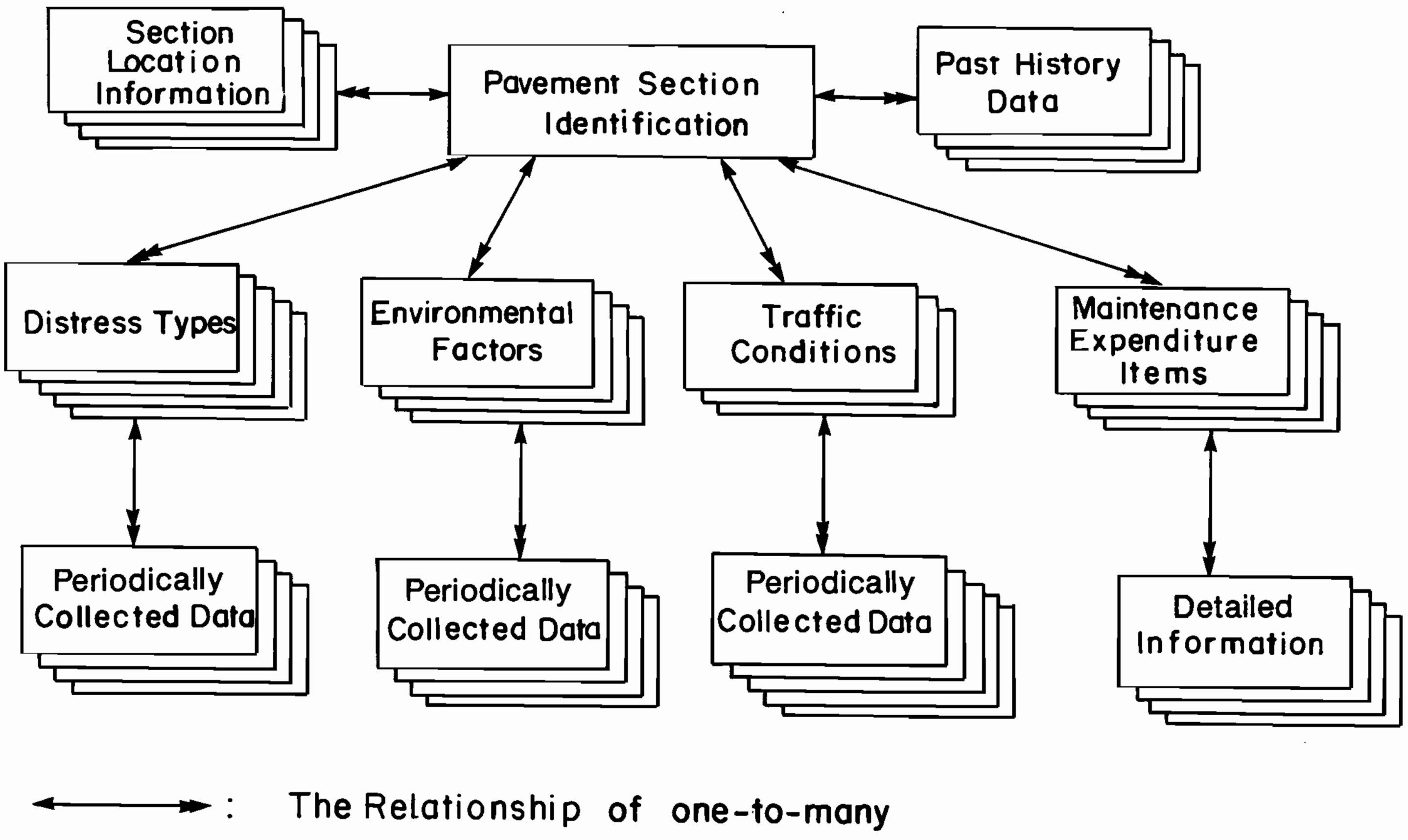


Fig 4.5. Simplified hierarchical data base structure diagram for the long-term pavement performance system.

CHAPTER 5. STOCHASTIC DECISION PROCESSES AND APPLICATION IN PAVEMENT MANAGEMENT

INTRODUCTION

Highway engineers are often faced with the need to devise models for operational systems, for example, pavement management systems. The systems generally contain both probabilistic and decision-making features, so the models can become quite complex and analytically intractable. This chapter presents a structure for a decision making system that is quite general and computationally feasible. It is based on the Markov process and uses a "policy iteration" technique as its optimization model.

In this chapter basic concepts in the Markovian decision process are defined, including "a policy" using a pavement rehabilitation example. When the number of policies is large (as is the case in practice), it is apparent that direct enumeration is not computationally feasible and a simple algorithm for finding the optimal policy is desirable.

First, the algorithm for finding an optimal policy is given by a linear programming technique. The linear programming technique has an important advantage since it can solve very large-scale problems using commercially available computer program packages. This technique has already been implemented in the state of Arizona (Ref 5). A second algorithm is given by a policy-iteration technique. The policy iteration algorithm to be presented is useful in that it often leads to finding the optimal policy quickly and is applicable for more general conditions than previously specified; e.g., under certain assumptions, the time between transitions is random. It is interesting to explore computational methods for solving discrete-time and finite-state problems using this algorithm. A computer program was developed in the project for solving a fairly large-scale problem in practice.

AN EXAMPLE DECISION MODEL IN PAVEMENTS

In this example a highway network includes a section of pavement which is deteriorating rapidly under heavy traffic and severe environmental conditions, which is evaluated periodically, say, at the end of each year. After evaluation (i.e., roughness measurement), the condition of the pavement sections can be classified into one of five possible states in terms of serviceability index (SI):

State	Condition
1	$3.5 \leq SI$
2	$3.0 \leq SI < 3.5$
3	$2.5 \leq SI < 3.0$
4	$2.0 \leq SI < 2.5$
5	$SI < 2.0$

SI = Serviceability Index

The performance prediction of the pavement can be specified through transition probabilities. A transition probability P_{ij} specifies the likelihood that a pavement section in state i moves to state j in unit time (e.g., one year). The transition probability is assumed to depend only on the present condition state i and not on how the specific pavement section reached the condition i. This assumption could impose a limitation on the feasibility of the Markovian decision model application in pavements. However, it is necessary to develop an analytically tractable model, and for obtaining analytical results. A convenient notation for representing these transition probabilities is the matrix form shown in Table 5.1. A sample transition probability matrix was developed based on a highway engineer's subjective opinion for this example decision model. It is shown in Table 5.1.

A corresponding transition diagram of the system illustrating the states and transition probabilities is in Fig 5.1. From the transition matrix in

TABLE 5.1. TRANSITION PROBABILITY MATRIX

(A) TRANSITION PROBABILITIES IN THE MATRIX FORM

State	1	2	3	4	5
1	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}
2	P_{21}	P_{22}	P_{23}	P_{24}	P_{25}
3	P_{31}	P_{32}	P_{33}	P_{34}	P_{35}
4	P_{41}	P_{42}	P_{43}	P_{44}	P_{45}
5	P_{51}	P_{52}	P_{53}	P_{54}	P_{55}

(B) A SAMPLE TRANSITION MATRIX FOR THE EXAMPLE DECISION MODEL

State	1	2	3	4	5
1	0.88	0.08	0.04	0.0	0.0
2	0.0	0.85	0.12	0.03	0.0
3	0.0	0.0	0.8	0.15	0.05
4	0.0	0.0	0.0	0.75	0.25
5	0.0	0.0	0.0	0.0	1.0

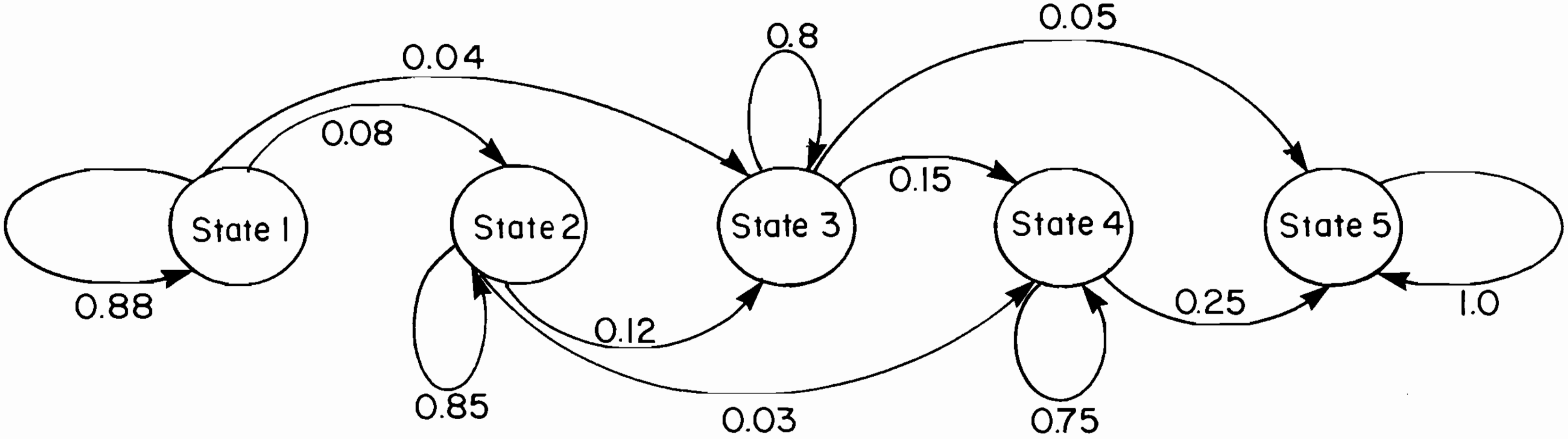


Fig 5.1. Transition diagram of the system.

Table 5.1 and the diagram in Fig 5.1 it becomes evident that once the pavement reaches the worst condition (SI < 2.0, state 5), it remains in the worst condition. Therefore, the analysis of this stochastic process is not of interest because state 5 is an "absorbing state" and eventually the pavement will enter this state and just remain there unless repaired.

Clearly, from a practical point of view this model is infeasible because a pavement cannot continue to remain in the highway network in the worst condition: it should be rehabilitated, replaced, or abandoned. The action of rehabilitation alters the behavior of the system, so that the system now evolves over time according to the joint effect of the probabilistic laws of motion and the action of rehabilitating a pavement in bad condition. The action of reconstructing a pavement in state 5 can be thought of as establishing a rehabilitation policy.

When a pavement reaches its worst condition and is reconstructed, the pavement is renewed, i.e., the pavement moves back to state 1 prior to the next condition survey. The costs incurred include several components. When the pavement section is in state 1, 2, 3, 4, or 5, costs of keeping the pavement section in that state, such as user costs and routine maintenance cost, will be incurred during the next year. However, user costs are very difficult to determine, and, therefore, in this example the expected costs are given only by maintenance cost. Examples are:

State	Expected Routine Maintenance Cost in State $_i$ (2-Mile Lane)
1	\$ 500
2	\$ 1,000
3	\$ 2,000
4	\$ 3,500
5	\$ 7,000

If the pavement is reconstructed, a reconstruction cost of, say, \$15,000 is incurred, and the routine maintenance cost is \$500. Hence, the cost incurred after the system is in state 5 is \$15,500.

The stochastic process resulting from the system under the aforementioned rehabilitation policy, i.e., reconstructing a pavement in state 5, is described by the transition matrix now given in Table 5.2. A corresponding transition diagram of the system with the transition probability matrix in Table 5.2 is shown in Fig 5.2.

