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16. Abstract

The important component of any rehabilitation and maintenance programming is an index or scale for selecting candidate projects for rehabilitation and establishing priority among the candidate projects. In the last two decades, tools and concepts of multiple attribute decision making (MADM) have been applied to developing a prioritization index for pavement rehabilitation. However, virtually no effort has been made towards developing a unified ranking system for both rigid and flexible pavements. This report presents a univariate time series model using roughness as a common attribute which exists in both rigid and flexible pavements. The single attribute is then extended by adding more attributes, such as cracking, rutting, punchouts, etc., to form a multiple attribute decision making process. A goal programming model was used to determine the relative weights for the multiple attributes. These models are easy to use in practice and the data for developing these models are easily available either in the files maintained by the Texas State Department of Highways and Public Transportation or by conducting an interview with their staff experienced in this area. Besides being simple to use and implement, there are several advantages to using these models for practical application, as discussed in this report.

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DEVELOPMENT OF UNIFIED RANKING SYSTEMS FOR RIGID AND FLEXIBLE PAVEMENTS IN TEXAS

by

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Research Report Number 307-4F

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
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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

This is the final report presenting results from Research Project 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 types of pavements and provide some means of updating the system with continued input of the latest research findings.

In this report, we have made no attempt to describe all the work done in the project since previous Research Reports 307-1, 307-2, and 307-3 provide that information. This report describes major findings from the previous reports very briefly and discusses the work accomplished during the final phase of the project. The objective of this phase was to develop a unified ranking system for pavement evaluation that will allow the Texas SDHPT to rank rigid and flexible pavement projects on an equitable basis. The efforts to develop such a system are documented in this report.

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, Lyn Gabbert for typing the manuscript and Art Frakes for the editorial comments.

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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.

Report No. 307-4F, "Development of Unified Ranking Systems for Rigid and Flexible Pavements in Texas," by Hosin Lee, W. R. Hudson, and C. L. Saraf, evaluates the available methods and describes two models for developing a common index for pavement evaluation that will allow the Texas SDHPT to rank rigid and flexible pavement projects on an equitable basis.

ABSTRACT

The important component of any rehabilitation and maintenance programming is an index or scale for selecting candidate projects for rehabilitation and establishing priority among the candidate projects. In the last two decades, tools and concepts of multiple attribute decision making (MADM) have been applied to developing a prioritization index for pavement rehabilitation. However, virtually no effort has been made towards developing a unified ranking system for both rigid and flexible pavements. This report presents a univariate time series model using roughness as a common attribute which exists in both rigid and flexible pavements. The single attribute is then extended by adding more attributes, such as cracking, rutting, punchouts, etc., to form a multiple attribute decision making process. A goal programming model was used to determine the relative weights for the multiple attributes. These models are easy to use in practice and the data for developing these models are easily available either in the files maintained by the Texas State Department of Highways and Public Transportation or by conducting an interview with their staff experienced in this area. Besides being simple to use and implement, there are several advantages to using these models for practical application, as discussed in this report.

SUMMARY

Two methodologies are presented for developing a unified ranking system that will allow the Texas State Department of Highways and Public Transportation to rank rigid and flexible pavements on an equitable basis. Application of a univariate time series of serviceability index is shown to be useful in establishing an objective way to assign priorities. The past serviceability history of the various pavement sections is taken into consideration in this method. As usually expected, the deterioration rate is shown to be a significant factor in the model. It is suggested that the model should be tested with the broad range of data in different situations, such as cold weather conditions, rigid pavement, etc.

The goal programming model using pairwise comparison data appears to be a useful methodology for explaining the process of how decisions are made. This model uses paired comparison judgements on the global conditions of the pavements directly, and estimates the set of weights for those conditions simultaneously. This method does not place heavy judgemental demand on the decision maker as do other methods. The procedure is generalized to estimate a common set of weights using paired comparison judgements of a group of highway engineers, using two different types of pavements with different pavement attributes. The application of this method to developing a common index will be helpful in understanding the decision maker's procedure of aggregating information across the attributes, and improving their decision making quality.

In general, the prioritization analysis shows the equivocal nature of the phenomenon. The different orderings resulting from different prioritization analyses could be thought of as a strength rather than a weakness. It should be noted that each prioritization procedure is based on some rational strategy and that each separate strategic approach affords a different view of the phenomenon.

IMPLEMENTATION STATEMENT

This project has concentrated on implementation from the beginning, as discussed in the previous research reports. This report describes the development of a unified ranking procedure for pavement evaluation that will allow the Texas State Department of Highways and Public Transportation to rank rigid and flexible pavement projects on an equitable basis. A simple computer program was written to generate input data for the linear programming package. Two equations were developed using multiple linear regression and goal programming techniques. A trial implementation of these models by the Texas State Department of Highways and Public Transportation is recommended as soon as possible.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

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, rehabilitation 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 1 and 2).

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.

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 (Ref 1).

BACKGROUND

Over the last 40 years, more than $1 trillion have been invested in the highway system of the United States. With much of the highway network system completed, national attention and interests are now directed toward the problems of maintaining and rehabilitating highways. Federal, state, and local governments spend $15 billion annually to maintain the nation's 4-million-mile network (Ref 3). Massive investments, which are estimated at $400 billion by the year 2000, will be required for rehabilitating and maintaining pavement. Consequently, it is necessary to develop a system for effectively programming the rehabilitation and maintenance of the pavement network.

Roads and highways are the primary assets of the Texas State Department of Highways and Public Transportation (SDHPT) 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 4), although the application of general systems methods is widespread in industry and the military.

During the period 1968-1975, comprehensive flexible and rigid pavement design systems (FPS and RPS) were developed for use by the Texas SDHPT (Refs 5, 6 and 7). This system has been implemented and used by the Design Division as well as some Districts for project level pavement design decision making. More recently, the SDHPT has embarked on development of a PMS (called PES) to assist in evaluating pavement information for planning and making investment decisions covering the highway network which emphasizes rehabilitation and maintenance. The Pavement Evaluation System (PES) was established in September, 1982, as the first statewide Pavement Management System (PMS). PES was intended to provide the Texas SDHPT with consistent quantifiable measures of statewide pavement condition and also to be used in estimating statewide pavement rehabilitation.

Early efforts at developing pavement rating systems began in 1946, when the Highway Research Board established a committee on pavement condition surveys in the Department of Design (Ref 8). In 1962, the Highway Research Board published a procedure for rating the condition of flexible pavements. This procedure assigns numerical deduct values for specific distress types, depending on extent and severity. A combined score was computed for the specific pavement section by adding up the deduct values and subtracting the sum from a perfect score of 100. This procedure has been adopted by numerous highway agencies throughout the country. The combined index was used to express the overall condition of the pavement. This "deduct point system" is one of the so-called "Multiple Attribute Decision Making" methods that have long traditions in many other disciplines (Ref 9).

In the past decade, tools and concepts of multiple attribute decision making (MADM) have been applied to the development of a prioritization index for pavement rehabilitation. However, virtually no effort has been made towards developing a unified ranking system for both rigid (concrete) and flexible (asphalt) pavements based on the different sets of pavement attributes. Recently, the Texas SDHPT has indicated its interest in developing a unified ranking system for selecting candidate projects in order to distribute rehabilitation funds to all types of pavement rehabilitation projects on an equitable basis.

OBJECTIVE OF PROJECT 307

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 for all pavement types, and, furthermore, to provide for updating the system with continued input of the latest research developments and findings.

The original <u>objective</u> of the study was to assist in developing a PMS methodology that will assist SDHPT in allocating its resources to the maintenance, rehabilitation, and design of pavements in an efficient manner. This overall objective was further divided into the following particular subobjectives:

(1) accelerate implementation of PMS in a logical progression for the department;
(2) develop a single system for managing the pavement resource for
    (a) legislative requirements and inquiries,
    (b) administrative and commission requirements,
    (c) maintenance activities,
    (d) RRRR activities, and
    (e) design criteria for necessary feedback data system material 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 network level PMS; and
(7) promote cooperative effort of research agencies.

In the last stage of Project 307, the original objective had been expanded to include another important subobjective:

(8) develop a unified ranking system for rigid and flexible pavements on an equitable basis.

SCOPE OF THE FINAL REPORT

As previously discussed, the long-range goal of this project is to assist the 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 findings. Research Reports 307-1, 307-2, and 307-3 covered all these aspects of the study.

The objective of this final report is to outline the development of a unified ranking system that will assist the SDHPT in allocating its resources for the maintenance, and rehabilitation of rigid and flexible pavements in an efficient manner.

In the past, prioritization indices have been developed separately for flexible and rigid pavements based on different sets of pavement attributes, due mainly to convenience and the limited information and methodology available. Some highway engineers believe that rigid and flexible pavements are two completely different entities and that therefore it is impossible to develop an index or method to compare one with the other. The Texas State Department of Highways and Public Transportation decided to investigate the possibility of developing a unified ranking system for rigid and flexible pavements. This decision related to the fact that both types of pavements (rigid and flexible) are competing for the same funding and therefore, it is necessary to distribute these funds on an equitable basis. The results of such an investigation are included in this report.

Chapter 2 summarizes the development of network level PMS in Texas to assist the Texas SDHPT in identifying the current problem areas and existing weakness in pavement management practices. It includes a discussion of the current status of PMS in Texas to promote the improvement of pavement management in Texas.

Chapter 3 includes a review of several approaches to developing a common priority index for pavement rehabilitation or maintenance in order to provide background information on existing practices. The selection of appropriate methods based on the criteria which are important to goals and objectives of the study is discussed in Chapter 4. Two selected methods, which are (1) the univariate time series model and (2) the goal programming model, are briefly discussed in Chapter 4. In Chapter 5, data requirements and their collection procedures are discussed. The univariate time series model uses historical serviceability index data as the only input. More detailed condition survey data are required for the goal programming model. Development of the time series model using historical serviceability index data is described in Chapter 6. Parameters of the model were estimated using a linear regression method. Chapter 7 describes the development of a goal programming model using pairwise comparison data. The model estimates weights for both flexible and rigid pavements simultaneously.

In Chapter 8, sample applications of these models to hypothetical pavement sections are provided to illustrate how they can be used to generate common prioritization indices. Results of the sample applications are also discussed. Chapter 9 presents a summary of the findings of this study, and provides conclusions stemming from these findings, together with the recommendations for future research activities.

CHAPTER 2. DEVELOPMENT OF PMS IN TEXAS

The historical development of pavement systems technology is presented in the previous chapter. The details of initial management systems concepts formulated in 1970 are presented in Report 123-1 (Ref 10), the first in a series of 30 reports concerning the use of pavement systems techniques in management decision making.

Unfortunately, the sheer complexity of pavement design problems has made the finding of a solution difficult. The systems approach provides a framework for collecting and coordinating available information and for moving step-by-step towards a rational solution. Accordingly, a PMS Workshop was held by the Texas SDHPT in February 1981 to address this problem in terms of establishing Texas' specific needs for a PMS as well as to determine the benefits associated with such a PMS.

A detailed description of the component parts of the pavement management system and of the concept of the system as a whole follows, along with an evaluation of the methodology in terms of the pavement management problem.

The pavement management system requires the operation and interaction of several components:

(1) working design system or computer program;
(2) pavement feedback data system or database;
(3) data collection and updating;
(4) subsystem updating;
(5) pavement research in systems, economics, materials, distress, performance, and condition evaluation; and
(6) implementation - schools, refresher courses, and computerized instruction in the use of working design systems.

The major emphasis in early developmental studies (Ref 5) has been in areas 1, 5, and 6 although some work was done on all items. The "working system" is at the center of all of the other tasks since it contains all of tne equations or models developed and makes use of the design data assembled. It is divided into several subsystems for at least two practical reasons.

(1) Each subsystem should operate separately so that it can be replaced with a minimum of effort when one which is more suitable is developed.

(2) Each subsystem allows experts in its own area to contribute the latest information and to keep the subsystem updated.

The major subsystems in both the rigid and the flexible pavement design systems have been detailed in Research Report 123-30F (Ref 5). FPS and RPS, the two series of Pavement Management Systems begun and implemented in Study 123 (Ref 5), must be evaluated as good to excellent. The benefits available to the user agency far outweigh the limitations if the methods are properly understood and applied. A series of computer programs called RAMS (Rehabilitation and Maintenance System) (Refs 11 and 12) have been developed by Dr. Lytton of Texas Transportation Institute (TTI) and related directly to proposed current work on PMS.

The planning and design activities related to providing new portland cement concrete (PCC) pavements or rehabilitating and maintaining existing ones are of capital importance to the primary highway system of the State of Texas. An improved rigid pavement overlay design method was developed by the Center for Transportation Research (CTR) of The University of Texas at Austin in Research Project 177, "Development and Implementation of the Design, Construction, and Rehabilitation of Rigid Pavements" (Ref 13). The results defined the course of the investigation conducted in Research Project 249, "Implementation of a Rigid Pavement Overlay and Design System" (Ref 14).

An extensive data base, which includes information on rigid pavements and data-processing computer programs, was started in Project 177 and continued in Projects 249 and 388. The information gathered came from in-service pavements (such as CRCP rigid-pavement, and experimental maintenance sections). The type of information collected included materials and environmental factors, riding quality, distress condition, deflection, and traffic volume.

At the network level, procedures were developed and improved for data collection for both rural and urban CRCP in Project 177. Furthermore, a methodology was provided in that project to estimate whether a given pavement has reached its terminal condition by means of a distress index developed from analysis of field data on overlaid and non-overlaid pavement sections.

In this study, the Center for Transportation Research has been assisting the Texas Department of Highways and Public Transportation in the development of a Pavement Management System with primary emphasis at the network level and in the implementation of the PMS in a logical progression for the Department. An advisory panel made up of representatives of appropriate groups within the SDHPT and the two research agencies was formed to guide the work to give direction to early phases of the work.

The Center for Transportation Research developed a skeleton plan for the Department's PMS work, coordinating with TTI and including objectives to be established in full cooperation with the Department Task Force on PMS and with the Transportation Planning Division and their continued development of the Roadway Information System (RIS).