Now, it is necessary to compute the cost of this "rehabilitation policy" to be used for finding a minimum cost optimal solution among numerous rehabilitation policies. The steady-state equation can be written as (Ref 11)

$$\begin{aligned}
\pi_1 &= 0.88\ \pi_1 + \pi_5 \\
\pi_2 &= 0.08\ \pi_1 + 0.85\ \pi_2 \\
\pi_3 &= 0.04\ \pi_1 + 0.12\ \pi_2 + 0.8\ \pi_3 \\
\pi_4 &= 0.03\ \pi_2 + 0.15\ \pi_3 + 0.75\ \pi_4 \\
\pi_5 &= 0.05\ \pi_3 + 0.25\ \pi_4 \\
1 &= \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5
\end{aligned}$$

where

π_1 = the probability that the system occupies the i^{th} state after a long period of time.

The simultaneous solution is

$$\begin{aligned}
\pi_1 &= 0.39 \\
\pi_2 &= 0.21 \\
\pi_3 &= 0.20 \\
\pi_4 &= 0.15 \\
\pi_5 &= 0.05
\end{aligned}$$

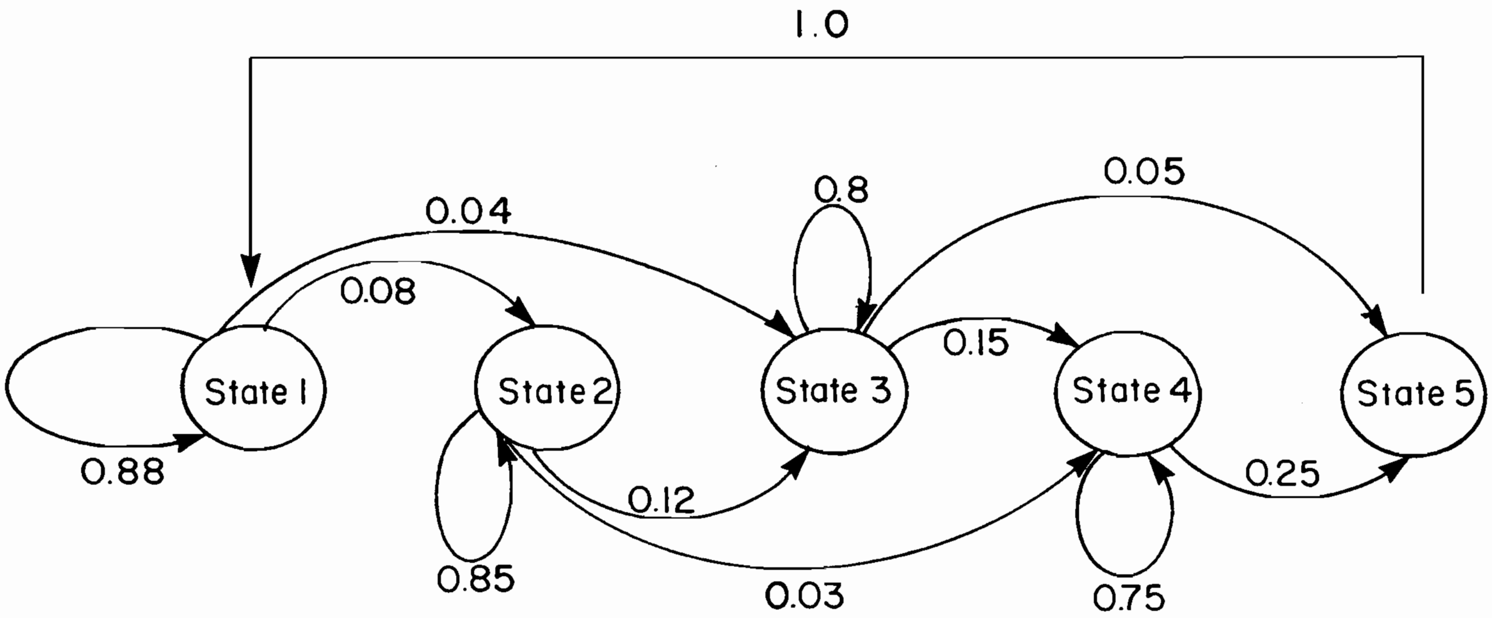


Fig 5.2. Transition diagram of the system with the policy of reconstructing a pavement in the state 5.

TABLE 5.2. TRANSITION PROBABILITY MATRIX FOR THE POLICY OF RECONSTRUCTING PAVEMENT SECTIONS IN STATE 5.

State	1	2	3	4	5
1	0.88	0.08	0.04	0.0	0.0
2	0.0	0.85	0.12	0.03	0.0
3	0.0	0.0	0.8	0.15	0.05
4	0.0	0.0	0.0	0.75	0.25
5	1.0	0.0	0.0	0.0	0.0

Hence the long-run expected average cost per year is given by

$$500 \cdot \pi_1 + 1{,}000\ \pi_2 + 2{,}000\ \pi_3 + 3{,}500\ \pi_4 + 15{,}500\ \pi_5 = \$2105$$

and this represents the cost of this rehabilitation policy, that is the policy to reconstruct pavements in state 5, and do routine maintenance only in other condition states (states 1, 2, 3, or 4).

A SUCCESSFUL APPLICATION IN ARIZONA (REF 5)

The pavement management system used for the state of Arizona is based on this Markovian Decision Process concept using a linear programming technique as a solution algorithm as described in the previous section. It is termed the Network Optimization System (NOS). Two functions of the NOS are (1) determination of the rehabilitation policies that achieves prescribed performance standards at a minimum cost, and (2) by iteration, determination of the highest standards that can be maintained with a fixed budget. The main steps involved in the NOS are (1) generation of feasible alternative rehabilitation policies, (2) prediction of future performance of the highway network and the total cost under alternative policies, and (3) determination of the minimum cost policy.

As applied to the Arizona Highway Network Optimization System, one interesting concept has been presented. Highway engineers are interested not only in making minimum cost decisions about pavement rehabilitation but also in keeping the highway network in good condition to satisfy the public. The constraints that arise out of the specification of performance standards can be added as important constraints to the system. The performance standards may state the minimum proportion of the network that must be in acceptable condition states and the maximum proportion of the network allowed to be in unacceptable condition states.

The potential advantages of implementing the NOS include the following:

(1) The NOS will permit the efficient use of limited funds in maintaining desired performance standards.

(2) The NOS will help maintain a uniform and consistent rehabilitation policy over a long period of time.

(3) In the NOS, decisions about rehabilitation actions are based on the most current information about the condition of various pavements in the network.

(4) The NOS will permit monitoring of the predicted system performance and cost against the observed performance and cost.

(5) The NOS will enable the Arizona DOT management to estimate consequences of significant changes in pavement rehabilitation budgets.

POLICY ITERATION SOLUTION TECHNIQUE TO MARKOVIAN DECISION PROCESSES

Consider an M-state Markov process described by a transition-probability matrix and a cost matrix. Suppose that the process is allowed to make transitions for a very long time and that we are interested in the cost of the process. A useful quantity is the average cost of the process per unit time. It is called the cost of the process, and can be defined as

$$c = \sum_{i=1}^{M} \pi_i q_i$$

where

π_i = the probability that the system is in state i after a large number of moves,

q_i = the expected cost in the next transition out of i, and

c = the cost of the system.

If we have several such processes and we should like to know which would be the least costly process on a long-time basis, we could find the cost of each and then select the one with minimum cost.

Selection of the policy can be defined as the set of decisions for all states thus determines the Markov Process that will describe the operations of the system. An optimal policy is defined as a policy that minimizes the cost or the average cost per transition (say one year if the transition occurs every year).

The policy-iteration method that will be described can find the optimal policy in a small number of iterations. It is composed of two parts, the value-determination operation and the policy-improvement routine (Ref 12).

Step 1 Value Determination. The algorithm begins by choosing an arbitrary policy R_1 and calculates the values of c (R_1), v_1 (R_1), ... v_{M-1} (R_1) [v_M (R_1) is chosen equal to zero] using the value determination equation

$$c + v_i = q_i + \sum_{j=1}^{M} P_{ij} v_j \qquad i = 1, 2, \ldots M$$

where

c = the cost of the system,

v_i = the effect on the total expected cost due to starting in state i,

q_i = the expected immediate cost in state i, and

P_{ij} = a probability that a system which now occupies state i will occupy state j after its next transition.

We have now obtained a set of M linear simultaneous equations that relate the quantities v_i and c to the probability and cost structure of the process (the derivation of the equation is omitted). However, it has M + 1 unknowns with M equations, so that the absolute value of the v_i cannot be determined by the equations. But if we set one of the v_i equal to zero (say,

v_M) then only M unknowns are present, and the equations may be solved for c and the remaining v_i. The v_i produced by the solution of the value determination equations will be the relative values of the policy.

Step 2 Policy Improvement. Using the current values of v_i (R_1) computed for policy R_1, find the alternative policy R_2 that would choose the alternative k, for each state i, that minimizes

$$q_i^k + \sum_{j=1}^{M} P_{ij}^k v_j$$

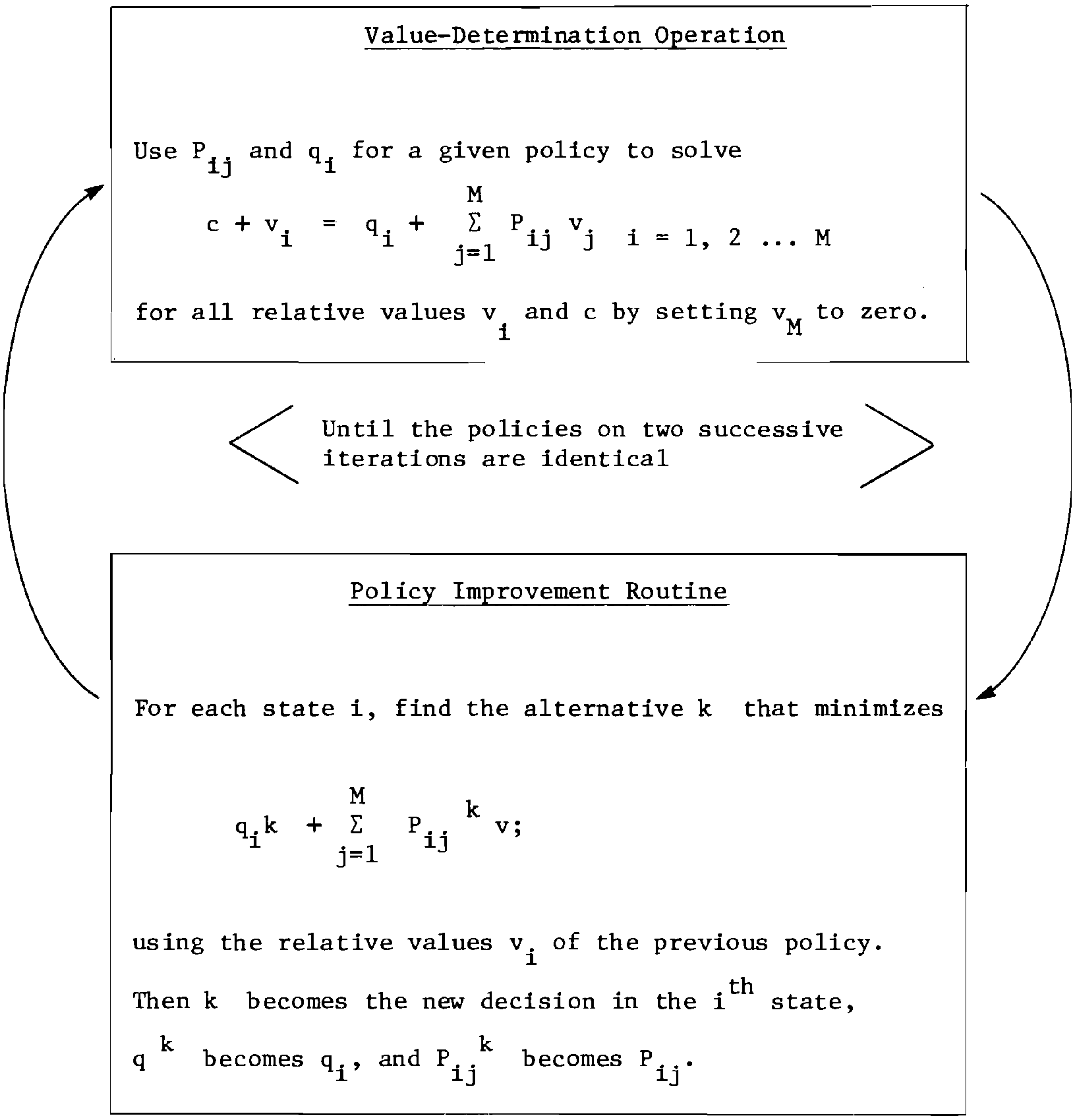
using the relative values determined under the old policy. A new policy has been determined when this procedure has been performed for every state. The basic iteration cycle may be diagrammed as shown in Fig 5.3.

THE PAVEMENT REHABILITATION EXAMPLE PROBLEM

Now we turn to a concrete example of how the policy-iteration technique may be applied to practical problems. The pavement rehabilitation example problem that was discussed in the previous section will be again used.

Given a 2-mile long pavement section which is deteriorating over time, we must decide (1) when to rehabilitate the pavement section and (2) what rehabilitation strategy to use. To frame the problem more precisely, we are to conduct condition surveys at regular intervals, say one year; at these times we decide either to leave the pavement section for another period or to rehabilitate it with a best strategy. Each possible decision gives rise to an expected cost for the upcoming period; the objective is to minimize the expected cost of the total highway network per period over the long run.

Having formulated the pavement rehabilitation problem as a Markovian Decision Model, we are now in a position to implement the policy iteration algorithm to find the optimal solution for given specifications, such as maintenance costs, rehabilitation costs, transition probabilities. The number of states is 5, and the number of decisions is 2 (routine maintenance only, and reconstruction). The problem is too small to serve as



Value-Determination Operation

Use P_{ij} and q_i for a given policy to solve

$$c + v_i = q_i + \sum_{j=1}^{M} P_{ij} v_j \quad i = 1, 2 \ldots M$$

for all relative values v_i and c by setting v_M to zero.

Until the policies on two successive iterations are identical

Policy Improvement Routine

For each state i, find the alternative k that minimizes

$$q_i^k + \sum_{j=1}^{M} P_{ij}^{k} v_j$$

using the relative values v_i of the previous policy.

Then k becomes the new decision in the i^{th} state,

q^k becomes q_i, and P_{ij}^k becomes P_{ij}.

Fig 5.3. Iteration cycle (Ref 12).

a real-life example but it is simple enough to analyze the operations and results. In order to solve the pavement rehabilitation problem using the policy-iteration algorithm, a computer program has been written in Fortran; the sample output is reproduced in Fig 5.4.

The computer program uses the input data described in the previous section. According to the optimal policy in Fig 5.4, we shall do routine maintenance only when it is in state 1 or 2 and reconstruct it when it is in state 3, 4, or 5. If you compare answers in iteration 3 and iteration 4, you will realize that the two policies are different only as to whether we shall do routine maintenance only or reconstruct it when the pavement stays in state 3. This comparison leads to an interesting result. If we reconstruct the pavement when it is in state 3 instead of doing routine maintenance only, we will not only save about $60/section/year but will also keep more pavement sections in better condition.

If we follow this optimal policy over a long period of time, then 60 percent of the highway network would stay in state 1, 32 percent would be in state 2, 6 percent in state 3, 1 percent in state 4, and none of the pavement sections would be in state 5, as seen in the last column of the printed results. This optimum proportion of the total highway network with the right action applied in each state will lead to the minimum cost rehabilitation policy with annual average cost of $1750 per pavement section.

```
          ITERATION  1
               ----
         COST =  -7000.00
                                          LIMITING STATE
    STATE    DECISION       VALUE          PROPORTIONS
      1          1         113467.                   0
      2          1          71200.               .0000
      3          1          35500.                   0
      4          1          14000.               .0000
      5          1               0              1.0000

          ITERATION  2
               ----
         COST =  -2107.14
                                          LIMITING STATE
    STATE    DECISION       VALUE          PROPORTIONS
      1          1          13393.               .8929
      2          2               0               .0714
      3          2               0               .0357
      4          2               0                   0
      5          2               0              -.0000

          ITERATION  3
               ----
         COST =  -1809.82
                                          LIMITING STATE
    STATE    DECISION       VALUE          PROPORTIONS
      1          1          13690.               .4601
      2          1           4638.               .2454
      3          1           -951.               .2393
      4          2              0.               .0433
      5          2               0               .0129

          ITERATION  4
               ----
         COST =  -1750.00
                                          LIMITING STATE
    STATE    DECISION       VALUE          PROPORTIONS
      1          1          13750.               .6048
      2          1           5000.               .3226
      3          2              0.               .0629
      4          2             -0.               .0097
      5          2               0               .0000

    ** OPTIMAL SOLUTION HAS BEEN FOUND**
```

Fig 5.4. Optimal solution of a pavement rehabilitation problem on a small scale.

CHAPTER 6. IMPLEMENTATION OF THE STOCHASTIC DECISION PROCESS IN TEXAS AT THE PROGRAM LEVEL

INTRODUCTION

The concept of the Markovian Decision Process has been explained in the previous chapters. The objective of the study is to determine the rehabilitation policy that selects the best strategy for each pavement condition state with minimum cost. Performance standards could be considered in terms of the minimum proportion of the network required or desired to be in acceptable condition states and the maximum proportion of the network allowed to be in unacceptable condition states.

The main steps involved in the implementation of the stochastic decision model are

(1) Define condition states,
(2) Define road categories,
(3) Select rehabilitation actions,
(4) Develop a cost model, and
(5) Develop transition probabilities.

A brief description of each step is given in comparison with a somewhat similar approach used in the state of Arizona (ADOT). Input data needed for Texas stochastic decision process are described. A set of computer programs were developed to accept those inputs and to generate the optimal solution to a pavement rehabilitation problem in practice.

THE STEPS TO THE DEVELOPMENT

Define Condition States (45 States) (see Fig 6.1)

The variables used by Arizona Department of Transportation (DOT) to define the condition states were (a) present roughness (3 levels), (b) present amount of cracking (3 levels), (c) change in amount of cracking during previous year (3 levels), and (d) index to the first crack (5 levels). A total of 135 combinations of these variables and levels are possible. However, 15 of these combinations are considered unlikely to exist, which leaves 120 practical condition states.

The PES will provide data on pavement condition and performance on a consistent basis that can provide information on the condition of the Texas highway network. The extent of distress defined in each of three categories for each distress being evaluated is shown in Fig 6.2.

The condition states proposed for use in Texas considering the PES data format and the complexity and size of the model are

(a) Pavement Roughness (5 levels)

-- Level 1 $3.5 \le SI$
-- Level 2 $3.0 \le SI < 3.5$
-- Level 3 $2.5 \le SI < 3.0$
-- Level 4 $2.0 \le SI < 2.5$
-- Level 5 $SI < 2.0$

(b) Present Cracking (3 levels)

-- Level 1: None of the cracking types (transverse, longitudinal, alligator) exist (all 000's in the PES file)

-- Level 3: At least one of the cracking types is severe (at least one 001 in the PES file)

-- Level 2: A combination of no, minimal, and medium cracks (the rest)

State Number	Roughness Level	Cracking Level	Rutting Level	State Number	Roughness Level	Cracking Level	Rutting Level
1	1	1	1	24	3	2	3
2	1	1	2	25	3	3	1
3	1	1	3	26	3	3	2
4	1	2	1	27	3	3	3
5	1	2	2	28	4	1	1
6	1	2	3	29	4	1	2
7	1	3	1	30	4	1	3
8	1	3	2	31	4	2	1
9	1	3	3	32	4	2	2
10	2	1	1	33	4	2	3
11	2	1	2	34	4	3	1
12	2	1	3	35	4	3	2
13	2	2	1	36	4	3	3
14	2	2	2	37	5	1	1
15	2	2	3	38	5	1	2
16	2	3	1	39	5	1	3
17	2	3	2	40	5	2	1
18	2	3	3	41	5	2	2
19	3	1	1	42	5	2	3
20	3	1	2	43	5	3	1
21	3	1	3	44	5	3	2
22	3	2	1	45	5	3	3
23	3	2	2				

Decision Number	Verbal Description
1	Routine Maintenance Only
2	Seal Coat
3	Thin Overlay (< 3-inches)
4	Thick Overlay (≥ 3-inches)
5	Reconstruction

Fig 6.1. Define condition states and rehabilitation actions.

Pavement Conditions	RUTTING	NO. PER STA	1 – 4 5 – 10 > 10
	ALLIGATOR CRACKING	LIN FT PER STA/LN	10–90 100–200 > 200
	LONGITUDINAL CRACKING	% AREA	1 – 10 11 – 50 > 50
	TRANSVERSE CRACKING	1/2"–1" =1" >1"–2" % AREA	1 – 25 26 – 50 > 50

Fig 6.2. The extent of distress in PES.

(c) Rutting (3 levels)

- Level 1: No Rutting exists (000 in the PES file)
- Level 2: Minimal rutting: less than 1" and 1 to 50% in extent (100,010 in the PES file)
- Level 3: Severe rutting greater than 1" or more than 50% in extent (001, 200, 020, 002 in the PES file)

Define Road Categories (12 Categories)

The statewide highway network was divided into 12 road categories, by the Arizona DOT, which were defined as combinations of average daily traffic (ADT) and a regional environmental factor that depends on several climatic conditions, such as elevation and rainfall.

The suggested road categories for the state of Texas, considering PES data, are

(a) Environmental Factors (4 categories)

- Wet, no freeze
- Wet, freeze/thaw cycling
- Dry, freeze/thaw cycling
- Dry, no freeze

Dry < 20 inches/year > Wet
No Freeze < 10 cycles/year > Cycling

(b) Average Daily Traffic (3 categories)

$$\text{ADT} < 1000$$
$$1000 \leq \text{ADT} < 10000$$
$$10000 \leq \text{ADT}$$

Select Rehabilitation Actions

A total of 17 alternative rehabilitation actions, ranging from routine maintenance to substantial corrective measures, were selected for asphalt concrete pavement by Arizona DOT. The rehabilitation actions proposed for the Texas SDHPT, considering that this PMS model is at the program level, and that the size of the model must remain manageable are:

- -- Routine (Repair) Maintenance Only
- -- Seal coat
- -- Thin overlay (thickness < 3 inches)
- -- Thick overlay (thickness ≥ 3 inches)
- -- Reconstruction

Develop Cost Model

The optimization model requires estimates of c (i,k) — the cost of k^{th} rehabilitation action for a pavement in i^{th} condition state. The total cost of a rehabilitation action consists of construction cost and routine maintenance cost:

$$C(i,k) + \mathrm{CREHAB}(k) + \mathrm{CMAINT}(i,k)$$

where

CREHAB (k) = construction cost of the k^{th} rehabilitation action, and

CMAINT (i,k) = routine maintenance cost on a pavement in i^{th} condition state following k^{th} action.