A Federal Highway Administration Workshop on Pavement Management Systems was held in February 1981 for the states in FHWA Region 6. The purpose of this workshop was to present PMS concepts and alternate approaches. As a follow-up to this workshop, a one-day special session with the Texas participants only was held. The purpose of this special session was to briefly review efforts to date and proposed plans for PMS in Texas and then to get input from the participants to be used in further planning. It was felt that the participation in the general workshop and the brief review provided an environment for valuable input from field personnel. It was also deemed desirable to make a general presentation for the Administration prior to the workshop to outline the direction being taken and obtain their concurrence.

The simplified PMS-N (Pavement Management System - Network Level), as presented in Research Report 307-1 (Ref 15), is based on the total framework for pavement management systems developed in Project 123 (1970-76) and NCHRP

Project 20-7, Task 15 (1978-81) (Ref 15). Each of the network level subsystems comprising this framework was incorporated as fully as possible into the simplified system. The development was focused on the rehabilitation of existing pavements, since this activity area has become increasingly important in recent years.

This approach and completion of the tasks did not provide an "ultimate" pavement management system. Nevertheless, it provided the basis for continuing improvements and modifications as new knowledge and research becomes available, as well as the foundation for an orderly and staged implementation. Figure 2.1 illustrates this concept. It suggests that pavement management system development should be a staged process and that "implementation plateaus" exist between successive improvements or updates.

In addition to the FHWA workshop activities in February 1981, the project staff participated in two PMS Task Force meetings that were held by the SDHPT in May and June. The purposes of these meetings was to get significant input from several of the highway districts within the State which could provide direction for the development and implementation of a PMS in Texas. Summaries of the discussions that transpired during these meetings were compiled by the Project staff, and distributed to the SDHPT for review. Among other things, the Task Force meetings have resulted in the adoption of PES as Release 1.0 for the Texas PMS. In addition, agreement was reached with respect to the decision criteria that shall be used for determining rehabilitation needs.

Further recommendations for the initial release of a Texas PMS along with suggestions for future development are contained in Research Report 307-1 (Ref 15). In addition to presenting an implementation plan for PMS, the report reviews the framework and essential characteristics of an ideal PMS, and the current state-of-the-art of PMS development in Texas and other states.

Research activities in the development of a prioritization variable for network level programming have also been undertaken by the project staff in cooperation with the SDHPT. In one of these activities, numerous highway engineers were consulted to see what pavement condition variables are the

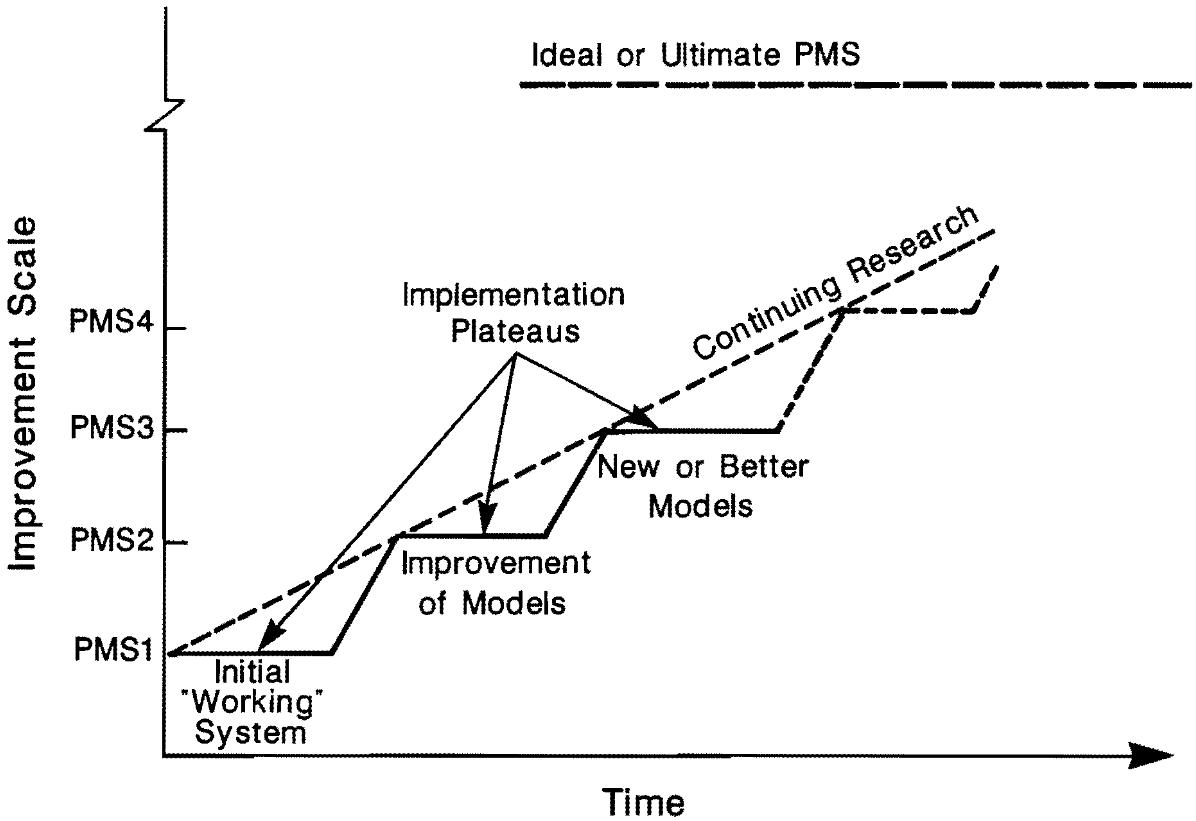


Fig 2.1. Schematic representation of progressive improvements in pavement management system development and implementation.

most important for network level programming considerations. The analysis of these responses was performed using a "factorial design method". This led to a better understanding of how highway engineers establish priorities for rehabilitation work. In addition, a review and evaluation of existing maintenance rating systems was made as part of the research efforts in the development of a prioritization index. The results have been documented in Research Report 307-2 (Ref 9). In the meantime, the Texas State Department of Highways and Public Transportation implemented a pavement evaluation system (PES) as its first network level PMS (Ref 17). The primary objective of PES is 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.

We continued our work with the department through task force meetings, presentations, discussions, and evaluation and testing of PES data sets. In particular, we compared and evaluated our measurements and findings with the project data in District 13 and also compared this to the results reported in PES. We noted a number of minor discrepancies which would have some effect on individual project level comparisons desired by the maintenance engineer, but which may have little effect on the overall rankings and programming which was the purpose of PES.

At the same time, we evaluated available pavement management optimization programs to see which programs would be most useful in upgrading the current PES system used by the department. The Network Optimization System (NOS) Program currently used by the Arizona DOT (Ref 18) was reviewed and evaluated. The basic concept used in this system was adopted in the development of a program level PMS for Texas. The development procedure using PES data has been documented in Research Report 307-3 (Ref 19).

A computer program was developed using a simple but efficient algorithm called "policy iteration technique" to solve a large-scale practical pavement rehabilitation problem. A recommended procedure for the implementation of this program level PMS model is described in the report (Ref 19).

The report (Ref 19) discusses the important PMS concepts which could be adopted by the state. Figure 2.2 illustrates that the PES needs to be tailored so that it serves the Texas PMS objectives effectively. Recommendations to improve the PES are also discussed in Report 307-3.

The second and third round of pavement evaluation for the PES was begun in October 1983 and was completed in April 1985. In the second round of evaluation, the Texas SDHPT reviewed the pavement distresses used in the analysis process and simplified the surveys by replacing raveling and flushing data with patching and block cracking. It also evaluated sampling techniques and changed the sampling procedures and amount. While there were a few problems in the segmentation of the highway system data collection and data processing, the first round of implementation was considered highly successful by the SDHPT. In the third round, the SDHPT has included an evaluation system for rigid pavements into the PES program.

One of the primary functions of the PES was to determine the condition of the pavement surface of each rated section. A pavement rating score was calculated for each pavement section. The pavement score was an indication of the relative priority for rehabilitation expressed as a number varying from 0 to 100. Therefore, pavement sections listed by pavement score would provide management with a priority listing of sections in need of rehabilitation. The technique based on utility theory was used for calculating these rating scores. The utility curves were developed using the preset deduct point system for each category of distress for flexible pavement only (Ref 17).

Evaluation of rigid pavement sections was included for the first time in the 1984 Survey (Ref 20). The utility curves were developed for calculating pavement scores for rigid pavement.

As mentioned earlier, the research on rigid pavement rehabilitation has been conducted by the Center for Transportation Research at The University of Texas at Austin since 1974. A distress index was developed for this purpose using the discriminate analysis (Ref 21). This discriminate equation developed for rigid pavements has not yet been tested to determine if it is comparable with equations for flexible pavements. Therefore, the Texas SDHPT indicated its interest in developing a unified ranking system to select

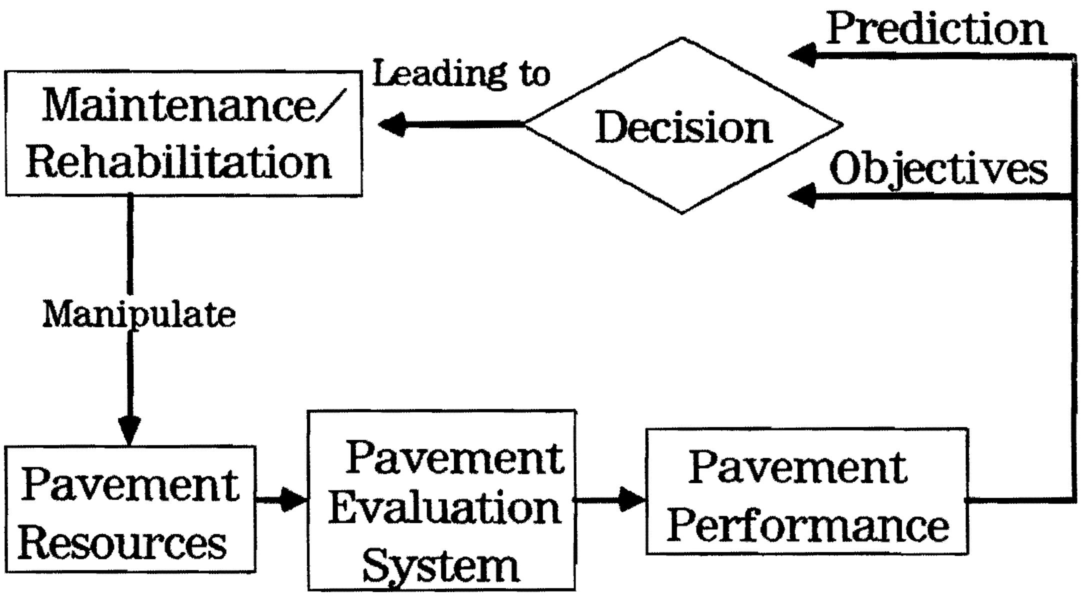


Fig 2.2. The role of Pavement Evaluation System in total Pavement Management System.

candidate projects in order to distribute rehabilitation funds to rigid and flexible pavements on an equitable basis.

Comparing rigid and flexible pavements is just like comparing apples and oranges. Virtually no effort has been made toward comparing two different entities composed of different sets of attributes. An extensive literature study was conducted in search of methodologies which could be used in developing a common index for two different types of pavements. As a result of these efforts, eight available methodologies were reviewed and are discussed in this report.

CHAPTER 3. REVIEW OF AVAILABLE METHODS

An extensive literature study was conducted in search of methodlogies which could be used in developing a unified ranking system for rigid and flexible pavements. However, no directly applicable methods of this kind were found in the pavement area or in other areas such as management science, decision analysis, etc. Since there was not an existing methodology which could be directly applied. A series of project meetings and an extensive literature study yielded eight possible methodologies to consider for developing a unified ranking system. These eight methodologies were thoroughly reviewed and evaluated. This chapter presents a brief discussion of each methodology. A more complete evaluation and comparison is presented in Chapter 4 prior to the final selection.

SERVICEABILITY INDEX APPROACH

In the early 1960's, the concept of pavement serviceability was developed by Carey and Irick at the AASHO Road Test (Ref 22). They proposed that the road users should evaluate the serviceability of a pavement. The Present Serviceability Rating (PSR) was defined as the mean of the individual ratings made by the members of a specific panel selected for this purpose. However, it is impractical and expensive to evaluate serviceability on any pavement section using the rating panel method except on a very limited basis. Consequently, considerable effort has gone into correlating various mechanical measurements with these subjective ratings. The PSR was correlated with a set of physical measurements, called Present Serviceability Index (PSI). When PSI is calculated from physical measurement data, it is only an approximation of PSR; that is,

$$PSI = PSR + Error \tag{3.1}$$

The following PSI equations were developed at the AASHO Road Test using a multiple regression technique for flexible and rigid pavements respectively (Ref 23):

$$\text{PSI (flexible)} = 5.03 - 1.91 \log (1 + \overline{SV}) - 1.38\ \overline{RD}^2 - 0.01 \sqrt{c + p} \qquad (3.2)$$

$$\text{PSI (rigid)} = 5.41 - 1.80 \log (1 + \overline{SV}) - 0.09 \sqrt{c + p} \qquad (3.3)$$

where

$\overline{SV}$ = mean slope variance obtained with the Road Test profilometer,

$\overline{RD}$ = mean rut depth as measured by simple rut depth indicator, and

$c + p$ = amount of cracking and patching.

Although these physical measurements include condition or distress data, it is the roughness that provides the major correlation variable. The correlation coefficients between PSR and PSI are increased by only about 5 percent after including the condition data with the serviceability information. The major use of roughness measurements, which are objective, is for estimating pavement serviceability, which is subjective.

The roughness is a common attribute existing in both flexible and rigid pavements. The serviceability index, solely based on roughness measurements, should be directly comparable among all types of pavements. However, the PSI equation for rigid pavements might be different from the PSI equation for flexible pavements because the same roughness may be perceived differently by the road users, depending on pavement type. This can be verified by forming a new pavement rating panel and correlating the results directly with the particular roughness instrument of interest by the different types of pavements.