The following regression equation was obtained for routine maintenance cost in Arizona using field data (Ref 5):

$$\text{Routine maintenance cost in \$ per lane-mile} = 950 - (200 \times \text{ride index}) + (43 \times \text{percent cracking})$$

For Texas, the construction costs can be obtained from the contract file and a similar type of regression equation for routine maintenance cost can be developed as follows:

Maintenance Cost = f (cracks, roughness, rutting, environment, traffic)

Develop Transition Probabilities

Ideally, the transition probabilities are obtained by observing the performance of a large number of pavements under different rehabilitation actions over a long period of time and then computing the proportion of roads that move from state i to j in one year, following k^{th} rehabilitation action for all values of i, j, and k.

However, the large amounts of pavement performance data required to develop this matrix are not available in Arizona. Hence, a different approach was taken to compute transition probabilities. In that approach, regression equations were developed for predicting pavement performance based on a sample of available data that Arizona had accumulated over the years on its road conditions and on the corrective actions taken on those roads.

To obtain better predictions, first develop a transition probability by observing the performance of a large number of pavements under the routine maintenance only. This transition probability can be refined as more data are being collected in the PES file every year. The transition probability under other rehabilitation actions could be developed later if PES data can be tied with the corrective actions taken on specific roads or if long-term monitoring data are available.

For example, under routine maintenance only, the condition of the pavement will change with P_{ij} in the matrix below.

$$\begin{array}{c|ccccc|}
 & 1 & 3 \;-- & j & - & 45 \\
1 & & & \vdots & & \\
2 & & & \vdots & & \\
i & ---- & ---- & P_{ij} & & \\
 & & & & & \\
45 & & & & &
\end{array}$$

P_{ij} the probability that a road of state i moves to state j in one year under routine maintenance only.

Due to the fact that there are not enough historical data to develop a transition probability matrix under different rehabilitation actions, a survey can be used for developing the matrix based on experience of highway personnel. Sample forms are reproduced in Appendix A.

INPUT DATA FOR TEXAS STOCHASTIC DECISION MODEL

In order to apply the stochastic decision model in Texas, we must obtain our own data. In collecting the data, we should try to gather data which are as objective as possible. The Pavement Evaluation System (PES) will consistently provide data on pavement condition and performance which can be used to determine the number of lane miles of highway which need rehabilitation and which can provide information on the condition of the highway system.

The Maintenance Management System (MMS) could provide data on pavement maintenance cost in different pavement control sections every year to be analyzed with PES data. There are three major sets of data to be collected, cost data, current condition data, and transition probability data. We also might be able to collect both objective and subjective data and to compare them to see how they differ.

Cost Data

This set of data should be obtained from maintenance and construction files of SDHPT. They are not automated, and they are arranged based on the control section instead of the milepost system. First, we have to find a way to convert the control-section location information into the milepost system. Then we will analyze the cost data using a regression analysis technique to find a correlation between maintenance cost and condition of the pavement. A cost prediction model can be developed, as a function of independent variables as follows:

Maintenance Cost = f (cracks, roughness, rutting, environment, traffic)

For this experimental design, the factorial design method is recommended because the independent variables are all categorized into different levels, and the interactions between variables might have an effect on the cost. However, this factorial design leads to 540 cells (5 roughness levels x 3 cracking levels x 3 rutting levels x 12 road categories). That is too large to model with the current state of the art. Therefore, the factorial design is modified to change factor levels into continuous variables except cracking and rutting. The proposed factorial design is

	Crack Level		
Rutting Level	1	2	3
1	x	x	x
2	x	x	x
3	x	x	x

This design reduces 540 cells to a 9-cell design, which is manageable.

With this factorial design we have to add continuous variables, such as traffic and serviceability index and environmental condition. The model will be

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 \text{ Traffic} + \beta_2 \text{ SI} + \beta_3 \text{ Rain} \\ & + \beta_4 \text{ Freeze} + \beta_5 \text{ Crack 1} + \beta_6 \text{ Crack 2} + \beta_7 \text{ Crack 3} \\ & + \beta_8 \text{ Rutting 1} + \beta_9 \text{ Rutting 2} + \beta_{10} \text{ Rutting 3} \end{aligned}$$

Even though the maintenance costs are dependent on the condition of pavements, the cost for rehabilitation action is not significantly affected by pavement condition. For example, the cost of the overlay will be about the same no matter how bad the pavement section was. Total cost will be divided by the length of the section in order to get the cost per unit area (2-mile lane).

Current Condition Data and Transition Probability Data

The first evaluation of pavement for ride quality and pavement distress for flexible pavements was begun in October 1982 and was completed by January 1983. Three Districts (8, 11, and 15) were selected to collect 100 percent sample data in order to provide representation of urban-rural and east versus west Texas conditions. A second round of evaluation was begun in October 1983 and was completed in February 1984, again only on flexible pavements.

The objective of PES was to determine the statewide current condition of the pavement of the highways and roads by highway system, utilizing a randomly selected sample. However, we need a set of data tied with a specific milepost system in order to get changes in the condition of the specific pavement sections in one year. This objective cannot be achieved with the current scheme of the PES. Hence we need a well-defined long-term pavement monitoring system.

Life Cycle Monitoring of the Pavement

The need for the aforementioned data can be achieved through observation of the specific pavement section's condition over a long period of time. If these sections are monitored until the end of their life cycle, valuable information, such as effectiveness of rehabilitation actions, maintenance costs under different condition states, and accurate performance prediction models, can be discovered.

It has been recognized that a continuing effort to monitor and record pavement condition, maintenance cost data, and rehabilitation actions on all experimental projects is needed. It is also important to maintain the data base of those studies. The objectives of the life-cycle monitoring project are defined as follows:

(1) Collect and code monitoring data on sections of pavement in experimental projects that are due to terminate in August 1984 or have previously terminated.

(2) Collect and code monitoring data on a cross section of pavement types and influential variables.

(3) Collect and code monitoring data for experimental and cross-sectional pavement sections that meet the selection criteria and are approved by the Pavement Data User Committee.

(4) Update pavement performance prediction and design equations as new sets of data are added; incorporate these equations into appropriate network and project level programs which estimate costs, service life, etc.

DEVELOPMENT OF COMPUTER PROGRAMS FOR IMPLEMENTATION

The application of a policy-iteration algorithm to the pavement rehabilitation problem in Texas will require a large amount of computer time to solve 45 equations in the 45 unknowns on successive iterations of the procedure. The 45 states are defined with the combinations of three variables, such as roughness (5 levels), cracking (3 levels), and rutting (3 levels). We could expand the system to incorporate other variables to define the state, but experience indicates that these three variables are the most prevalent ones, particularly in Texas. In this program we confine our attention to a flexible pavement under one of 12 road categories. We review the rehabilitation program at the end of every year with 5 rehabilitation options, as defined in the previous section. Thus we have 45 states and 5 alternatives in each state or 5^{45}.

First, we need estimates of the probabilities of going from each condition state to others in one year, following a specified rehabilitation action. After the network inventory data are accumulated under the long-term monitoring plan, these probabilities can be best estimated directly from field data. Because sufficient field data are not available at this time, the transition probability matrix can be developed based on experienced highway engineers' opinions. Draft survey forms that can be used to develop a transition probability matrix for the Texas SDHPT are given in Appendix A.

As discussed previously, we must solve 45 equations with 45 unknowns several times until we find an optimal solution. Therefore, we developed a computer program in Fortran to perform policy-iteration routine. A listing of this program and its subroutines is presented in Appendix B. The simplified flowchart of the computer program is shown in Fig 6.3.

In this pavement rehabilitation problem in practice, the number of states is 45, and the number of choices is 5, as explained previously. A sample data set used for the numerical example is listed with a description in Appendix C. These data values are for illustrative purposes only, and need to be changed as more reliable data become available through the methods provided in Chapter 5.

The sample output is reproduced in Appendix D. The decrease of annual cost with iteration is shown in Fig 6.4. In order to get the total cost of the optimal policy we should multiply the cost per 2-mile lane by the total network mileage, and divided it by 2. For example, if there is a highway network of 1,000 miles long with 4 lanes, then the minimum annual maintenance/rehabilitation cost of this network would be, based on the result obtained at the 6th iteration in Appendix C:

$$(\$3625/\text{2-mile-lane}) \times (1{,}000 \text{ miles } \times 4 \text{ lanes}/2) = 7{,}250{,}000/\text{network}.$$

The miles of road in each condition state would be obtained by multiplying the limiting state proportions at the iteration 6 in Appendix C by the total network mileage. They are shown in Fig 6.5.

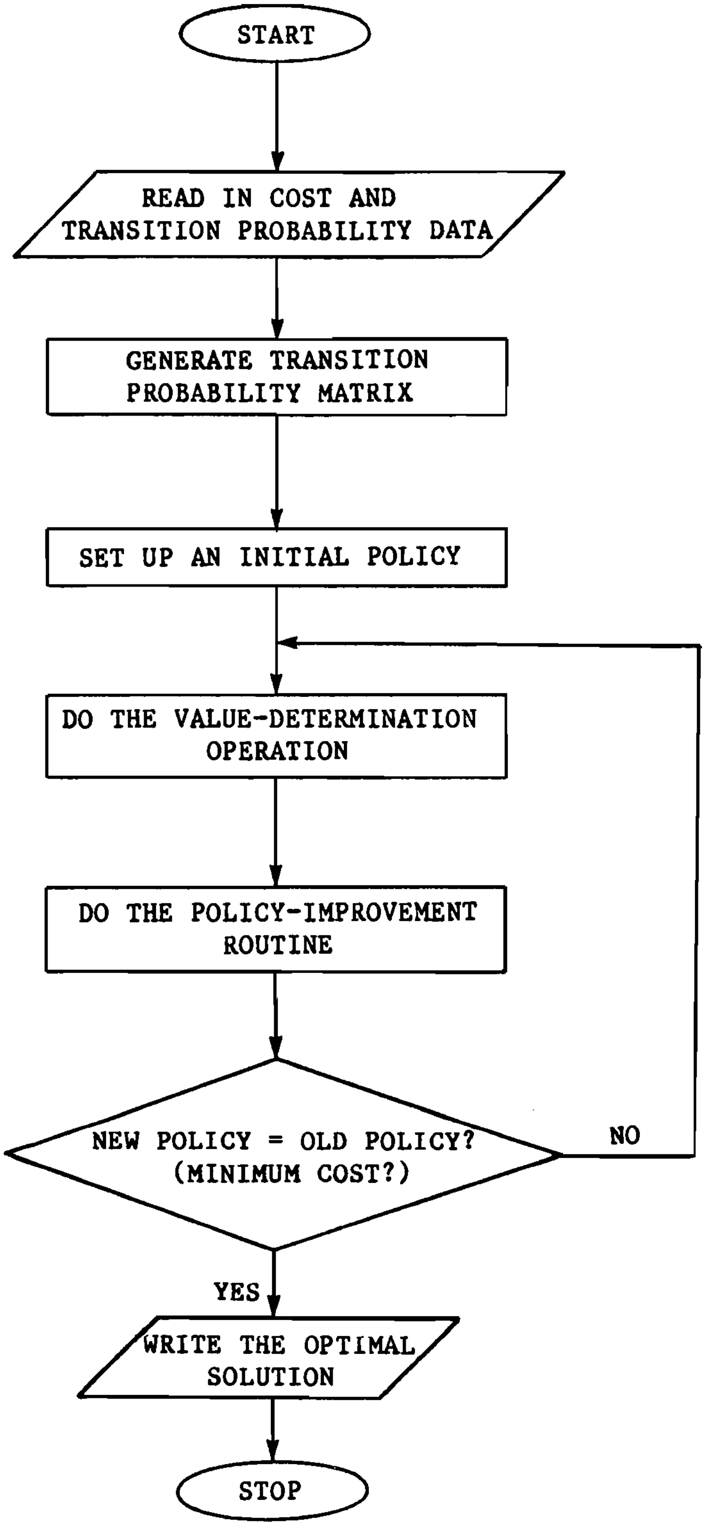


Fig 6.3. A simplified flow chart of the computer program.

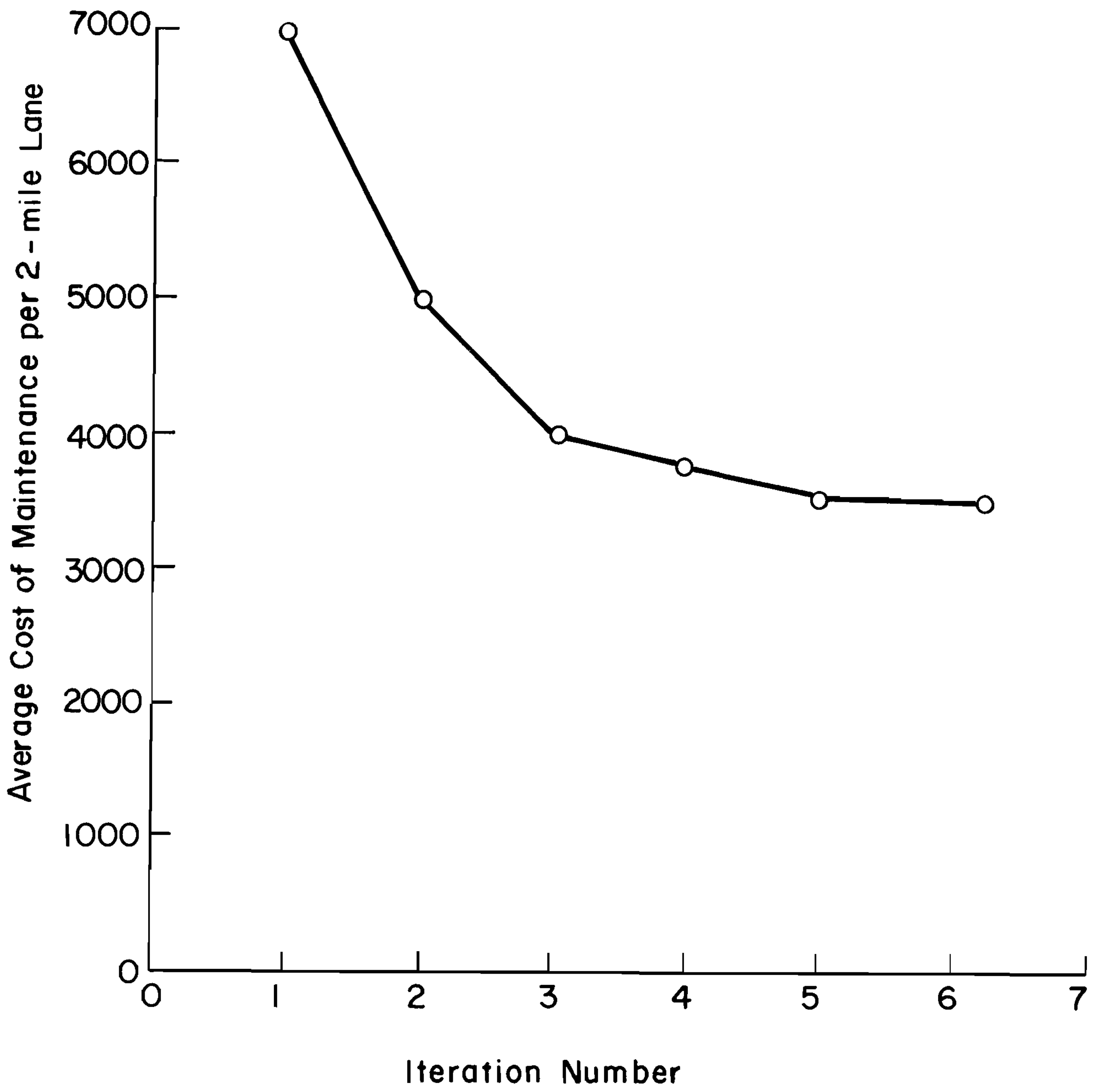


Fig 6.4. Decrease in average maintenance and rehabilitation cost per 2-mile lane after adopting the better rehabilitation policy based on the results in Appendix C.

Condition State	Miles in Each State	Condition State	Miles in Each State
1	232.8	24	0.2
2	42.4	25	0.0
3	7.6	26	0.0
4	13.5	27	0.0
5	3.7	28	10.94
6	0.5	29	9.1
7	0.0	30	1.1
8	0.0	31	6.1
9	0.0	32	0.5
10	264.4	33	0.1
11	74.7	34	0.0
12	19.5	35	0.0
13	18.9	36	0.0
14	4.4	37	25.7
15	1.0	38	1.4
16	0.0	39	0.0
17	0.0	40	1.4
18	0.0	41	0.0
19	132.6	42	0.0
20	17.1	43	0.0
21	3.3	44	0.0
22	7.6	45	0.0
23	0.9		

Fig 6.5. Miles of road in each condition state.

CHAPTER 7. SUMMARY AND CONCLUSIONS

Pavements represent a substantial investment in transportation, and substantial annual expenditures are required to preserve and maintain this investment. However, funds available for investment in maintenance of pavements are generally limited.

Pavement management is a process which encompasses the set of all activities required to provide and maintain pavements. The important concepts were discussed and activities, such as planning and prediction in PMS, have been emphasized. The key aspects about reorganizing PMS concepts are summarized as follows:

(1) Generally, four subsystems (planning, design, construction, and maintenance) share equally in the total PMS. In some agencies, the planning subsystem may be emphasized more than the others due to its higher influence-level.

(2) The PMS could better be divided into three levels of decision making, (a) project level, (b) project selection level, and (c) program level, in order to explain different formulation procedures of PMS models effectively.

At the program level, budgets are the major concern, and the problems become complex. There is a need for an objective procedure for distributing maintenance funds efficiently and for measuring the effectiveness of the maintenance actions taken on the overall highway network. The establishment of this objective procedure is essential to the development of a program level PMS. In connection with this task, a stochastic decision model is illustrated as a possible program level PMS for use in Texas.

This stochastic decision model is based on a Markovian decision process using a policy iteration algorithm as a solution technique. A set of computer programs was developed to accept the engineering inputs and generate an optimal solution to rehabilitation problems in practice. It is recommended that a trial implementation of this program level PMS be accomplished to see if it is feasible for the State of Texas.

The main steps involved in the implementation of this stochastic decision model using a policy iteration algorithm are

(1) Define condition states,
(2) Define road categories,
(3) Select rehabilitation actions,
(4) Develop a cost model, and
(5) Develop transition probability matrices.

One major limitation of the method is the problem associated with collecting the necessary data. The Pavement Evaluation System (PES) would consistently provide data on the current pavement condition of the highway network. However it is important to know how the individual pavement section deteriorates in terms of ride quality and distress under different levels of traffic and environmental conditions.

These data will be used to develop transition probability matrices. However, the data-collection requirements are very high. Large amounts of pavement performance data are required to develop reliable transition matrices. The transition matrix is the back bone of the Markovian decision process model. It allows the model to predict pavement performance based on past historical data. It is then used for formulation of an optimization program.

First, the transition probability matrix needs to be developed by observing the performance of a large number of pavements under routine maintenance over different categories of traffic and environments. This transition matrix can be refined as more data are collected through the PES every year. The transition probability matrices under other rehabilitation measures could be developed later if the rehabilitation construction files can be transferred into the PES.

The PES data have not been collected and organized for developing transition probability matrices. At the present time, it may not be feasible to develop reliable transition matrices using the PES data without rehabilitation construction files. However, a subjective survey method can be used for developing the transition matrices based on the experiences of highway engineers. If subjective inputs from the district engineers could be incorporated in the transition matrices, the output of the Markovian decision mdel might be more acceptable to them. There are some difficulties in obtaining reliable subjective answers from highway engineers. Survey forms to be used for developing transition probability matrices subjectively are shown in Appendix A. There should be a well-defined procedure for continuously updating and refining the transition matrices through time.

The maintenance and rehabilitation cost data could be obtained from the maintenance and construction files of the SDHPT. However, the maintenance costs are available only by major category of work and are not tied to or recorded in accordance with the milepost system. Nevertheless, we should develop a cost model to predict maintenance cost as a function of the condition of pavements.

The necessary data mentioned above can be successfully collected through a well-defined long-term pavement monitoring system for a large number of pavement sections under different traffic and environmental conditions. The program level PMS can continue to be improved as new sets of data are available through this pavement monitoring system.

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APPENDIX A

SURVEY FORMS FOR DEVELOPING TRANSITION PROBABILITY MATRICES

APPENDIX A. SURVEY FORMS FOR DEVELOPING TRANSITION PROBABILITY MATRICES

INSTRUCTIONS FOR COMPLETING FLEXIBLE PAVEMENT PERFORMANCE RELATIONSHIP DEVELOPMENT FORMS

Attached is a set of forms which can be adopted for use in the development of probability based pavement performance relationships for application in program level PMS methodology.

Three pavement performance variables (roughness, cracking, and rutting) have been selected, for evaluation, and the levels for each variable have been defined in the survey form. The rutting and cracking distress types in the condition survey are described in the following sections, as used for PES.

Rutting

Rutting is characterized by longitudinal channelized depressions that develop in the wheel paths of flexible pavements. Rutting may result from consolidation or lateral movement under traffic in one or more of the underlying courses, by displacement in asphalt pavements that had too little compaction during construction, or from plastic movement in a mix that does not have enough stability to support traffic. The degree of distress or level rutting is defined by the depth of the rutting, from 1/2 inch to 1 inch and greater than 1 inch. Rutting of less than 1/2 inch is considered to be "no rutting". The extent of distress for rutting would be shown as the percent of the length of the 2 wheel paths. If a single wheel path indicates rutting for less than 1/2 its length, the percent rutting is less than 25. If a single wheel path indicates continuous rutting the percent is 50. If two wheel paths indicate continuous rutting the percent of the area is greater than 100 percent.

Alligator Cracking

Alligator cracking is indicated by interconnected cracks forming a series of small blocks resembling an alligator[s skin or chicken wire. It is often associated with pavements that deflect excessively under traffic loads. The excessive deflection is due to improper design or weak base, subbase, or subgrade pavement layers in relation to traffic loads on the facility. The extent is the percent of the length of the wheel paths that is alligator cracked.

Longitudinal Cracking

Longitudinal cracking is a crack or break approximately parallel to the pavement centerline. Edge cracks, edge joint cracks between the pavement and shoulder, lane joint cracks, reflection cracks, and cracks created by volume changes in the subgrade or pavement materials are common forms of this type of distress. Poor construction practices and volume changes occurring in the pavement materials and subgrade are common causes of this form of distress. Longitudinal cracking is recorded when there is evidence of spalling or pumping, the crack is greater than 1/8-inch, or the crack is sealed. The extent is shown by the number of linear feet of cracking per station per lane.