The research using a new rating panel and instrument has been conducted by the CTR, and the results show that there is a significant difference between the PSI equation for rigid and the PSI equation for flexible pavement, given the same measured roughness (Ref 24). One of the newly obtained equations using a new 690D Surface Dynamics profilometer as a roughness measurement device is

$$PSI = 4.31 - 0.04\ VA_2 - 0.50\ VA_8 - 8.22\ VA_{128} + 0.37\ PTYPE \qquad (3.4)$$

where

PTYPE = 1 for rigid pavements,

PTYPE = 0 for flexible pavements, and

VA_x = vertical acceleration associated with x feet wavelength.

Using this equation, for the same level of roughness, the PSI in rigid pavement is predicted to be higher than the PSI in flexible pavement by 0.37 rating points for the same VA levels. This means that the public might feel more comfortable riding on rigid pavement than riding on flexible pavement even if roughness levels are same, or they may subconsciously "feel" that the rigid pavement is better if all else (e.g., roughness) is equal.

RATE OF LOSS OF SERVICEABILITY INDEX

The Present Serviceability Index has been previously discussed as a rational way to develop a common index for all types of pavements. The present serviceability index represents a means of using objectively obtained data, such as roughness, to estimate subjective user evaluations in terms of the mean panel rating values, Present Serviceability Rating. However, pavement sections with the same PSI values do not necessarily perform in the same manner.

Generally, a pavement section which is deteriorating, i.e., losing SI at a faster rate, should be ranked higher for rehabilitation than others because rapid loss of SI foretells rapid deterioration of pavement in the future. The rate of deterioration might be different by pavement types, performance histories, traffic, environmental factors, etc. In other words, a deterioration rate higher than previously considered normal might be due to inadequate design, heavier traffic, severe weather, and so on. It is recommended that the rate of loss of SI should be considered together with the present SI in order to develop a common prioritization index model based on the pavement serviceability concept.

ANALYTICAL EXAMINATION OF DISTRESS

Before methods of evaluation can be discussed, it is necessary to have a clear understanding of types of pavement distress. It is important to ascertain whether certain types of pavement distress are progressive, leading to eventual failure of the road, or not. Two types of failures, functional failure and structural failure, need to be reviewed. Functional failure depends primarily on the surface roughness. Structural failures in flexible pavements may result from surface fatigue cracking, consolidation, or shear. Distress of rigid pavements is due to the deterioration of the pavement itself or structural inadequacy of the pavement-base-subgrade structure (Ref 25).

Distress in pavements is usually due to a combination of several causes, and considerable variation can be found in their effects. Investigations could be made by trenching the pavement; however, usually only visual inspection and measurements are available for the empirical studies. The objective of the analytical examination of distress would be to predict the life of a pavement to be used as a common prioritization index. To compute the remaining life of the pavement:

(1) The limiting amount of distress is to be determined for each distress type.
(2) Relationships between distresses need to be established through statistical correlation studies.
(3) Performance prediction equations need to be developed for the important distress types.

ECONOMIC ANALYSIS (MAINTENANCE COST)

Maintenance consists of a set of activities directed toward keeping a pavement structure in a serviceable state. This includes such work as patching, crack filling, and so on. The pavements might be prioritized by maintenance expenditure to be required on each pavement section, simply because the pavement in worse condition would require more maintenance expenditure.

However, this approach may not be appropriate for comparing rigid pavements with flexible pavements, because maintenance strategies for rigid pavements would generally cost more but make pavements last longer than maintenance strategies for flexible pavements. Therefore, the effectiveness and benefit of maintenance strategies, such as increased life, should also be considered an economic analysis.

In order to conduct the life cycle benefit/cost analysis, maintenance strategies and rehabilitation actions should first be determined. Once the maintenance or rehabilitation strategy is determined for each pavement section, it is possible to calculate benefit and cost figures over the life cycle of the pavement. Then a pavement can be selected based on the benefit/cost ratio of the pavement section with a predetermined strategy.

DISCRIMINANT ANALYSIS

Discriminant analysis and classification are multivariate techniques concerned with separating distinct sets of objects and with allocating new objects to previously defined groups. We try to find the "discriminants" whose numerical values are such that the collections are separated as much or as distinctly as possible. The goal of classification is to sort objects into two or more labeled classes. The emphasis is on deriving a rule or rules that can be used to optimally assign a new object to the labeled classes.

A function that separates may serve as an allocator, and, conversely, an allocatory rule may suggest a discriminatory procedure. In practice, the distinction between discrimination (or separation) and classification (or allocation) is not clear. Classification rules are usually based on the function derived from the discriminant analysis. One of the objectives of conducting discriminant analysis would be to provide the basis for a classification rule. At this point, we shall concentrate on discrimination.

A discriminant index or score can be obtained by maximizing the absolute differences in the average values of the index for the two groups with known mean vectors and covariance matrix. Generally, more mean difference and less variance involving each factor will lead to more weight.

Discriminant analysis has already been applied in developing an equation to discriminate between CRC pavements with an acceptable level of distress and pavements requiring overlay (Ref 21). Distress data for several pavements in Texas, including condition before overlay, were used to determine the reasons leading to overlays; that is, having data from two groups, overlaid and non-overlaid pavements, an equation was developed to differentiate between the two groups.

This technique can be used for selecting rehabilitation projects among all types of pavements based on common attributes such as serviceability index and traffic. Consider two groups of pavements -- π_1, pavement sections selected for rehabilitation, and π_2, those not selected for rehabilitation. In order to select pavement sections for rehabilitation, we are interested in classifying pavement sections as prospective candidates for rehabilitation on the basis of X_1, serviceability index (SI), and X_2, the average daily traffic (ADT). In other words, we are investigating how the highway engineers consider the serviceability index and the volume of the traffic in their decision processes.

Suppose we have randomly sampled data points as plotted in Fig 3.1. We can see that highway engineers tend to select pavement sections for rehabilitation if the serviceability index is low with a high volume of traffic. However, if we were to select pavement sections for rehabilitation based on the equation derived from the discriminant analysis, we would make

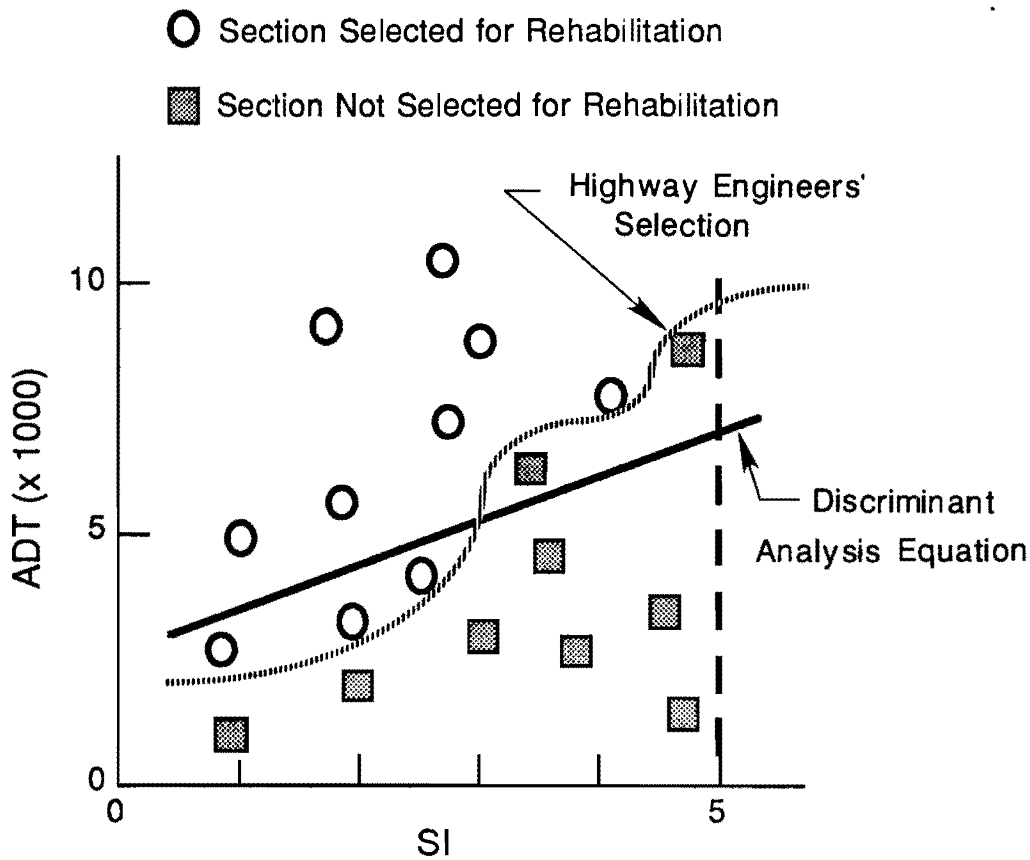


Fig 3.1. A simplified example of selecting pavement sections for rehabilitation using discriminant analysis.

some mistakes because there are more factors to be considered in the decision making process.

UTILITY THEORY (VALUE FUNCTION)

Utility theory has been applied to the development of a measure of overall pavement performance in Arizona and Texas (Refs 17 and 26). The procedure involves the assessment of value functions which quantify a decision maker's subjective opinions according to selected pavement attributes. A value function is developed for each attribute by soliciting expert opinions through interviews. Then a set of weights is developed for expressing the preferences given to various attributes.

A value function is a way to transform values into a commensurable (directly comparable) unit for cross attribute comparison. As shown in Fig 3.2, the trigger value concept and linear scale transformation are the two extreme cases of the value function. In the case of pavement attributes in practice, linear transformation may not be desirable. An example is discussed herein to illustrate a procedure for developing a value function for a pavement attribute, such as failures, and a set of weights for various attributes (Ref 27).

Step 1. Assess a Value (Utility) Function, given that the value function of 0 failures/lane mile is 100 and that of 10 failures/lane mile is 0.

(Method 1)
Failures per lane mile (0 ~ 10)

	Question	Hypothesized Answer
(1)	What is the midvalue point between 0 and 10?	(say) 3
(2)	The midvalue between 3 and 10?	(say) 5
(3)	The midvalue between 0 and 3?	(say) 1

The developed value function using the above information is shown in Fig 3.3.

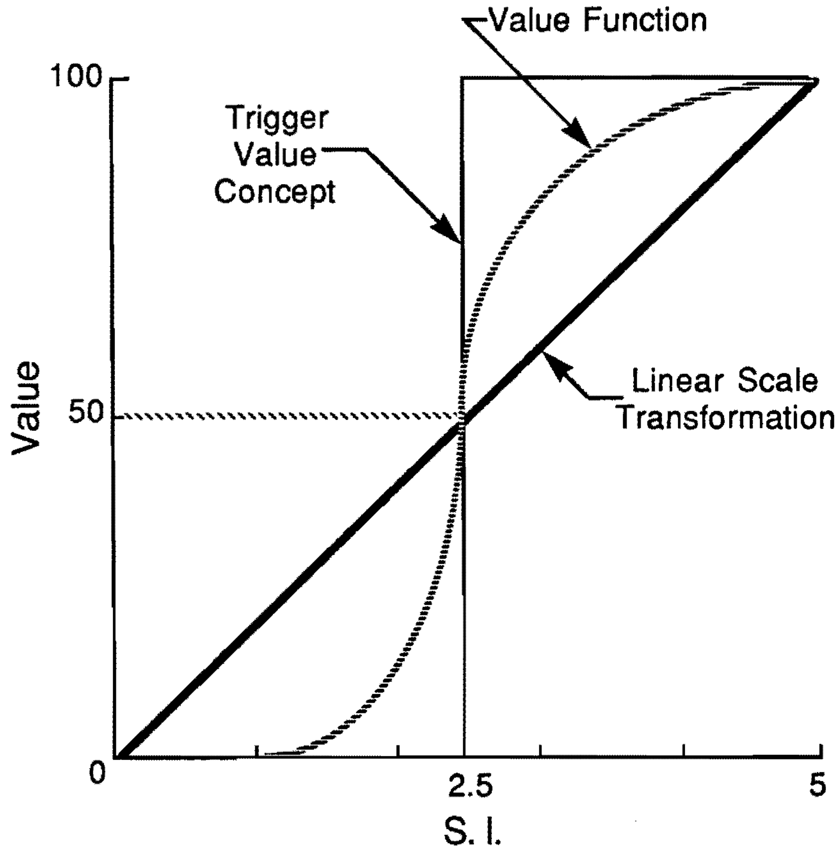


Fig 3.2. Value transformation concept.

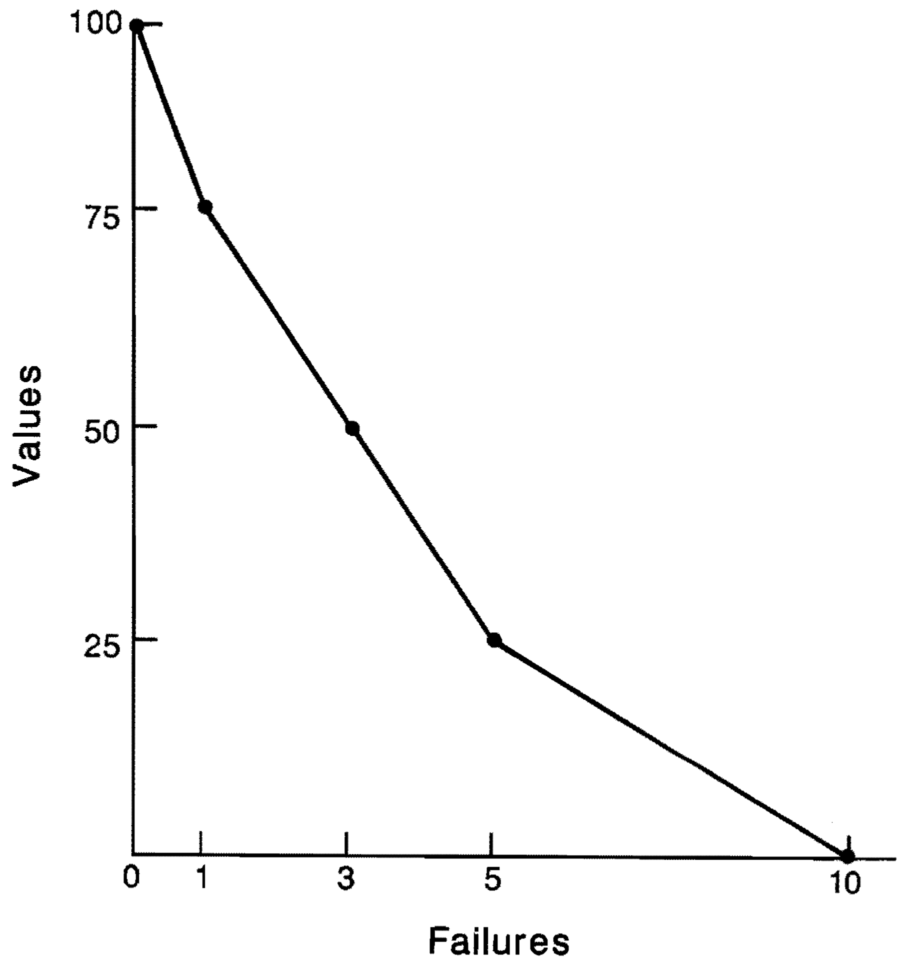


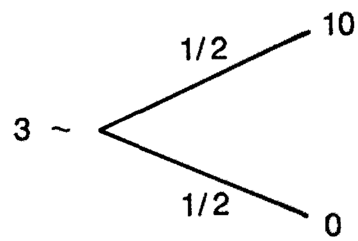
Fig 3.3. Value function developed using method 1.