Transverse Cracking

Transverse cracking is cracking or rupture approximately perpendicular to the pavement centerline. Reflection cracks and cracks associated with shrinkage of pavement materials are typical of this form of distress. Transverse cracking is recorded when there is evidence of spalling or pumping, the crack is greater than 1/8-inch, or the crack is sealed. The extent is shown by the number of cracks per station per lane.

The Extent of Distress as Defined in the PES for the Condition Survey

The extent of distress for rutting or alligator cracking is defined as the percent of the wheel path displaying this type of distress. If a single wheel path illustrates a particular type of distress continuously, the extent is 26 to 50 percent of the area (11 to 50 percent for alligator cracking). If two wheel paths demonstrate a particular type of distress continuously, the extent is greater than 50 percent of the area. If a single wheel path has discontinuous distress, the extent is 1 to 25 percent (1 to 10 percent for alligator cracking).

Longitudinal cracking and transverse cracking are recorded as linear feet of crack per station per lane and number per station, respectively.

A single continuous crack along the centerline or lane line of a highway would be considered as half in each lane and would indicate at 10 to 99 linear feet per station lane. A single continuous crack along a lane would indicate that the longitudinal crack length is 100 to 200 linear feet per station lane. Similarly, two continuous cracks along a lane would indicate that the longitudinal crack length is 100 to 200 linear feet per station lane. More than two cracks along a lane would indicate that the longitudinal crack length is greater than 200 linear feet per station lane.

INSTRUCTIONS

The blanks in the survey form should be filled in according to the following instructions.

(1) Imagine all pavement sections with the given combinations of variables.

(2) Assume that the pavements under consideration are in the environmental zone and in the level of ADT indicated at the right hand corner of the sheet.

(3) Assume that they currently have the given level of cracking (or roughness or rutting).

(4) If the only rehabilitation actions taken during the following year are of a routine maintenance nature, complete the first row of blanks to reflect the percentage of these roads you would expect to be in Level 1, Level 2, or Level 3 of cracking at the end of the one-year period.

(5) Another way to think of this is to suppose there are 100 miles of roadway under consideration (or 100 separate pavement sections) and to estimate how many miles would be in each cracking level category in one year following application of the rehabilitation action.

(6) As you may have noted, no matter which method is used, the sum of the values in each row should equal to 100.

(7) A similar analysis is to be applied if rehabilitation action 2 - seal coat is applied at the beginning of the one-year period to be followed by routine maintenance for the remainder of the period.

(8) This same analysis procedure is then applied to rehabilitation action 3 - thin overlay (< 3-inch thickness), rehabilitation action 4 - thick overlay ($\underline{[}$ 3-inch thickness), and rehabilitation action 5 - reconstruction.

(9) This would complete the single form for which the present amount of cracking is at the assumed level. The same approach would then be applied to the other levels of present cracking as well as all levels of present roughness (a total of 11 pages) for pavements in the given "combination" of (1) Environmental area and (2) ADT range. These combinations are referred to as "Traffic-Regions" and a set of eleven forms should be completed for each Traffic-Region with which an individual rater is familiar.

001 22

DATE ____________

PERFORMANCE RELATIONSHIP DEVELOPMENT: ROUGHNESS

Serviceability Index Ranges

Level 1 - $3.5 \leq$ S.I.
Level 2 - $3.0 \leq$ S.I. < 3.5
Level 3 - $2.5 \leq$ S.I. < 3.0
Level 4 - $2.0 \leq$ S.I. < 2.5
Level 5 - S.I. < 2.0

ADT Range ADT < 1,000

Environmental Zone ____________

Probability that S.I. will be at a given level one year after specified rehabilitation action.

Present Roughness Level	Rehabilitation Action	Level 1	Level 2	Level 3	Level 4	Level 5
Level ____	Routine Maintenance Only					
	Seal Coat					
	Thin Overlay (< 3-inches)					
	Thick Overlay ($\geq$ 3-inches)					
	Reconstruction					

Name ____________

Major Work Area ____________

State ____________

Date ______

PERFORMANCE RELATIONSHIP DEVELOPMENT: CRACKING

Cracking Ranges
(Transverse, Longitudinal, Alligator)

Level 1 - No cracking at all

Level 2 - Intermediate cracking

Level 3 - At least one cracking type is severe*

ADT Range 1,000 ≤ ADT < 10,000

Environmental Zone ______

Probability that crack will be at a given level one year after specified rehabilitation action.

Present Cracking Level	Rehabilitation Action	Level 1	Level 2	Level 3
Level ______	Routine Maintenance Only			
	Seal Coat			
	Thin Overlay (< 3-inches)			
	Thick Overlay (≥ 3-inches)			
	Reconstruction			

*Severe Cracking
Transverse - more than 10 per station
Longitudinal - longer than 200 feet per station
Alligator - greater than 50 percent area

Name ______
Major Work Area ______
State ______

Date ______________

PERFORMANCE RELATIONSHIP DEVELOPMENT: RUTTING

Rutting Ranges

Level 1 - No rutting
Level 2 - Less than 1-inch, and 1-50 percent area
Level 3 - Greater than 1-inch, or more than 50 percent area

ADT Range $10{,}000 \leq$ ADT

Environmental Zone ______________

Probability that rutting will be at a given level one year after specified rehabilitation action.

Present Rutting Level	Rehabilitation Action	Level 1	Level 2	Level 3
Level ______	Routine Maintenance Only	______	______	______
	Seal Coat	______	______	______
	Thin Overlay (< 3-inches)	______	______	______
	Thick Overlay (≥ 3-inches)	______	______	______
	Reconstruction	______	______	______