(Method 2)

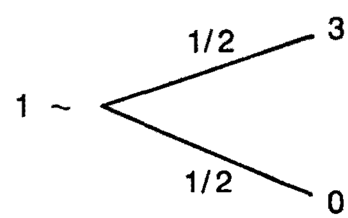
$U(\widetilde{X}) = p\,U(b) + (1-p)\,U(a)$, given

$U(0) = 2$, $U(10) = 0$
$p = 1/2$

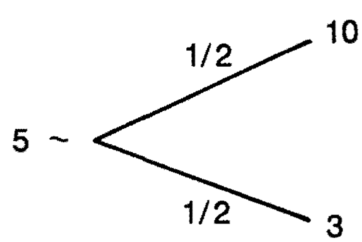
(1) $U(3) = 1/2\,U(10) + 1/2\,U(0) = 1/2\,(0) + 1/2\,(1)$
$= 0.5$



(2) $U(1) = 1/2\,U(3) + 1/2\,U(0)$
$= 0.5/2 + 1/2$
$= 0.75$



(3) $U(5) = 1/2\,U(10) + 1/2\,U(3) = 1/2\,(0) + 0.5/2$
$= 0.25$



Step 2. Assess Scaling Constants (λ_j)

Failures (0 - 10/lane mile)

Alligator Cracking (0 - 50 percent area)

Rutting (0 - 50 percent area)

Longitudinal Cracking (0 - 200 ft)

Assume: Failures > Alligator Cracking > Rutting > Longitudinal Cracking

λ_1 λ_2 λ_3 λ_4

$$\nu(\chi_1, \chi_2, \chi_3, \chi_4,) = \sum_{j=1}^{4} \lambda_j \ \nu_j \ (\chi_j)$$

where

(a) ν_j (worst χ_j) = 0

ν_j (best χ_j) = 1

j = 1: failures

j = 2: alligator cracking

j = 3: rutting

j = 4: longitudinal cracking

(b) $0 < \lambda_j < 1$

(c) $\sum_{j=1}^{4} \lambda_j = 1$

Find χ_1 where

$(\chi_1, b_2, b_3, b_4) = (b_1, w_2, b_3, b_4)$

b: best, w: worst

$$\nu(7, 0, 0, 0) = \nu(0, 50, 0, 0)$$

$$\lambda_1 \cdot \nu_1(7) + \lambda_2 + \lambda_3 + \lambda_4 = \lambda_1 + \lambda_3 + \lambda_4$$

From step 1, utility value of ν_1 (7) = 0.4; utility value of 7 failures.

$$\lambda_2 = 0.6 \lambda_1$$

Similarly, the proportional relationships between λ_2, and λ_3, and between λ_3 and λ_4 can be determined.

Given

ν_2 (30) = 0.6; utility value of 30 percent alligator cracking,
$\nu(o, 30, 0, 0,) = \nu(0, 0, 50, 0)$
so that $0.4 \lambda_2 = \lambda_3$

Similarly, if

$\nu(0, 0, 40, 0) = \nu(0, 0, 0, 200)$
given ν_3 (40) = 0.3
$0.7 \lambda_3 = \lambda_4$

Thus

$$\lambda_3 = 1.43 \lambda_4$$
$$\lambda_2 = 3.57 \lambda_4$$
$$\lambda_1 = 5.95 \lambda_4$$
$$\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1$$
$$\lambda_4 = 0.08 \quad \lambda_3 = 0.11 \quad \lambda_4 = 0.29 \quad \lambda_5 = 0.52$$

TRIGGER VALUE METHOD

There are varied objectives for evaluating the conditions and performance of a pavement and several ways of doing it. However, the main objective is to identify candidate pavement improvement projects for rehabilitation. The methods for developing a prioritization index discussed earlier are comparable with one another because each of them attempts to quantify the subjective opinions of pavement engineers with regard to the establishment of priorities through the use of a numerical system of weights.

Most agencies use a formula type of assessment where candidate projects are subjectively selected and weights are subjectively assigned to various surface distress measurements, roughness, and traffic volumes. A combined index is then assigned to each project and the projects are ranked according to these ratings. This combined index is very simple and easy to apply in practice. However, the results could be misleading in some cases.

For example, in the PES, a relatively high utility score of 0.9 for all seven distress types will give a combined score of 48 ($0.9^7 \times 100$). On the other hand, the lowest possible utility score of 0.72 for the worst rutting condition, combined with the others, each with utility score of 1.0, will give a final combined index of 72. From the analysis of the final combined index, the former should have higher priority for rehabilitation, but actually the latter may be in more critical need for repair.

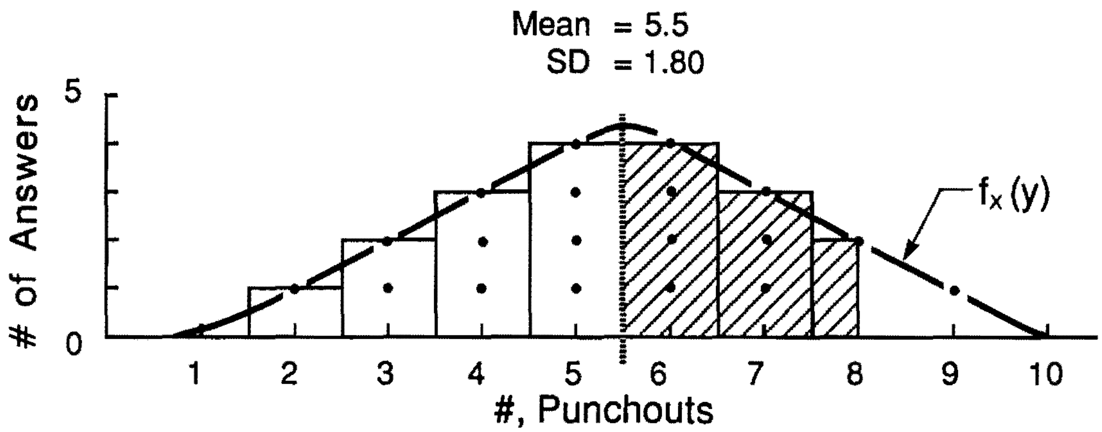
Usually the procedures for developing utility equations or deduct points for each pavement condition attribute and assigning an appropriate weight for the attribute are quite heuristic, arbitrary, and without a logical argument. The procedures for obtaining subjective opinions from numerous highway engineers about pavement behavior could be too lengthy. Hence, the trigger value method is recommended as an alternative to solving those problems. Trigger value is the minimum acceptable level for each attribute that will trigger the repair action.

Each defect attribute identified in the condition survey should be assigned a trigger value (minimum acceptable level) which contributes to a determination of the need for pavement repair. Those existing pavement sections which exceed the minimum acceptable level in one or more of the pavement condition attributes should be selected as candidates for rehabilitation. For example, if the serviceability index is equal to or less than 2.5, then the trigger value has been met and pavement repair action is required. In the case of alligator cracking, if the extent exceeds 50 percent of the total area, then a repair is necessary. All of the defects are evaluated against established trigger values, each of which is associated with a need for repair. At this point, no priorities are established for repairs.

In practice, the priority for repairs needs to be established because there are not enough funds to do all repairs according to the degree of distress and roughness under different traffic, and environmental conditions. A prioritization scheme can be developed by considering the differences in highway engineers' estimates of the trigger values for pavement condition attributes. Greater deviation in their estimates makes us believe that there is more variability and uncertainty in their decision making process. Therefore, fewer deduct points should be assigned for a pavement attribute with more standard deviation in the trigger value estimates.

First, as discussed earlier, two pavement ranking score systems are proposed in order to prevent a severe condition attribute not being detected due to the good conditions in the other attributes which produce a relatively high combined index. One is for pavement sections which have reached a minimum acceptable level in one or more of the pavement condition attributes, and the other is for pavement sections in which all of the attributes are above the minimum acceptable level.

The trigger value method will be explained with the help of the following example: Suppose we ask 20 highway engineers to provide the trigger values of punchouts in rigid, and alligator cracking in flexible pavements. If the data is plotted as shown in Fig 3.4, then, under the assumption of normal distribution, the ranking score of the pavement section with eight punchouts is 42, and the ranking score of the pavement section with 60 percent alligator cracking is also 42. The ranking score has been



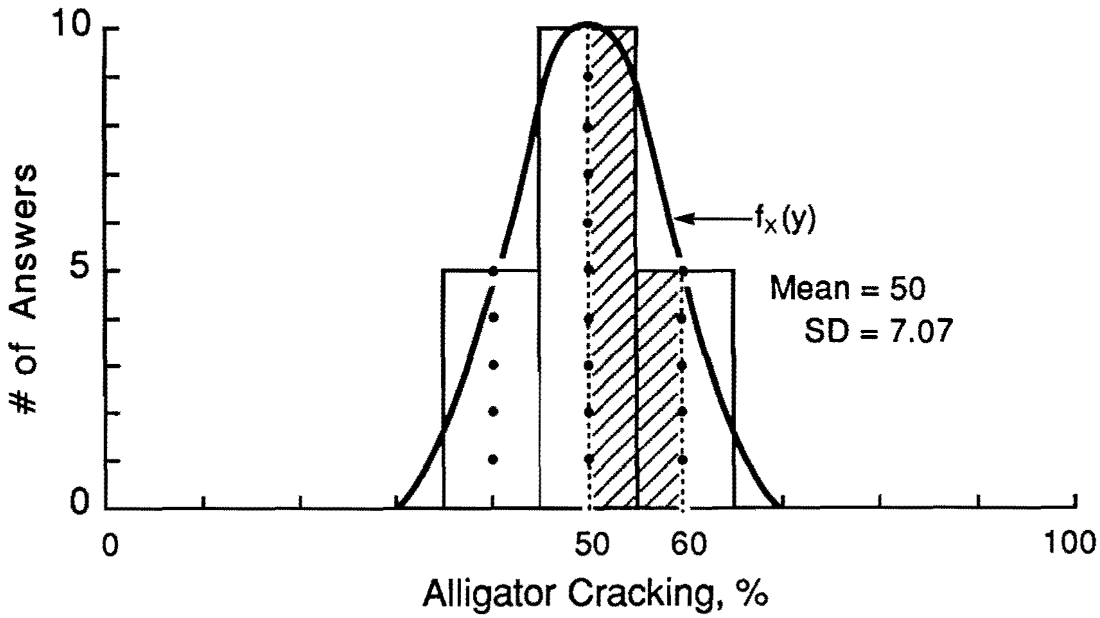


Fig 3.4. Trigger values for punchouts and alligator cracking assuming the data were obtained from twenty highway engineers.

derived from the hatched area between the current condition and the trigger value as shown in Fig 3.4 (see Eqs 3.5 and 3.6). The ranking number in this case will range between 0 and 50. However, if the range is extended to 0 to 100, the estimated alues should be multiplied by 2.

Group 1: For pavement sections which have reached a minimum acceptable level in one or more pavement attributes

$$R_1 = \left[\sum_{i=1}^{\nu} \int_{mean_i}^{b_1} fX_i \; (y) \; dy \right] / N \tag{3.5}$$

where

- n = number of attributes which are equal to or below the minimum acceptable level
- N = total number of attributes considered
- X_i = attributes equal to or below the minimum acceptable level
- b_i = current condition of attribute i
- $mean_i$ = trigger value of attribute i
- $fX_i \; (y)$ = density function of attribute i
- R_1 = ranking number for repair that ranges from 0 to 100.

Group 2: For pavement sections in which all of the attributes are above the minimum acceptable level

$$R_2 = \left[\sum_{i=1}^{N} \int_{a_i}^{mean_i} fX_i \; (y) \; dy \right] / N \tag{3.6}$$

where

- a_i = current condition of attribute i, and
- R_2 = ranking number for non-repair (0 to 100).

This trigger value method is a new concept introduced by the author of this report in developing a prioritization index for any type of pavement. The method needs to be further refined for the implementation. However, this trigger value concept is rational with logical arguments, and simple enough to be understood and implemented compared to other methods discussed previously.

PAIRWISE COMPARISON METHOD

A pavement section can be characterized by its performance attributes, such as roughness, cracking, rutting, punchouts, etc. When a highway engineer selects candidate projects for rehabilitation, he considers some or all of these pavement performance attributes to a greater or lesser degree. This relative importance of each attribute in the decision making process can be estimated using a pairwise comparison method. This method requires that the highway engineer be able to indicate his preference between two pavement sections of different pavement types and conditions.

The pairwise comparison method does not place unusual judgemental demands on the decision maker as do other methods, such as the utility function method. This method takes the pairwise preference information as the only input. This input consists of a set of forced choices between pairs of pavement sections. It is then expected that the set will contain inconsistent choices. For example, pavement section A is preferred to section B, and pavement section B is preferred to section C. However, pavement section C may be preferred to section A. The pairwise comparison method will allow this inconsistency and will try to minimize it by assigning different weights to pavement performance attributes (Refs 28 and 29). In this method, the highway engineer provides a set of choices between pairs of pavement sections. These data are used to estimate the weights of various attributes associated with the pavement sections being compared. A detailed discussion of this method is included in Chapter 7.