Name ______________

Major Work Area ______________

State ______________

APPENDIX B

COMPUTER PROGRAMS BASED ON THE POLICY-ITERATION ALGORITHM FOR THE STOCHASTIC DECISION PROCESS WITH SAMPLE INPUT DATA

```
C*********************************************************************
C
C      THIS PROGRAM PERFORMS THE POLICY-ITERATION ALGORITHM FOR
C      A MARKOVIAN DECISION PROCESS DESCRIBING PAVEMENT REHABILITATION
C      PROBLEM IN TEXAS.  PROVISION IS MADE UP TO 45 STATES AND 5
C      REHABILITATION ALTERNATIVES FOR EACH STATE.
C
C*********************************************************************
C
C
       PROGRAM POLICY(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
       DOUBLE PRECISION A(56,56),P(45,45,5),Q(45,45),X(55),EPS,XTEST
       DIMENSION CMAINT(45),CREHAB(5)
       DIMENSION V(45),TEST(5),KACT(45)
       DOUBLE PRECISION B(56,56),C(56,56)
       DIMENSION W(45)
       DIMENSION Y(45)
       COMMON P
       COMMON V Y
C
C
C*********************************************************************
C
C      READ IN COST AND TRNSITION PROBABILITY DATA
C
C*********************************************************************
C
       EPS=0.00001
       READ (5,10) CMAINT,CREHAB
10     FORMAT(5F10.0)
C
C
       CALL TRANS
C
C
C      WRITE(6,333) (((P(I,J,K),J=1,45),I=1,45),K=1,5)
C333   FORMAT(9F7.3)
C
C*********************************************************************
C
C      DETERMINE INITIAL POLICY BY MINIMIZING EXPECTED IMMEDIATE COST
C
C*********************************************************************
C
       DO 30 I=1,45
       Q(I,1)=CMAINT(I)
       Q(I,2)=CMAINT(I)+CREHAB(2)
       Q(I,3)=CMAINT(2)+CREHAB(3)
       Q(I,4)=CMAINT(1)+CREHAB(4)
       Q(I,5)=CMAINT(1)+CREHAB(5)
30     CONTINUE
C
C
       ITERAT = 1
       DO 50 I=1,45
       XTEST = Q(I,1)
       LL=1
       DO 45 K=2,5
       IF (XTEST .GT. Q(I,K)) GO TO 45
       XTEST = Q(I,K)
```

```
      LL=K
45    CONTINUE
50    KACT(I)=LL
C
C**********************************************************************
C
C     VALUE DETERMINATION OPERATION - SET UP A 45 X 45 MATRIX
C     TO BE PASSED TO THE SUBROUTINE GAUSS THAT SOVES 45
C     EQUATIONS WITH 45 UNKNOWNS.
C
C**********************************************************************
C
100   DO 150 IROW =1,45
      DO 150 JCOL =1,46
      IF (JCOL .NE. 1) GO TO 110
      A(IROW,JCOL) = -1.
      GO TO 150
110   IF (JCOL .NE. 46) GO TO 120
      A(IROW,JCOL) = -Q(IROW,KACT(IROW))
      GO TO 150
120   IF (IROW .NE. 45) GO TO 130
      A(IROW,JCOL) = P(IROW,JCOL-1,KACT(IROW))
      GO TO 150
130   IF (JCOL .EQ. (IROW+1)) A(IROW,JCOL)=P(IROW,JCOL-1,KACT(IROW))-1.
      IF (JCOL .NE. (IROW+1)) A(IROW,JCOL)=P(IROW,JCOL-1,KACT(IROW))
150   CONTINUE
C
C**********************************************************************
C
C     CALL SUBROUTINE GAUSS TO FIND RELATIVE VALUES FOR V(I)
C
C**********************************************************************
C
C
      CALL GAUSS (45,A,X,EPS,56,DETER)
C
C
      IF(DETER .NE. 0.) GO TO 185
      WRITE(6,180)
180   FORMAT(* NO UNIQUE SOLUTION FOR V(I),I=1,..45, COULD NOT BE FOUND
     *---- PROCESS TERMINATED*)
      STOP
185   V(45) = 0
      COST=X(1)
      DO 190 I=2,45
190   V(I-1) = X(I)
C
C
C**********************************************************************
C
C     CALL GAUSS TO CALCULATE THE PROPORTION OF EACH STATE
C
C**********************************************************************
C
C
      DO 151 IROW =1,45
      DO 151 JCOL =1,46
      IF (JCOL .NE. 46) GO TO 153
      C(IROW,JCOL) = 0.0
      GO TO 154
153   IF (JCOL .EQ. IROW) C(IROW,JCOL)=P(IROW,JCOL,KACT(IROW))-1.
      IF (JCOL .NE. IROW) C(JCOL,IROW)=P(IROW,JCOL,KACT(IROW))
```

```
150    IF (IROW .EQ. 45) C(IROW,JCOL)=1.0
151    CONTINUE
C
C
C
       CALL GAUSS (45,C,X,EPS,56,DETER)
C
C
       IF(DETER .NE. 0.) GO TO 191
       WRITE(6,181)
181    FORMAT(* NO UNIQUE SOLUTION FOR W(I),I=1,..45, COULD NOT BE FOUND
      *---- PROCESS TERMINATED*)
       STOP
191    DO 192 I=1,45
192    W(I) = X(I)
C
       WRITE (6,195) ITERAT,COST
195    FORMAT(*0*,5X,*ITERATION *,I2/10X,*----*/5X,*COST =*,F10.2
      */,31X,*LIMITING STATE*/
      **STATE   DECISION     VALUE       PROPORTIONS*)
       DO 196 I=1,45
196    WRITE (6,197) I,KACT (I),V(I),W(I)
197    FORMAT (2X,I2,7X,I2,4X,F10.0,5X,F10.4)
       IPOINT=0
C
C
C**********************************************************************
C
C      POLICY-IMPROVEMENT ROUTINE TO CHECK WHETHER THE CURRENT
C      SOLUTION IS OPTIMAL.
C
C**********************************************************************
C
       DO 400 I=1,45
       DO 300 K=1,5
       TEST(K) = Q(I,K)
       DO 200 J=1,45
200    TEST(K) = TEST(K) + P(I,J,K)*V(J)
300    CONTINUE
       DO 350 K=1,5
       JJJ=KACT(I)
       IF (TEST(JJJ) .GE. TEST(K)) GO TO 350
       IPOINT = 1
       KACT(I) = K
350    CONTINUE
400    CONTINUE
       ITERAT = ITERAT + 1
       IF (IPOINT .EQ. 1) GO TO 500
       WRITE(6,450)
450    FORMAT(*0**** OPTIMAL SOLUTION HAS BEEN FOUND*****)
       WRITE(6,460)
460    FORMAT(*1*,*******************************************************/
      *****                                                 ****/
      *****              THE OPTIMAL SOLUTION                ****/
      *****                                                  ****,/,
      ******************************************************,//,
      *31X,*LIMITING STATE*,/,*STATE   DECISION     VALUE       *,
      **PROPORTIONS*)
C
C
C      CALL SORT
C
```

```
C
      DO 470 I=1,45
470   WRITE(6,480) Y(I),KACT(I),V(I),W(I)
480   FORMAT(2X,I2,7X,I2,4X,F10.0,5X,F10.4)
      STOP
500   IF(ITERAT .LE. 50) GO TO 100
      WRITE(6,550)
550   FORMAT(*0PROCESS DID NOT CONVERGE IN 50 ITERATIONS----
     *EXECUTION TERMINATED*)
      STOP
      END
C
C
C
      SUBROUTINE GAUSS(N,A,X,EPS,NRC,DETER)
C
C
C*******************************************************************
C
C     THIS SUBROUTINE EMPLOYS THE GAUSS-JORDAN REDUCTION METHOD
C     WITH MAXIMUN PIVOT STRATEGY TO SOLVE THE SYSTEM OF EQUATIONS
C     ARISING FROM THE VALUE-DETERMINATION OPERATION AND STEADY-
C     STATE PROPORTION OF NETWORK CALCULATION.
C
C*******************************************************************
C
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION IROW(55),JCOL(55),JORD(55),A(NRC,NRC),X(N)
C
C
      EPS=0.00001
      MAX=N+1
      IF (N .LE. 55 ) GO TO 600
      DETER = 0
      RETURN
600   DETER =1.
      DO 610 K=1,N
      KM1=K-1
      PIVOT = 0.
      DO 620 I=1,N
      DO 620 J=1,N
      IF (K .EQ. 1) GO TO 630
      DO 640 ISCAN = 1,KM1
      DO 640 JSCAN = 1,KM1
      IF ((I .EQ. IROW(ISCAN)) .OR. (J .EQ. JCOL(JSCAN))) GO TO 620
640   CONTINUE
630   IF (DABS(A(I,J)) .LE. DABS(PIVOT)) GO TO 620
      PIVOT = A(I,J)
      IROW(K) = I
      JCOL(K) = J
620   CONTINUE
C
C
      IF (DABS(PIVOT) .GT. EPS) GO TO 650
      DETER = 0.
      RETURN
C
C
650   IROWK = IROW(K)
      JCOLK = JCOL(K)
      DETER = DETER*PIVOT
```

```
      DO 660 J=1,MAX
660   A(IROWK,J) = A(IROWK,J)/PIVOT
      A(IROWK,JCOLK) = 1./PIVOT
      DO 610 I=1,N
      AIJCK = A(I,JCOLK)
      IF (I .EQ. IROWK) GO TO 610
      A(I,JCOLK) = -AIJCK/PIVOT
      DO 670 J=1,MAX
670   IF (J .NE. JCOLK) A(I,J) = A(I,J) -AIJCK*A(IROWK,J)
610   CONTINUE
C
C
      DO 21 I=1,N
      IROWI = IROW(I)
      JCOLI = JCOL(I)
      JORD(IROWI) = JCOLI
21    X(JCOLI) = A(IROWI,MAX)
C
C
      INTCH = 0
      NM1 = N - 1
      DO 22 I=1,NM1
      IP1=I+1
      DO 22 J=IP1,N
      IF (JORD(J) .GE. JORD(I)) GO TO 22
      JTEMP = JORD(J)
      JORD(J)= JORD(I)
      JORD(I) = JTEMP
      INTCH = INTCH + 1
22    CONTINUE
      IF (MOD(INTCH,2) .NE. 0) DETER = (-1.)*DETER
      RETURN
      END
C
C
      SUBROUTINE TRANS
C
C**********************************************************************
C
C     THIS SUBROUTINE GENERATES THE TRANSITION PROBABILITY MATRIX
C     BASED ON THE EXPERIENCED HIGHWAY ENGINEER#S OPINIONS.
C
C***********************************************************************C
C
      DOUBLE PRECISION P(45,45,5),X(5,5),Y(3,3),Z(3,3)
      COMMON P
      IACT=1
      INDEX=1
      ICOUNT=1
      DO 100 II =1,5
      READ (5,200) ((X(I,J),J=1,5),I=1,5)
      READ (5,250) ((Y(I,J),J=1,3),I=1,3),((Z(I,J),J=1,3),I=1,3)
200   FORMAT(5F3.0)
250   FORMAT(9F3.0)
C
      WRITE (6,260) X,Y,Z
260   FORMAT(20F4.0)
C
      DO 10 L=1,5
      DO 10 M=1,3
      DO 10 N=1,3
C
```

```
      DO 20 I=1,5
      DO 20 J=1,3
      DO 20 K=1,3
      P(INDEX,ICOUNT,IACT)=X(L,I)*Y(M,J)*Z(N,K)/1000000.
      ICOUNT =ICOUNT +1
20    CONTINUE
C
      ICOUNT=1
      INDEX=INDEX+1
10    CONTINUE
C
      INDEX=1
      IACT=IACT+1
100   CONTINUE

      RETURN
      END
C
C
      SUBROUTINE SORT
C
C*********************************************************************
C
C     THIS SUBROUTINE IS TO SORT STATES BY THE VALUES IN ORDER
C     TO PRODUCE OUTPUT IN THE DESCENDING ORDER.
C
C*********************************************************************
C
      DIMENSION V(45), Y(45),W(45),KACT(45)
      COMMON V,Y,W,KACT

      DO 6 I=1,45
      IN = I+1
      DO 6 J=IN,45
      IF (V(I) .GE. V(J)) GO TO 6
      TEMP = V(I)
      V(I) = V(J)
      Y(I) = J
      W(I) = W(J)
      KACT(I) = KACT(J)
      V(J) = TEMP
6     CONTINUE
      RETURN
      END
```

```
  -2000.      -2500.    -3000.        -3000.      -3500.
  -4000.      -4000.    -4500.        -5000.      -2500.
  -3000.      -3500.      -3500.      -4000.      -4500.
  -4500.      -5000.      -5500.      -3000.      -3500.
  -4000.      -4000.      -4500.      -5000.      -5000.
  -5500.      -6000.      -3500.      -4000.      -4500.
  -4500.      -5000.      -5500.      -5500.      -6000.
-6500.        -4000.      -4500.      -5000.      -5000.
-5500.        -6000.      -6000.      -6500.      -7000.
            -1500.      -5000.        -12000.      -15000.
 80  20   0   0   0
  0  80  15   5   0
  0   0  80  15   5
  0   0   0  80  20
  0   0   0   0100
 95   5   0   0  95   5   0   0100
 95   5   0   0  95   5   0   0100
 90  10   0   0   0
  0  85  10   5
         75  20   5
             90  10
             95   5
100   0   0  60  40   0   0  50  50
 95   5   0   0  95   5   0   0100
100
 20  65  10   5
  0  10  70  15   5
  0   0  10  80  10
  0   0  30  50  20
100   0   0  70  30   0   5  85  10
 95   5   0   5  90   5   5  70  30
100
 85  15
 80  20
 70  30
 65  35
100   0   0100   0   0  80  15   5
100   0   0100   0   0  90  10   0
100
100
100
100
100
100   0   0100   0   0100   0   0
100   0   0100   0   0100   0   0
```

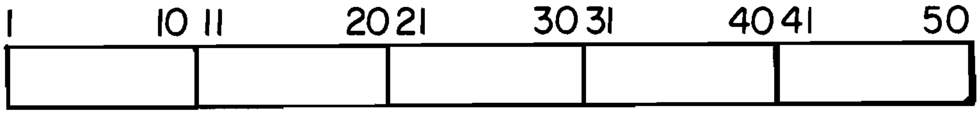
APPENDIX C

INPUT GUIDE TO THE COMPUTER PROGRAM

APPENDIX C. INPUT CARDS USED FOR THE COMPUTER PROGRAM

The notation CC refers to card columns, with the range of columns being inclusive. All REAL values are punched with a decimal point as a part of a value and all INTEGER values are punched without a decimal point and right justified in the data field.

Card Type 1 (9 Cards)



CC 1-10 (REAL) the routine maintenance cost per 2mile lane in condition state 1 per year

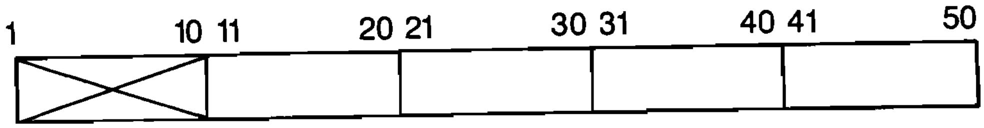
CC 11-20 (REAL) the routine maintenance cost per 2-mile lane in condition state 2 per year

.
.
.
.

9th Card

CC 41-50 (REAL) the routine maintenance cost per 2-mile lane in condition state 45 per year

Card Type 2 (1 Card)



CC 11-20 (REAL) the cost of a seal coat per 2-mile lane section.

CC 21-30 (REAL) the cost of a thin overlay (< 3 inches) per 2-mile lane section.

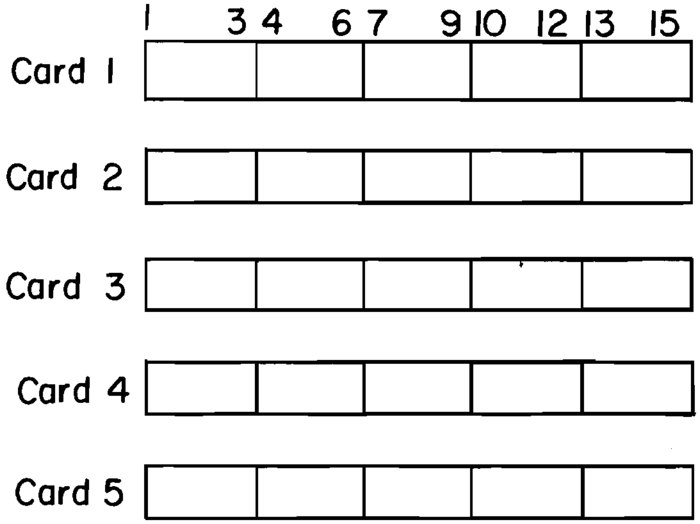
CC 31-40 (REAL) the cost of a thick overlay (≥3 inches) per 2-mile lane section.

CC 41-50 (REAL) the cost of a reconstruction per 2-mile lane section.

Card Type 3 (7 Cards)

The transition probability under routine maintenance only.

Card Type 3-1 (5 Cards): Roughness



Card i CC 1-3 (INTEGER) a probability that a pavement section currently in roughness level i will move to the level 1 after one year undr routine maintenance only (i = 1, 2, 3, 4, 5)

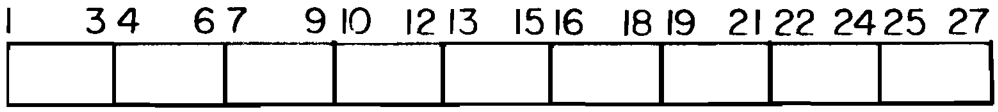
Card i CC 4-6 (INTEGER) a probability that a section in roughness level i will move to the level 2 after one year under routine maintenance only

Card i CC 7-9 (INTEGER) a probability a section in roughness level i will move to the level 3 after one year under routine maintenance only

Card i CC 10-12 (INTEGER) a probability a section in roughness level i will move to the level 4 after one year under routine maintenance only

Card i CC 13-15 (INTEGER) a probability a section in roughness level i will move to the level 5 after one year under routine maintenance only

<u>Card Type 3-2 (1 Card): Cracking</u>



CC 1-3 (INTEGER) a probability that a pavement section in cracking level 1 will stay at the same level after one year under routine maintenance only (P_{11} (cracking))

CC 4-6 (INTEGER) a probability that a section in cracking level 1 will move to the level 2 after one year under routine maintenance only (P_{12} (cracking))

CC 7-9 (INTEGER) P_{13} (cracking)

CC 10-12 (INTEGER) P_{21} (cracking)

CC 13-15 (INTEGER) P_{22} (cracking)

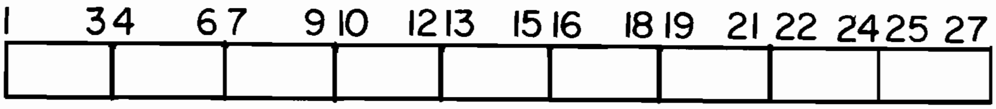
CC 16-18 (INTEGER) P_{23} (cracking)

CC 19-21 (INTEGER) P_{31} (cracking)

CC 22-24 (INTEGER) P_{32} (cracking)

CC 25-27 (INTEGER) P_{33} (cracking)

Card Type 3-3 (1 Card): Rutting



CC 1-3 (INTEGER) a probability that a pavement section in rutting level 1 will stay at the same level after one year routine maintenance only (P_{11} (rutting))

CC 4-6 (INTEGER) a prabability that a pavement section in rutting level 1 will move to the level 2 after one year under routine maintenance only (P_{12} (rutting))

CC 7-9 (INTEGER) P_{13} (rutting)

CC 10-12 (INTEGER) P_{21} (rutting)

CC 13-15 (INTEGER) P_{22} (rutting)

CC 16-18 (INTEGER) P_{23} (rutting)

CC 19-21 (INTEGER) P_{31} (rutting)

CC 22-24 (INTEGER) P_{32} (rutting)

CC 25-27 (INTEGER) P_{33} (rutting)

Card Type 4 (7 Cards)

The transition probability after a seal coat has been applied.

Card Type 4-1 (5 Cards): Roughness

Card Type 4-2 (1 Card): Cracking

Card Type 4-3 (1 Card): Rutting

Card Type 5 (7 Cards)

The transition probability after a thin overlay has been applied.

Card Type 5-1 (5 Cards): Roughness

Card Type 5-2 (1 Card): Cracking

Card Type 5-3 (1 Card): Rutting

Card Type 6 (7 Cards)

The transition probability after a thick overlay has been applied.

Card Type 6-1 (5 Cards): Roughness

Card Type 6-2 (1 Card): Cracking

Card Type 6-3 (1 Card): Rutting

Card Type 7 (7 Cards)

The transition probability after a pavement section has been reconstructed.

Card Type 7-1 (5 Cards): Roughness

Card Type 7-2 (1 Card): Cracking

Card Type 7-3 (1 Card): Rutting

APPENDIX D

THE SAMPLE OUTPUT OF THE EXAMPLE PROBLEM

```
         ITERATION   1
              ----
        COST =  -7000.00
                                                    LIMITING STATE
   STATE     DECISION          VALUE                 PROPORTIONS
     1           1            113281.                          0
     2           1             93281.                      .0000
     3           1             83281.                          0
     4           1             73281.                      .0000
     5           1             53281.                          0
     6           1             43281.                      .0000
     7           1             53281.                          0
     8           1             33281.                          0
     9           1             23281.                          0
    10           1            103281.                          0
    11           1             83281.                          0
    12           1             73281.                          0
    13           1             63281.                          0
    14           1             43281.                      .0000
    15           1             33281.                          0
    16           1             43281.                          0
    17           1             23281.                          0
    18           1             13281.                      .0000
    19           1             96875.                          0
    20           1             76875.                          0
    21           1             66875.                          0
    22           1             56875.                          0
    23           1             36875.                          0
    24           1             26875.                          0
    25           1             36875.                          0
    26           1             16875.                          0
    27           1              6875.                          0
    28           1             92500.                          0
    29           1             72500.                          0
    30           1             62500.                          0
    31           1             52500.                          0
    32           1             32500.                          0
    33           1             22500.                          0
    34           1             32500.                          0
    35           1             12500.                          0
    36           1              2500.                      .0000
    37           1             90000.                          0
    38           1             70000.                          0
    39           1             60000.                          0
    40           1             50000.                          0
    41           1             30000.                          0
    42           1             20000.                      .0000
    43           1             30000.                          0
    44           1             10000.                          0
    45           1                 0                      1.0000
```

```
          ITERATION  2
             ----
         COST =  -4968.88
                                           LIMITING STATE
   STATE    DECISION        VALUE           PROPORTIONS
     1          2           12031.              .8601
     2          4            3000.              .0387
     3          4            2097.            -.0000
     4          4            3000.                  0
     5          4            3000.                  0
     6          4            2097.            -.0000
     7          5              -0.                  0
     8          5              -0.                  0
     9          5              -0.                  0
    10          4            1406.              .0969
    11          4            1406.              .0043
    12          5              -0.                  0
    13          4            1406.                  0
    14          4            1406.                  0
    15          5              -0.                  0
    16          5              -0.                  0
    17          5              -0.                  0
    18          5              -0.                  0
    19          4             875.                  0
    20          4             875.                  0
    21          5              -0.                  0
    22          4             875.                  0
    23          4             875.                  0
    24          5              -0.                  0
    25          5              -0.                  0
    26          5              -0.                  0
    27          5              -0.                  0
    28          5              -0.                  0
    29          5              -0.                  0
    30          5              -0.                  0
    31          5              -0.                  0
    32          5              -0.                  0
    33          5              -0.                  0
    34          5              -0.                  0
    35          5              -0.                  0
    36          5              -0.                  0
    37          5              -0.                  0
    38          5              -0.                  0
    39          5              -0.                  0
    40          5              -0.                  0
    41          5              -0.                  0
    42          5              -0.                  0
    43          5              -0.                  0
    44          5              -0.                  0
    45          5                0              .0000
```

```
        ITERATION  3
           ----
       COST =  -3940.27
                                            LIMITING STATE
STATE    DECISION        VALUE               PROPORTIONS
   1         1           13060.                 .1804
   2         1            7088.                 .0266
   3         1            4736.                 .0042
   4         2           10157.                 .0105
   5         1            1453.                 .0056
   6         1            1029.                 .0018
   7         4            2012.                 .0000
   8         4            2012.                 .0002
   9         4            1404.                 .0001
  10         1            5632.                 .1209
  11         1            1629.                 .0402
  12         1             747.                 .0107
  13         1              56.                 .0241
  14         1            -927.                 .0146
  15         4            1318.                 .0015
  16         1           -2332.                 .0038
  17         5               0.                 .0008
  18         5              -0.                 .0001
  19         1            1322.                 .0589
  20         1           -1935.                 .0337
  21         1           -1474.                 .0124
  22         1           -1453.                 .0229
  23         1           -1883.                 .0167
  24         4             957.                 .0014
  25         5              -0.                 .0016
  26         5              -0.                 .0008
  27         5              -0.                 .0000
  28         1           -1684.                 .0483
  29         1           -4261.                 .0306
  30         1           -2332.                 .0157
  31         1           -2013.                 .0242
  32         5              -0.                 .0057
  33         5              -0.                 .0010
  34         5              -0.                 .0013
  35         5              -0.                 .0002
  36         5              -0.                 .0000
  37         1           -3409.                 .1166
  38         1           -5741.                 .1339
  39         5              -0.                 .0103
  40         5              -0.                 .0115
  41         5              -0.                 .0081
  42         5              -0.                 .0006
  43         5              -0.                 .0003
  44         5              -0.                 .0001
  45         5               0                  .0000
```

```
            ITERATION  4
               ----
           COST =  -3808.23
                                          LIMITING STATE
     STATE    DECISION        VALUE        PROPORTIONS
       1         1           13192.            .4074
       2         1            7414.            .0701
       3         1            4946.            .0118
       4         2           10336.            .0235
       5         2            4532.            .0059
       6         4            2422.            .0007
       7         3            6081.                0
       8         4            2216.                0
       9         4            1647.                0
      10         1            6300.            .3557
      11         4            1966.            .0305
      12         4            1410.            .0029
      13         4            1966.            .0183
      14         4            1966.            .0019
      15         4            1410.            .0002
      16         4            1164.                0
      17         4            1164.                0
      18         4             629.                0
      19         4            1622.            .0482
      20         4            1622.            .0025
      21         4            1073.                0
      22         4            1622.            .0025
      23         4            1622.            .0001
      24         4            1073.                0
      25         4             813.                0
      26         4             813.                0
      27         5               0.           -.0000
      28         4             933.            .0161
      29         4             933.            .0008
      30         4             398.                0
      31         4             933.            .0008
      32         4             933.            .0000
      33         4             398.                0
      34         5              -0.                0
      35         5              -0.                0
      36         5              -0.                0
      37         4             588.                0
      38         4             588.                0
      39         5              -0.                0
      40         4             588.                0
      41         4             588.                0
      42         5              -0.                0
      43         5              -0.                0
      44         5              -0.                0
      45         5               0             .0000
```

```
           ITERATION  6
                   ----
         COST =  -3625.10
                                              LIMITING STATE
  STATE    DECISION        VALUE             PROPORTIONS
     1         1          13375.                   .2328
     2         1           8042.                   .0424
     3         1           4527.                   .0076
     4         2          10437.                   .0135
     5         2           4919.                   .0037
     6         3           2939.                   .0005
     7         3           5998.                       0
     8         4           2190.                       0
     9         4           1662.                       0
    10         1           7236.                   .2644
    11         1           3927.                   .0747
    12         1           1726.                   .0195
    13         2           3861.                   .0189
    14         4           2079.                   .0044
    15         4           1576.                   .0010
    16         4           1270.                       0
    17         4           1270.                       0
    18         4            777.                       0
    19         1           3635.                   .1326
    20         4           1772.                   .0171
    21         4           1279.                   .0033
    22         4           1772.                   .0076
    23         4           1772.                   .0009
    24         4           1279.                   .0002
    25         4            964.                       0
    26         4            964.                       0
    27         4            483.                       0
    28         1           1387.                   .1094
    29         4           1158.                   .0091
    30         4            686.                   .0011
    31         4           1158.                   .0061
    32         4           1158.                   .0005
    33         4            686.                   .0001
    34         4            350.                       0
    35         4            350.                       0
    36         5              0.                  -.0000
    37         4            851.                   .0257
    38         4            851.                   .0014
    39         4            389.                       0
    40         4            851.                   .0014
    41         4            851.                   .0001
    42         4            389.                       0
    43         4             44.                       0
    44         4             44.                       0
    45         5              0                   -.0000

      ** OPTIMAL SOLUTION HAS BEEN FOUND**
```

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