CHAPTER 4. SELECTION OF METHODS

A brief discussion of eight different approaches to the development of a unified ranking system is provided in the previous chapter. These are

(1) analytical examination of distresses,
(2) economic analysis,
(3) utility theory,
(4) trigger value method,
(5) discriminant analysis,
(6) serviceability index approach,
(7) rate of loss of SI approach, and
(8) pairwise comparison method.

Which method(s) we should use is another very difficult decision making problem. Different methods can be used for different situations. Therefore, an evaluation of these methods should be based on the criteria which are important to the specific goals and objectives of the study.

Methods (1) and (2) pose serious measurement problems. The major premise of these methods is that if all subcriteria could be related to a single measure, such as remaining life of the pavement or dollar value, then the problem of complex subcriteria would disappear. However, the benefits of rehabilitation strategies should be considered in the economic analysis, and they can not be easily converted into dollars. Accident and user costs would also be very difficult to measure.

In order to apply method (1), we will encounter the following tasks to be solved:

(1) determining distress limits,
(2) establishing relationships between distresses, and
(3) developing performance prediction equations.

Methods (1) and (2) would be considered as ideal solutions to the development of unified ranking system, but they are just beyond the scope of this study.

The estimation procedure of method (3) and (4) should consider the multidimensional nature of the composite criterion, i.e., while estimating the weight for one attribute, its relationship with other attributes should be explicitly considered. Methods (3) and (4) will lead to a biased estimation of weight since the weight for each attribute is assigned independently. For instance, if two pavement performance attributes are highly correlated, application of these methods would normally result in double-counting the importance of each attribute. Method (3) will be highly subjective and will not lead to a comparable common index between different types of pavements. Preferential assumptions for the method are too stringent and assessment procedures of value functions and scaling constants are very tedious. Method (4) makes use of an arbitrary statistical objective by weighting attributes proportional to their variance.

Method (5) requires accumulated decision making data. It is very difficult to insure that previous decisions have been made by knowledgeable and unbiased experts considering differences between rigid and flexible pavements. The past decisions could have been based on non-quantifiable factors, such as politics. These data are very difficult to obtain and analyze, because the amount of data is limited and the condition data of pavements prior to rehabilitation action may not be available. Furthermore, this method may not be applicable because it only considers objects with the same attributes.

The serviceability index approach and the rate of loss of SI approach are suggested by the author because they are easy to develop and implement and could be adopted by the SDHPT. The present SI method and rate of loss of SI approach should be applied together for developing a rational way to compare rigid and flexible pavements on an equitable basis. These methods are recommended for the development of an initial prioritization index procedure.

A method using a single attribute, such as PSI, can be improved by adding more attributes, such as cracking, rutting, punchouts, etc, to form a multiple attribute decision making process. A goal programming model using pairwise comparison data can be used to estimate a set of attribute weights using inputs of several highway engineers. A goal programming model is also preferred to others because it estimates the set of attribute weights simultaneously and hence is truly multidimensional.

This method does not place unusual judgemental demands on the decision maker, as like the other methods do. Furthermore, the method can be used for estimating the weights in generalized composite criteria. The application of this method for developing a common index will be helpful in understanding the decision maker|s responses in aggregating information across the attributes, and to improve their decision making ability.

A brief description of the two methods recommended for use by the Texas State Department of Highways and Public Transportation follows.

UNIVARIATE TIME SERIES OF SERVICEABILITY INDEX MODEL

One of the methods recommended for the development of a unified ranking system is the univariate time series of serviceability index model. A sequence of observed data at uniform intervals, usually ordered in time, is called a time series. The statistical methodology dealing with the analysis of such a sequence of data is called time series analysis. Regression approaches to time series analysis have been widely used in the social sciences (Refs 30, 31, and 32). The particular class of stochastic process models is the Auto Regressive Integrated Moving Average (ARIMA) model of George E.P. Box and Gwilyn M. Jenkins (Ref 33). Although elements of ARIMA modeling can be traced back some 50 years, Box and Jenkins integrated the elements into a comprehensive theory, extended it greatly, and popularized it (Ref 34).

When a model is constructed it is not intended to be an exact description of the real world. On the contrary, the aim is to simplify the underlying processes in such a manner than only the essential features are brought out. A simple model allows us to focus attention on the variables which are important. Therefore, the PSI and the rate of loss of SI were used in the development of this model.

The basic concept is described here using a pavement example. The Present Serviceability Index (PSI) represents a means of using objective data, such as roughness, to estimate the Present Serviceability Rating (PSR). Generally, a pavement section which is deteriorating or losing SI at a faster rate than other pavement sections should be ranked higher for rehabilitation than others, because rapid loss of SI represents rapid deterioration of pavement in the future. An increasing deterioration rate might be due to inadequate design, heavier traffic, severe environment, etc.

This concept can be illustrated by comparing three pavement sections as shown in Fig 4.1. Three pavement sections are currently at the 3.0 SI level and are 5, 8, and 10 years old, respectively. Which section should be ranked higher for rehabilitation? Using the above mentioned concept, it is clear that the sections will be ranked in the order of A, B, and C, because section A is deteriorating at the fastest rate and PSI values for all three section are same.

GOAL PROGRAMMING MODEL USING PAIRWISE COMPARISON DATA

The second method recommended for the development of a unified ranking system is the goal programming model using pairwise comparison data. In the last two decades, substantial advancement has been made in multiple attribute decision making (MADM) methods. A review of literature on methods and applications of MADM has been published by Hwang and Yoon (Ref 10). In recent years, there has been tremendous growth of research in the MADM area; especially, in the area of theoretical development of multi-attribute utility theory, which is a solution approach to MADM uncertainty (Refs 35, 36, 37, 38, 39, 40, and 41). However, the state of the art in representing, assessing, and subsequently using the preferential information in the form of a complex utility function is not adequate for pavement problems. The basic proposition which motivates pavement research is the idea that pavement

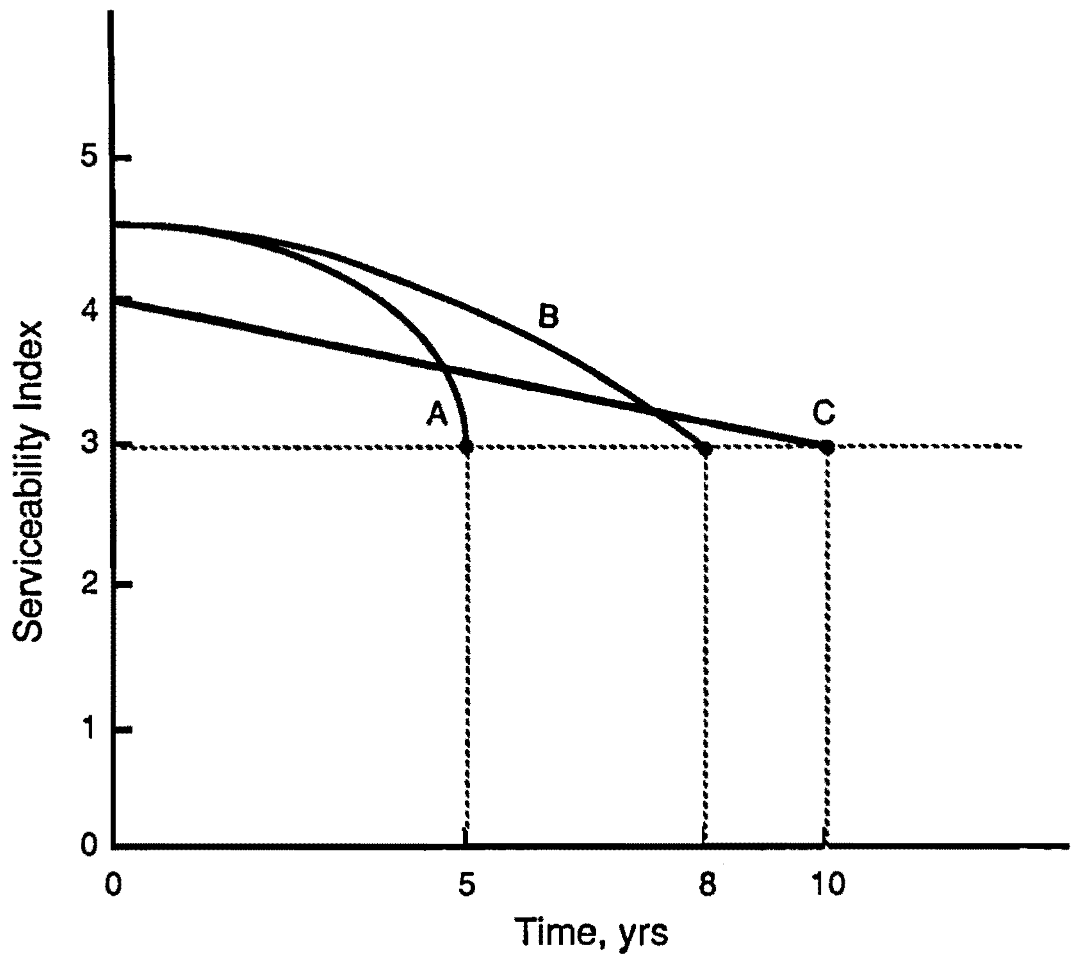


Fig 4.1. Three pavement sections with the same present SI but different rate of loss of SI.

selection for rehabilitation is influenced by perceptions and values of specific attributes of the pavement sections (Refs 42, 43, 44, and 45). A decision analysis method should be structured so that a decision maker feels comfortable with it, in order to reduce the biases and misrepresentations of his preferences (Ref 46).

This method has been used in marketing research to predict consumer preferences for several brands of a particular product class (Ref 47). The methods in this class require that the decision maker be able to indicate his preference between two alternatives. LINMAP technique (Linear Programming techniques for Multidimensional Analysis of Preferences) was originally developed to explain, rationalize, help to understand, and predict decision behavior, but they are well fitted for normative decision making (Refs 28, 29, and 48).

The basic model is described here using a pavement example. There are n candidate pavement sections each of which can be characterized by t attributes. For each attribute, an ideal point needs to be specified. The distance between a candidate section's location on each attribute and the ideal point can be estimated. Then the overall distance from the ideal point will be the sum of the individual attribute distances.

For example, if the rigid pavement section j is preferred to the flexible pavement section k, the distance between rigid section j and the ideal point (d_j) should be greater than the distance between flexible section k and the ideal point (d_k). However, choosing project k is a violation of this particular paired preference according to the above assumption. The objective of this model is to select weights such that the sum of these violated distances is minimized. The further discussion of the goal programming model using pairwise comparison data will be presented in Capter 8 along with its development procedure. The next chapter discusses data requirements and collection for the development of these two models before getting into the detailed model formulation procedures.

CHAPTER 5. DATA REQUIREMENTS AND COLLECTION

INTRODUCTION

A pavement section can be described by a set of attributes representing its physical characteristics and the circumstances surrounding its utilization. How many and what kinds of attributes should be considered for developing a common index for rehabilitation programming? In general, fewer attributes means lower computation costs and simplifies the problem of interpretation. The actual selection of attributes is, however, limited by the data sources and research objectives.

The data requirements and their collection for the univariate serviceability index model are described. To develop the univariate model, the historical serviceability index data are needed for a regression equation which uses the present SI and the rate of change of SI information.

The model with a single attribute such as the serviceability index has been improved by adding more attributes to form a multiple attribute decision making model. The data requirements and their collection procedure for a goal programming model which estimates the relative weights for the selected attributes are discussed next. A survey was conducted to collect data, which was used as input to this model.

SERVICEABILITY INDEX AND RATE OF LOSS OF SI

Since a serviceability concept was developed at the AASHO Road Test, it has been applied for evaluating the overall performance of a pavement. Highway agencies are increasingly becoming conscious of the importance of pavement performance evaluation, therefore many agencies are spending considerable effort in developing, applying, and analyzing serviceability measurement techniques.

The serviceability index was developed by correlating a PSR with objective mechanical measurements such as roughness. Present SI values have been used in ranking pavement sections for rehabilitation. There is a massive inventory of serviceability indices all over the United States; however, little effort has been made toward collecting historical SI data from specific sections. Data have been collected over the years to be used for the Pavement Evaluation System (PES) in Texas, but they have been collected from the randomly selected pavement sections every year. As a result, it was very difficult to obtain section-specific data for predicting the future performance of a pavement based on historical performance data.

Even though section-specific data may be available from the PES data base, the SI values may be increasing every year due to the maintenance or rehabilitation. The effects of maintenance can be analyzed only after a basic pavement performance model using historical SI data without any maintenance is developed. Then, various performance curves based on historical SI data can be developed according to different levels of maintenance.

In order to estimate the parameters of the serviceability index model which is described in Chapter 3, data were obtained from the Center for Transportation Research (CTR) serviceability index data base, where historical data have been collected for 26 test sections in Austin over three years, starting in 1982. They are shown in Table 5.1. These data are listed in Table 5.1 and were used for developing a common prioritization index for rehabilitation as discussed later in this chapter.

PAIRWISE COMPARISONS

A goal programming model using pairwise comparison data was discussed in the previous chapter. This model was used to estimate the weights of multiple attributes in a composite criterion measure. The inputs to the model consist of

(1) a set of pavement sections, with each section defined by its pavement attribute values; and

TABLE 5.1. SERVICEABILITY INDICES FOR THE AUSTIN TEST SECTIONS (PROFILOMETER)

Section No.	July 1982	October 1982	January 1983	April 1983	July 1983	October 1983	January 1984	April 1984	July 1984	December 1984	February 1985	April 1985
2	-----	2.77	2.59	2.50	2.48	2.47	2.48	2.38	2.50	1.88	1.79	1.84
3	3.72	3.47	3.58	3.50	3.37	3.41	3.37	3.25	3.52	3.19	3.20	3.10
5	4.57	4.52	4.57	4.50	4.47	3.27	3.41	3.40	3.46	3.43	3.43	3.33
6	2.54	2.41	2.28	2.31	2.35	2.42	2.36	2.51	2.42	2.35	2.35	2.30
7	4.79	4.73	4.75	4.80	4.78	4.78	4.75	4.78	4.82	4.69	4.63	4.63
8	3.70	3.64	3.72	3.72	3.72	3.64	3.67	3.65	3.80	3.43	3.32	3.40
9	3.56	3.51	3.58	3.74	3.52	3.32	3.06	3.16	3.34	3.11	3.15	3.15
10	4.42	4.48	4.52	4.46	4.41	3.57	3.67	3.69	4.49	4.41	4.29	4.25
12	3.56	3.55	3.56	3.45	3.49	3.41	3.13	1.24	2.56	2.01	2.05	1.94
14	3.23	3.03	3.03	3.10	3.05	3.03	2.97	2.94	3.22	3.00	4.13	4.03
15	3.28	3.38	3.48	3.42	3.44	3.44	.98	1.43	1.34	1.17	1.11	.66
19	3.58	3.65	3.61	3.62	3.63	3.62	3.60	3.57	3.71	3.51	3.50	3.42
23	4.23	4.17	4.15	4.23	4.15	4.25	4.15	4.12	4.27	3.98	3.68	4.00
28	3.85	3.80	3.77	3.81	3.00	3.06	3.09	3.08	3.14	2.98	3.07	2.94
32	4.37	4.39	4.45	4.44	4.44	4.42	4.41	4.39	4.54	4.33	4.23	4.23
33	4.47	4.43	4.53	4.48	4.45	4.42	4.44	4.37	4.46	4.37	4.88	4.09
34	3.87	3.99	3.97	3.92	4.01	3.97	3.88	3.88	3.94	3.95	3.69	3.70
35	2.33	2.29	2.39	2.90	2.86	2.59	2.60	2.68	2.66	2.53	2.49	2.07
36	4.37	4.46	4.40	4.44	4.46	4.48	4.44	4.43	4.54	4.33	4.26	4.35
37	3.16	3.14	3.20	3.24	4.52	4.52	4.48	4.47	4.57	4.41	4.32	4.31
38	2.12	2.05	2.08	2.07	1.95	1.87	1.89	1.80	1.91	1.66	1.42	1.49
39	1.00	1.09	1.10	.98	.96	.91	.93	.78	.79	.75	2.09	----
40	3.72	3.69	3.59	3.65	3.62	3.56	3.61	3.62	3.83	3.52	3.69	3.67
41	3.39	3.47	3.54	3.58	3.55	3.51	3.47	3.48	3.70	3.50	3.48	3.42
44	1.20	1.09	1.18	1.21	1.21	1.21	1.19	1.24	1.36	1.03	1.09	1.02
45	.53	.46	.48	.49	.48	.41	.44	.46	.46	2.34	1.91	1.61
Mean	3.35	3.29	3.31	3.33	3.32	3.21	3.09	3.03	3.20	3.11	3.09	3.08
SD	1.146	1.138	1.141	1.136	1.160	1.128	1.194	1.224	1.235	1.153	1.867	1.145

(2) a set of paired comparison preference judgements made on the pavement sections by a highway engineer.

The data for this purpose were obtained by conducting a survey using 27 highway engineers who had been participating in the Pavement Management Training Program in Austin. A set of forced choices between two pavement sections of different types and with different conditions was obtained from each engineer. The survey form used is reproduced in Appendix A. The four attributes selected for flexible pavements were patching, rutting, alligator cracking, and serviceability index. The four attributes selected for rigid pavements were patches, spalled cracks, punchouts, and serviceability index. These pavement attributes are described briefly in Appendix A.

These eight attributes were selected because they are commonly used by the state of Texas and others in their condition surveys of rigid and flexible pavements. A frequency distribution of four distress types for continuously reinforced concrete pavement (CRCP) sections is shown in Table 5.2. The measurement units for the distresses used in the current surveys are comparable with those used in the PES so that a pavement score could be generated for each section using PES data directly.

It is recommended that a survey be conducted using as small a set of pavement attributes as possible because of the human limitations in aggregating information over several attributes. In general, four attributes are recommended as a maximum limit in psychometric literature (Refs 44, and 47).

Pairwise comparison sets were presented to a group of engineers on a projection screen. This method prevents the engineers from relating a current selection to the previous selections, since it was expected that the previous sets of forced choices might contain inconsistent choices in making a series of pairwise comparisons. This inconsistency is allowed in the model and is minimized by using the goal programming technique. The analysis of the data produced the weights for all the attributes selected for this purpose. If any attribute was chosen inconsistently, the analysis assigned a low weight to this attribute.

TABLE 5.2. FREQUENCY DISTRIBUTION OF DISTRESSES IN RIGID PAVEMENT (CRCP) IN TEXAS

Number/Mile	Spalls	Punchouts	AC Patches	PC Patches
0	218	644	733	619
1	131	211	157	169
2	73	65	47	58
3	83	34	21	40
4	66	16	10	25
5	61	7	5	18
6	29	4	7	13
7	30	5	3	7
8	25	4	5	6
9	26	2	4	12
10	14	3	1	6
11	11	2	1	2
12	13	2	0	2
13	14	1	1	1
14	17	1	3	6
15	10	0	3	2
16	8	1	1	1
17	7	1	0	3
18	8	1	2	2
19	2	0	0	2
20	3	0	0	1
21	7	0	0	1
22	5	0	0	2
23	8	0	0	0
24	8	0	0	0
25	7	0	0	2
26	9	0	0	0
27	3	0	0	0
28	10	0	0	0
29	8	0	0	0
30	8	0	0	1
Total	922	1004	1004	1001

Note:
N = 1,004 Sections

Maximum values for each distress were:
- 358 spalled cracks per mile
- 18 punchouts per mile
- 18 AC patches per mile
- 50 PC patches per mile

Mean values for each distress were:
- 11.01 spalled cracks per mile
- 0.73 punchouts per mile
- 0.64 AC patches per mile
- 1.49 PC patches per mile

The main objective of this research was to estimate the average response of the group. A separate analysis for each highway engineer's judgement was also performed to ascertain whether his set of estimated weights differed significantly from others. An equation representing the responses of the entire group of highway engineers has been derived using a linear programming computer package.

A set of variables or factors is considered when a decision is to be made. However, we know that different individuals faced with identical circumstances and options will often choose differently due to their own preferences. Moreover, an individual in apparently identical situations will often make different choices. This can be expalined as random human behavior or by concluding that the situations were not in fact identical. Considering these facts, a second survey was conducted to verify the equation derived with the first survey data and to determine if it would be different from the one using the second survey. A highway engineer may perceive pavement attributes differently at different times or in different environments. He may make comparisons differently with the different sets of comparison pairs. He may possibly commit some error due to fatigue, boredom, etc. The main objective of the second survey was to find whether these errors would significantly affect the decision making process.

The same group of highway engineers was asked to evaluate another 31 comparison pairs of pavement sections under different conditions than those selected in the first survey. An equation using the second survey data was derived using the same procedure. The two equations thus derived, along with their practical applications, are compared and discussed in the next chapter.

CHAPTER 6. UNIVARIATE TIME SERIES OF SERVICEABILITY INDEX MODEL

MODEL FORMULATION

When the physical mechanism of a phenomenon is completely understood, it may be possible to write down a mathematical expression which describes it. In this way we obtain a mechanistic or theoretical model. In pavement research, the problems are complex and the experimental resources needed to develop a mechanistic model are sometimes not available. In such cases, an empirical model must be used.

The proposed model is based on a single time series that is a sequence of observed SI data at equally spaced time intervals, say X_t, where $t = 1, 2, \ldots n$ (years). The correlation between observations expresses the dependence of the time series observations on each other (Ref 49). This dependence can be expressed by an ordinary regression model using time t as an independent variable as follows:

$$X_t = \beta_0 + \beta_1 t + a_t \qquad (6.1)$$

where

X_t = Serviceability Index at time t,

β_0, β_1 = parameters to be estimated, and

a_t = random error entering the model at time t, which is assumed to be independent, and a normally distributed random variable with mean zero and constant variance σ_a^2.

The parameter β_1 is interpreted as the slope or linear trend of the X_t process. This model requires that a_t's, and therefore X_t's, be independent. Howvever it is expected that if X_{t-1} is small, X_t tends to be small. Therefore, the above model is clearly inappropriate for the pavement serviceability index data since X_t may depend on X_{t-1}, X_{t-1} on X_{t-2}, and so on.

Furthermore, there are other factors that should be included such as traffic, pavement structure, environmental factors, etc. These factors vary across time and interact in complex and complicated patterns. None of these factors alone could explain the performance of pavements. But, jointly, the effects of these factors are aptly described using the history data of Serviceability Index, because the rate of loss of SI is due to all the factors that affect pavement performance. Therefore, a model that expresses dependence of X_t on X_{t-1}, X_{t-2}, X_{t-3} ... rather than that of X_t on time t can be developed as follows:

$$X_t = \beta_1 X_{t-1} + \beta_2 X_{t-2} + \dots + \beta_n X_{t-n} + a_t \qquad (6.2)$$

Equation 6.2 expresses the dependence of the variable on itself at different points in time, or, in other words, the variable X_t is regressive. In Eq 6.2, n is the number of years in the past that may have a correlation with the current serviceability of a pavement. Although there is no theoretical limit to how large n should be, in practice the value of n is usually small; in fact, $n = 2$ was found to be sufficient in many cases (Ref 30). This is also sufficient to develop a common index involving present SI and rate of loss of SI. Hence, Eq 6.2 reduces to

$$X_t = \beta_1 X_{t-1} + \beta_2 X_{t-2} + a_t \qquad (6.3)$$

MODEL ESTIMATION

In the previous section, a model was formulated. Now it is necessary obtain estimates of the parameters. After the parameters have been estimated, the fitted model will be subjected to diagnostic checks and tests of goodness of fit. A previously developed model (Eq 6.3) is just an autoregressive model of order two; X_t is predicted by only X_{t-1} and X_{t-2}. In order to solve this time series model, a set of historical data collected over the life span of a specific section is needed.

Currently these long-term life cycle serviceability index data are not available. Therefore it is necessary to interpret the time series model as an ordinary regression model by fixing the time span to 3 years. Data have been collected from the 26 flexible pavement sections in Austin, starting in 1982. SI data from four pavement sections were not used because they were rehabilitated during the three year time period. The average of four measurements was used as a representative serviceability index for one year for each section. These values are shown in Table 6.1.

The least square estimates of β_1 and β_2 in Eq 6.3 were obtained by using an ordinary least square method (Ref 50). The cross-sectional data in Table 6.1 were fitted to the model as follows:

$$X_t = 1.53\ X_{t-1} - 0.55\ X_{t-2} \tag{6.4}$$

$$(R^2 = 0.96)$$

Assuming that X_t will be interpreted as a future serviceability index, the above equation can be rewritten as

$$\begin{aligned} X_t &= 1.53\ X_{t-1} - 0.55\ X_{t-2} \\ &= 0.98\ X_{t-1} - 0.55\ (X_{t-2} - X_{t-1}) \end{aligned}$$

TABLE 6.1. ANNUAL SI DATA FOR 22 AUSTIN TEST SECTIONS

	Year		
Section No.	1983	1984	1985
7	4.47	4.77	4.69
5	4.54	3.64	3.41
33	4.48	4.42	4.33
36	4.42	4.45	4.37
32	4.41	4.42	4.33
23	4.20	4.18	3.98
34	3.96	3.94	3.82
28	3.81	3.06	3.03
8	3.70	3.67	3.49
40	3.66	3.60	3.68
19	3.62	3.61	3.54
9	3.60	3.27	3.19
3	3.57	3.35	3.25
12	3.53	2.82	2.14
41	3.50	3.50	3.53
15	3.38	2.32	1.07
2	2.62	2.11	2.00
35	2.48	2.69	2.44
6	2.39	2.41	2.36
38	2.08	1.88	1.62
44	1.17	1.21	1.12
39	1.05	0.90	0.77

or

$$FSI = 0.98\ (PSI) - 0.55\ \ (LSI) \qquad (R^2 = 0.96) \tag{6.5}$$

where

FSI = future serviceability index (X_t),

PSI = present serviceability index (X_{t-1}), and

LSI = loss of serviceability index during the previous year (X_{t-2} - X_{t-1}).

We can use this model to predict the serviceability index in the future using the current serviceability index and the loss of serviceability index over recent time. This predicted serviceability index can be used as a common index for rehabilitation. The model can be updated from time to time as more data become available. In those cases where past-history data for more than three years are available, we can expand the model to consider the more distant past history of serviceability indices.

VALIDATION OF THE MODEL

The model was formulated and the parameters were estimated in the previous sections. In this section, diagnostic checks are applied to the fitted model. The final model to be tested is represented by equation (6.5).

To check the prediction capability of the model, the observed values for 1985 were plotted against the predicted values, as shown in Fig 6.1. It can be seen that the model predicts the future serviceability reasonably well. A high R^2 value supports this explanatory power of the model. The F-statistic value of the fitted regression falls in the critical region at the one percent level of significance. Therefore the null hypothesis (Ho : $\beta_1 = \beta_2 = 0$) is rejected, and thereby the notion that our regression slopes are different from zero purely by chance is rejected (Ref 51). Parameters of

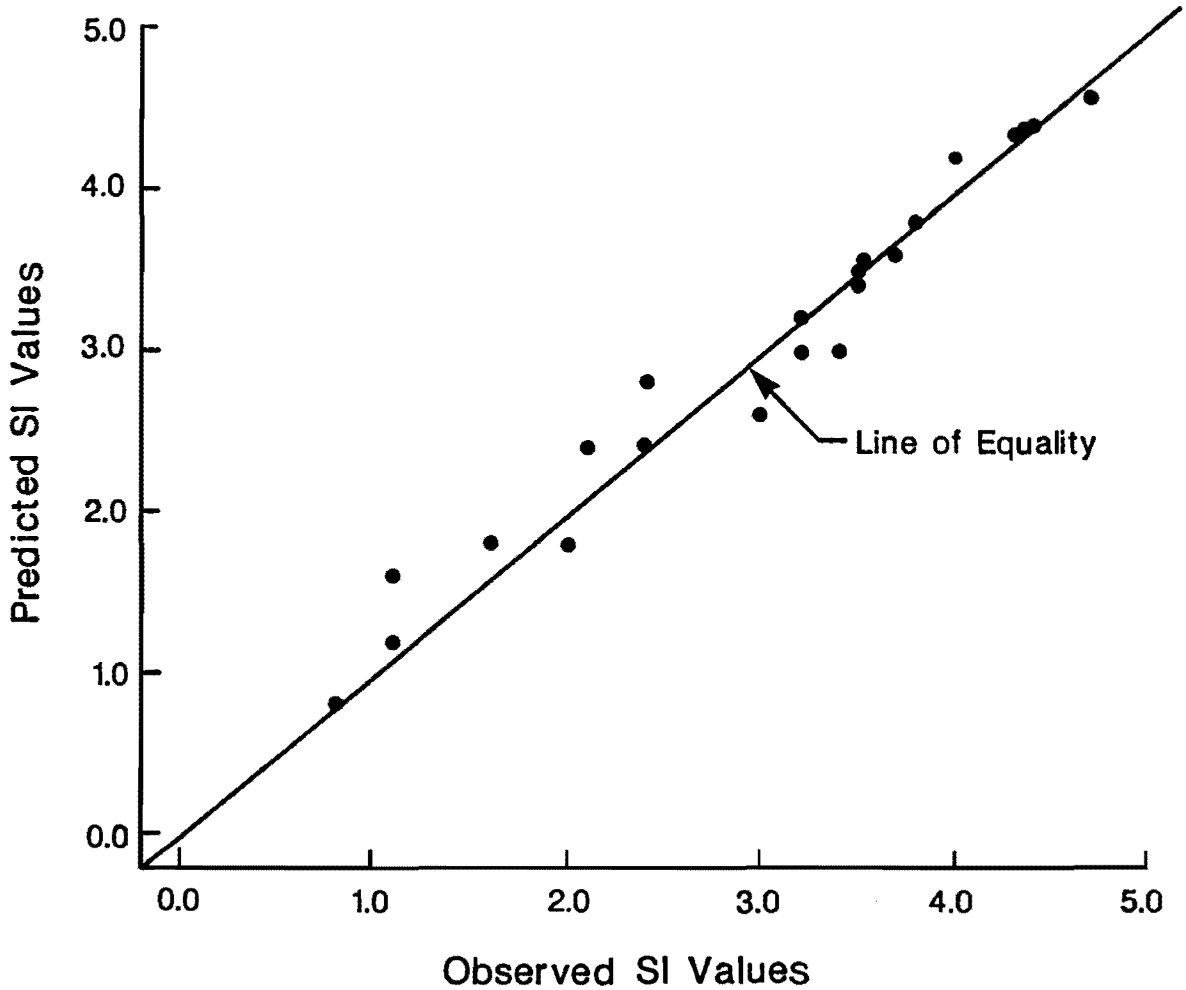


Fig 6.1. Plot of predicted SI values against observed SI values.

independent variables were found to be significantly different from zero using the t-statistic at the level of significance $\alpha = 0.01$.

An error term exists in any model unless the model is a perfect representation of reality. In a good regression model, the error term is assumed to be normally distributed with a mean of zero and a constant standard deviation. Furthermore, the errors are assumed to be independent. The residual is an estimate of the error. The residuals can be used to test the original assumptions, normality, constant variance, and independence, the error term.

In order to check the normality assumption, the frequency histogram for the residuals was constructed in Fig 6.2. A normality of residuals was assured by Shapiro-Wilk's test (W = 0.937). A hypothesis of normality could not be rejected at an $\alpha = 0.05$ (Ref 52). The bell-shaped distribution in Fig 6.2 is supportive of the normal distribution.

To check common variance and independence assumptions, residuals were plotted against the predicted serviceability indices in Fig 6.3. It is very difficult to detect "heteroscedasticity" (that is the formal name for the case in which the error term has no constant variance), because of the randomness of errors. A pattern in the residuals neither supports the heteroscedasticity, shows any dependency of residuals a hypothesis of autocorrelation that successive residuals tend to be close together was rejected by Durbin-Watson's test (D = 2.64) at $\alpha = 0.05$ (Ref 52).

Multicollinearity is said to exist when any independent variable is correlated with another independent variable. It is one of the main causes of misinterpretation and misuse of regression. The correlation between variable "PSI" and "LSI" in Eq 6.5 is -0.219. This low value shows that the correlation between these two independent variables are not significant. In

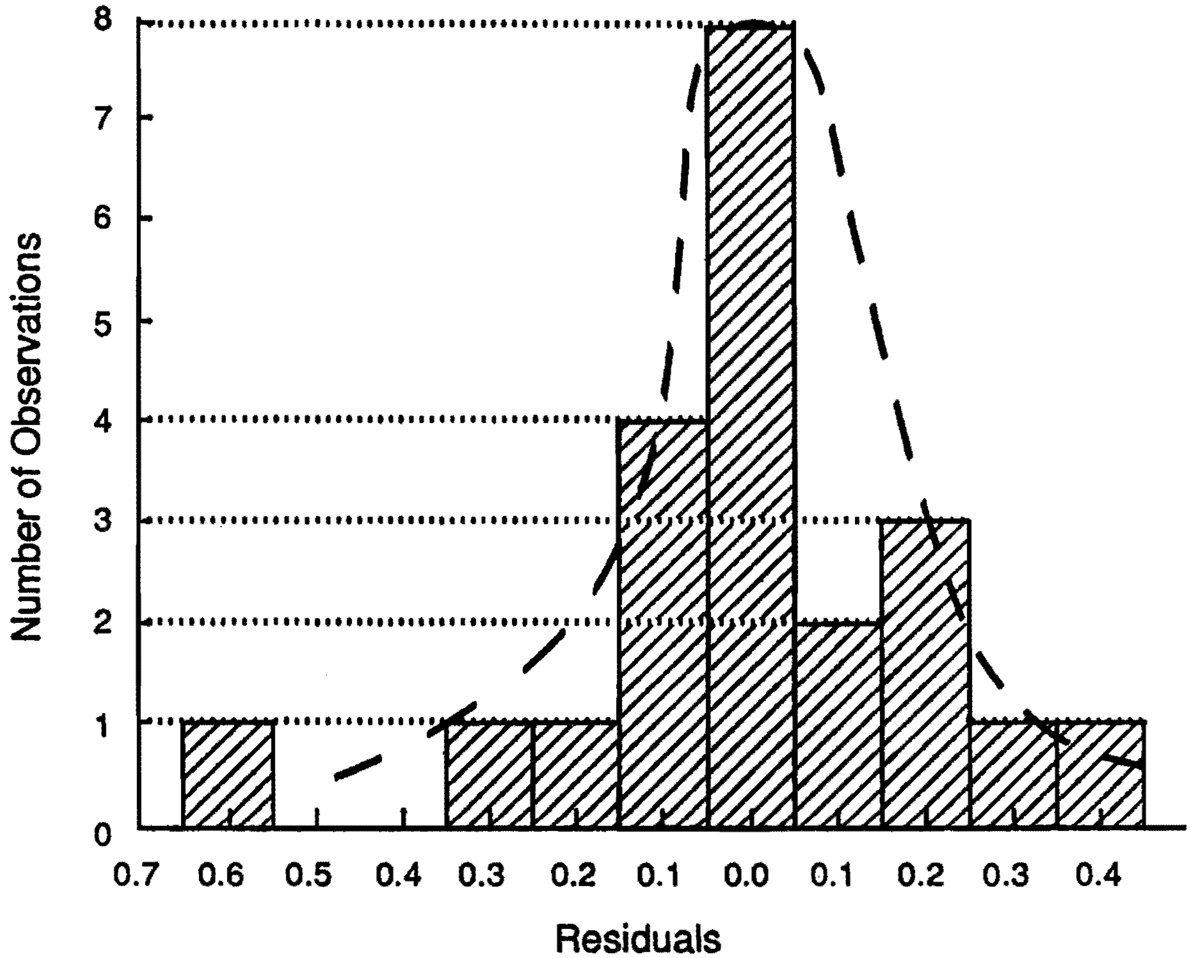


Fig 6.2. Frequency histogram of residuals.

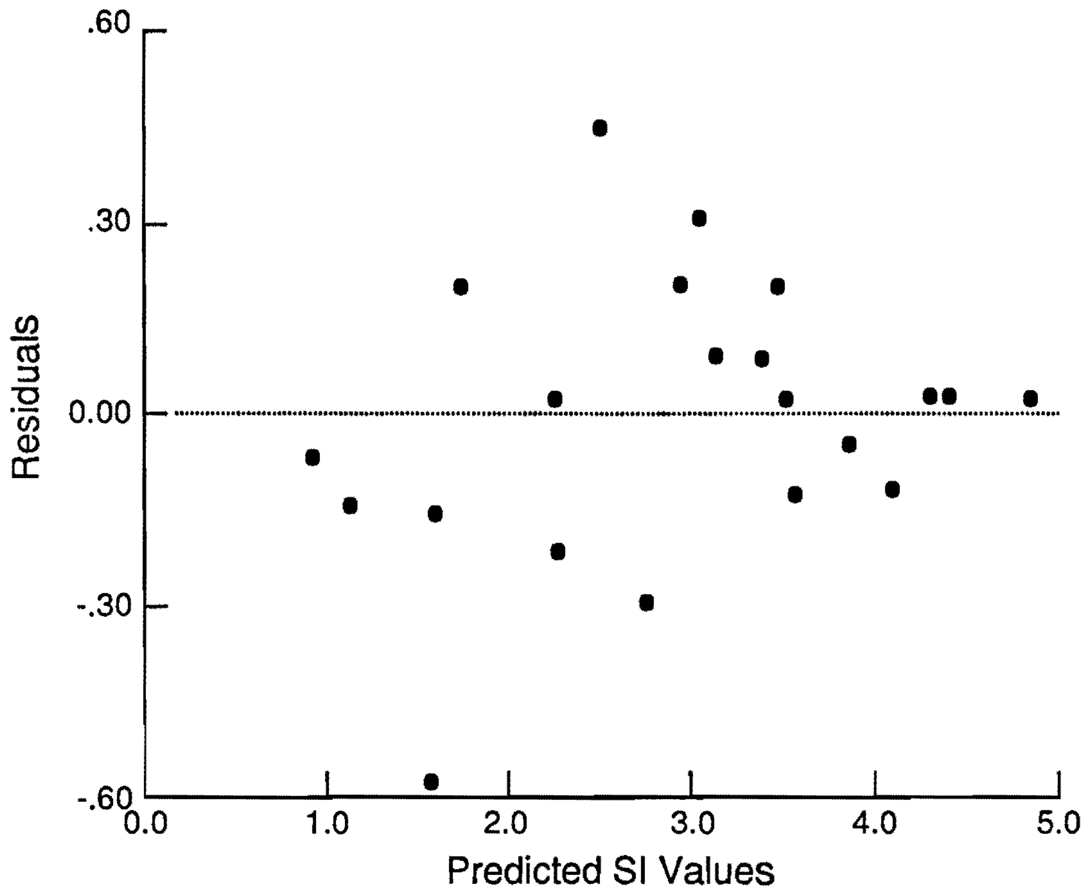


Fig 6.3. Plot of residuals against predicted serviceability index values.

other words, a hypothesis of no correlation could not be rejected at $\alpha = 0.05$ (Ref 53).

All these test statistics and plots show that regression Eq 6.5 satisfies all the assumptions and requirements. The negative parameter associated with the rate of loss of SI shows that rapid loss of SI suggests potential rapid deterioration of a pavement in the future. The intercept was not significant enough to be included in the final equation. The model should be further verified as more data become available.

CHAPTER 7. GOAL PROGRAMMING MODEL USING PAIRWISE COMPARISON DATA

A simple time series of serviceability index model was developed and discussed in the previous chapter. A model using such a single attribute, can be extended by considering other attributes such as rutting, punchouts, etc., to form a multiple attribute decision making (MADM) model. An extensive literature study was conducted in this MADM area by the author. As a result of the literature study, a goal programming model using pairwise comparison data was formulated so that a decision maker feels comfortable with providing his preferential information in the form of pairwise comparison. This chapter presents a detailed development procedure of a goal programming model using pairwise comparison data which were obtained from a number of highway engineers over the United States. This was done to illustrate the method of collecting the data and its analysis for estimating the model parameters. The model formulation proceure is followed by estimation of model parameters and validation of the model.

MODEL FORMULATION

A set of pavement sections was selected randomly from section with a wide range of field conditions in order to represent overall condition of highway network. Each section is described by its four selected attributes, as shown in Appendix A (see survey forms). A set of preference judgements (j,k) was obtained by conducting the surveys discussed previously and asking if pavement section j was preferred to section k in a forced-choice pairwise comparison. It is assumed that the judgements were made by the highway engineer or professional on the basis of some global criteria, possibly with some error. A highway professional makes paired comparison judgements, such as: "pavement section k needs to be rehabilitated before section j." Overall pavement performance is the global criterion and presumably the highway engineer made this overall judgement in consideration of some of the pavement attributes mentioned earlier, but it cannot be known exactly.

Let d_{jp} denote the difference of the condition of pavement section j from the perfect condition in terms of attribute p. Let W_p denote the weight or importance of attribute p. Then the global criterion D_j for the pavement section j is given by

$$D_j = \sum_{p \varepsilon P} W_p d_{jp} \tag{7.1}$$

The global criterion model states that, given any pair (j,k), the condition of pavement section j is better than that of section k only if

$$D_j < D_k \tag{7.2}$$

The global criterion is but a model of a highway engineer's decision making process. It is not necessary that a highway engineer compute Eq 7.1 to arrive at his decision.

The objective is to develop a set of weights such that the global criterion D_j defined in Eq 7.1 is "as consistent as possible" with the given pairwise comparison judgements made by a highway engineer. Inconsistencies of judgements will be minimized by assigning lower weight to the attributes which involve inconsistent decisions. This leads to the following formulation, which belongs to a particular class of linear programming problems known as goal programming problems (Ref 54, 55, and 56).

Minimize

$$\sum_{(j,k) \varepsilon S} Y_{jk} \tag{7.3a}$$

subject to constraints

$$\sum_{p \varepsilon P} a_{jkp} W_p + Y_{jk} \geq 0 \tag{7.3b}$$

$$\sum_{p \varepsilon P} A_p W_p = 1, \tag{7.3c}$$

$$Y_{jk} \geq 0 \quad \text{for } (j,k) \varepsilon S$$

$$W_p \geq 0 \quad \text{for } p \varepsilon P$$

where

$J = \left\{ 1, 2, \ldots n \right\}$: n pavement sections

$P = \left\{ 1, 2, \ldots t \right\}$: t pavement attributes

j = decision maker's section preferred to section k

S = set of all ordered pairs (j,k) of the n pavement sections

$W = \left\{ W_p \right\}$, $p \in P$: weights assigned to pavement attribute p

Y_{jk} = the amount of violation to be minimized by the computer program
$= (D_k - D_j)^-$

d_{jp} = distance of pavement section j from the ideal point of attribute p

$a_{jkp} = (d_{kp} - d_{jp})$

$A_p = \sum_{(j,k) \in S} a_{jkp}$

Given any particular solution W, we can determine the global criterion D, for j ε J using Eq 7.1, since d_{jp}'s are known. Consider any pair (j, k) S. Since pavement section j has been judged to be preferred to pavement section k in a pairwise comparison, we would like the estimated weights to lead to global criteria D, and D_k such that $D_j \; \varepsilon \; D_k$. However, if the weights lead to $D_j = D_k$, this represents an error in the estimated weights. Also these weights are not in conformity with the input of paired comparisons. More generally, we define

$$(D_k - D_j)^- = 0 \text{ if } D_k \geq D_j,$$

and

$$(D_k - D_j)^- = D_j - D_k$$

if

$$D_j > D_k,$$

i.e., $(D_k - D_j)^- = \max \left\{ 0, (D_j - D_k) \right\}$,

then $(D_k - D_j)^-$ was used as a measure of error corresponding to the pair (j,k) associated with a given solution W. Summing this over all the pairs in S, we get

$$\text{Inconsistency} = \sum_{(j,k)\varepsilon S} (D_k - D_j)^-$$

Formuation 7.3 allows us to find optimum weights, i.e., a solution $\{W_p\}$ which satisfies constraints and for which the objective function $\sum_{(j,k)\varepsilon S} Y_{jk}$ is minimum.

Constraint (7.3c) was added tothe formulation in order to preclude the trivial solution $\{W_p = 0\}$ and hence $\sum_{(j,k)\varepsilon S} Y_{jk}$ becomes zero. This constraint does not impose any real restriction on the procedure (Ref 55).

ESTIMATION OF WEIGHTS

The goal programming model was developed to estimate the weights of multiple attributes in a composite criterion. The inputs to this model include

(1) a set of pavement sections, with each section defined by its pavement attribute values, and
(2) a set of paired preference judgements that were made on the pavement sections by highway engineers.

The surveys were conducted using 27 highway engineers from all over the United States. First, each of 35 pairwise comparison sets of flexible pavements was presented individually on a projection screen, to prevent the highway engineers from relating a current selection with the previous selections. A typical pairwise comparison set of flexible pavements is shown in Fig 7.1. They had to choose either section 1 or section 2 as the candidate for rehabilitation.

It was expected that the set of forced choices might result in some inconsistent choices among the 35 pairwise comparison choices. In the model, this inconsistency is allowed and is minimized using a goal programming technique. As a result, preferences and attributes of pavement sections

1.

ATTRIBUTE \ SECTION	Section 1	Section 2
Patching	50 %	0 %
Rutting	0 in	0.5 in
Alligator Cracking	0 %	30 %
Serviceability Index	2.5	3.0

2.

ATTRIBUTE \ SECTION	Section 1	Section 2
Patching	0 %	20 %
Rutting	1.0 in	0 in
Alligator Cracking	0 %	30 %
Serviceability Index	3.0	2.0

3.

ATTRIBUTE \ SECTION	Section 1	Section 2
Patching	0 %	30 %
Rutting	0 in	0.5 in
Alligator Cracking	50 %	0 %
Serviceability Index	2.0	1.5

Fig 7.1. A typical pairwise comparison set of flexible pavements.

under different conditions were measured by assigning less weight to attributes involved in the inconsistent choices.

The objective of this research is to estimate the average response of the group. A separate analysis of each highway engineer's decisions was also performed, to ascertain whether his set of estimated weights differed significantly from the others. A set of weights has been developed for each highway engineer's choices using a linear programming computer package. The weights are summarized in Appendix B. A simple computer program was developed for generating input for linear programming package MPOS. An equation representing the group opinion of the total group was developed by selecting a pavement based on the majority rule:

$$\text{Flexible Index} = 0.07\ PA + 5.62\ RD + 0.09\ CR + 4.22\,(5.0 - SI) \qquad (7.4)$$

where

PA = percentages of patching,

RD = inches of average rut depth,

CR = percentages of alligator cracking, and

SI = serviceability index.

Then, 35 pairwise comparison sets of rigid pavements were presented in the same way. A typical pairwise comparison set of rigid pavements is shown in Fig 7.2. Weights for rigid pavement attributes for each highway engineer were developed. They are also summarized in Appendix B. An equation representing the group opinion was developed as follows:

$$\text{Rigid Index} = 0.67\ PT + 0.72\ SC + 0.98\ PO + 7.63\,(5.0 - SI) \qquad (7.5)$$

ATTRIBUTE \ SECTION	Section 1	Section 2
Patches (#/mile)	10	0
Spalled Cracks (#/mile)	5	0
Punchouts (#/mile)	0	5
Serviceability Index	2.0	3.0

ATTRIBUTE \ SECTION	Section 1	Section 2
Patches (#/mile)	0	5
Spalled Cracks (#/mile)	15	0
Punchouts (#/mile)	0	10
Serviceability Index	2.5	3.0

ATTRIBUTE \ SECTION	Section 1	Section 2
Patches (#/mile)	15	0
Spalled Cracks (#/mile)	10	0
Punchouts (#/mile)	0	15
Serviceability Index	2.0	2.5

Fig 7.2. A typical pairwise comparison set of rigid pavements.

where

PT = number of patches,

SC = number of severely spalled cracks, and

PO = number of punchouts.

The basic model (Eq 7.3) was modified to estimate weights for both flexible and rigid pavement simultaneously without changing the basic concept, as follows:

$$\text{Minimize} \sum_{(j,k)\varepsilon S} Y_{jk}$$

subject to constrants

$$\sum_{p\varepsilon P} W_p\, d_{jp} - \sum_{q\varepsilon Q} W_q\, d_{kq} + Y_{jk} \geq 0 \quad \text{for } (j,k)\varepsilon S$$

$$\sum_{p\varepsilon P} A_p\, W_p - \sum_{q\varepsilon Q} A_q\, W_q = 1$$

$$Y_{jk} \geq 0 \quad \text{for } (j,k)\varepsilon S$$

$$W_p,\, W_q \geq 0 \quad \text{for } p\varepsilon P,\ q\varepsilon Q$$

where

k = decision maker's section preferred to section j,

p = pavement attributes of section j,

q = pavement attributes of section k,

$A_p = \sum_{j\varepsilon S} d_{jp}$,

$$A_q = \sum_{k \varepsilon S} d_{kq},$$

s = set of all ordered pairs (j,k) of the n pavement sections, and

Y_{jk} = amount of violations to be minimized by optimum W_p, W_q.

Thirty-one pairwise comparison sets were presented to each engineer in the same manner. A typical pairwise comparison set is shown in Fig 7.3. Weights for eight pavement attributes were developed for each highway engineer and they are summarized in Appendix B. An equation representing the group opinion was developed, as follows:

$$\text{Common Index} = 3.8\ RD + 0.08\ CR + 0.38\ PO + 2.86\ (5.0 - SI) \tag{7.6}$$

where

PO = 0, for flexible pavement,

RD = CR = 0, for rigid pavement, and

SI = Serviceability index for rigid or flexible pavements.

Patches in either flexible or rigid pavements and spalled cracks in rigid pavements did not affect the group's decision process significantly. They were dropped out of the equation because too much inconsistency was observed with these three attributes in the decision making process. Weights can be compared between attributes considering their different measurement units. For example, four punchouts will have the same effect on pavement performance as approximately 20 percent alligator cracking, according to the common index equation. A higher number in the common index means a higher priority for rehabilitation. Perfect pavement should have an index value of zero.

Flexible Pavement

Attribute \ Section	Section 1
Patching	0 %
Rutting (inches)	1.0 in
Alligator Cracking	20 %
Serviceability Index	2.5

Rigid Pavement

Attribute \ Section	Section 2
Patches (#/mile)	10
Spalled Cracks (#/mile)	5
Punchouts (#/mile)	0
Serviceability Index	2.0

Fig 7.3. A typical pairwise comparison set of flexible and rigid pavements.

VALIDATION OF THE MODEL

This goal programming model is an acceptable way to represent the decision making process of a highway engineer. The perceptions of the attribute values are different for each individual; therefore additional factors should be considered in the decision process.

One disadvantage of this procedure is that appropriate statistical tests of significance for the parameter estimates are lacking. The optimal value of the objective function shows the fit of the model to the data. This objective function value can be used to test the goodness of fit of the model, such as R^2 in the regression method. The objective function of equations based on group opinions was zero, which means that group decisions were made very consistently.

A second survey was conducted to verify whether the equation derived using the first survey data could be repeated in the second survey. A highway engineer may perceive pavement attributes differently at different times or in different environments. He may make pairwise comparison judgements differently with different sets of comparison pairs. He may possibly commit some error due to fatigue, boredom, etc. The main objective of the second survey was to find whether these errors significantly affect his decision making process.

A different set of pavement sections was selected randomly for this purpose. The same group of highway engineers who participated in the first survey was asked to evaluate three sets of comparison pairs composed of pavement sections under conditions different from that of the first survey. Again, the engineers were free to use the provided information in whatever way they chose to arrive at their comparative evaluation.

Weights for each highway engineer, are summarized individually in Appendix B. Three equations representing the group opinion from the second survey have been developed:

$$\text{Flexible Index} = 0.05\ PA + 5.61\ RD + 0.10\ CR + 4.24\ (5.0 - SI) \tag{7.7}$$

$$\text{Rigid Index} = 0.19\ PT + 0.46\ SC + 0.74\ PO + 8.61\ (5.0 - SI) \tag{7.8}$$

$$\text{Common Index} = 0.03\ PA + 3.54\ RD + 0.06\ CR + 2.71\ (5.0 - SI_f) + 0.24\ PO + 3.43\ (5.0 - SI_R) \tag{7.9}$$

where

SI_f = SI of flexible pavement,

SI_R = SI of rigid pavement,

PA = RD = CR = SI_f = 0, for rigid pavement, and

PO = SI_R = 0, for flexible pavement.

Patches or spalled cracks in rigid pavement still did not affect the group's decision process significantly in the common index Eq 7.9 developed from the second survey. Equation 7.9 is very similar to Eq 7.6 except that patching was not included for flexible pavements, and the weights for SI were not distinguished for rigid and flexible pavements. The weight for punchouts went down in Equation 7.9. As a result, a little more weight was given to SI in rigid pavement than in flexible pavement. It can be seen that more weight is assigned to SI of rigid pavement than SI of flexible pavement by comparing Eqs 7.4 and 7.7 with Eqs 7.5 and 7.8.

More weight was given to SI in Eq 7.8 than SI in Eq 7.5. There is virtually no difference between Eqs 7.4 and 7.7. Two surveys produced almost identical solutions using the same modeling procedure. Therefore, the goal programming model using pairwise comparison data was proved to be stable despite random errors previously discussed. The optimal attribute weights corresponded to a zero value for the objective function of the goal programming models regarding Eq 7.6 and Eq 7.9. Therefore either Eq 7.6 or Eq 7.9 would make the same pairwise comparison judgements about 31 selected pavement sections as stated by 27 highway engineers. Equation 7.6 is further verified by Eq 7.9 in the next chapter, using a Spearman rank correlation measure with a sample application example of the model.

CHAPTER 8. SAMPLE APPLICATION OF THE MODELS

In the previous chapters, two common prioritization index equations were developed that can be used for establishing rehabilitation priorities between rigid and flexible pavements at the network level PMS. In this chapter an application of these equations is described.

The univariate time series model is used here to develop an initial common index for both types of pavements with the help of SI data only. The predicted serviceability index obtained from this model can be used for assigning priority rankings to the given pavement sections. The goal programming model can be applied to develop a common index for both rigid and flexible pavements on an equitable basis using condition survey data and present serviceability index. A common index is calculated for each of the hypothetical sections. The results from the sample application are discussed.

APPLICATION OF THE UNIVARIATE TIME SERIES MODEL

In order to show how this procedure is used for developing a common index, a number of hypothetical pavement sections were set up as shown in Table 8.1. The equation developed in Chapter 6 for predicting the future serviceability index (FSI) is

$$FSI = 0.98\ PSI - 0.55\ LSI \qquad (6.5)$$

where

PSI = present serviceability index and

LSI = loss of serviceability index.

TABLE 8.1. HYPOTHETICAL PAVEMENT SECTIONS RANKED ACCORDING TO FUTURE SERVICEABILITY INDEX

Section No.	Pavement Type	Present SI	Loss of SI	Future SI	Ranking for Rehabilitation
1	Flexible	3.40	0.80	2.89	18
2	Rigid	3.40	0.60	3.00	20
3	Flexible	3.20	0.50	2.86	17
4	Rigid	3.20	0.40	2.92	19
5	Flexible	3.00	0.30	2.78	16
6	Rigid	2.90	0.20	2.73	15
7	Flexible	2.80	0.10	2.69	14
8	Rigid	2.70	0	2.65	13
9	Flexible	2.60	0.80	2.11	10
10	Rigid	2.50	0.60	2.12	11
11	Flexible	2.40	0.50	2.08	9
12	Rigid	2.40	0.40	2.13	12
13	Flexible	2.20	0.30	1.99	7
14	Rigid	2.20	0.20	2.05	8
15	Flexible	2.00	0.10	1.91	6
16	Rigid	1.90	0	1.86	5
17	Flexible	1.80	0.80	1.32	1
18	Rigid	1.70	0.60	1.34	2
19	Flexible	1.60	0.20	1.46	3
20	Rigid	1.50	0	1.47	4

Using this equation, the predicted serviceability index was calculated for each of the sections listed in Table 8.1. The predicted serviceability index can be used as a common prioritization index for assigning priority rankings to the given sections. These rankings are listed in Table 8.1.

The results show that the pavement with the faster deterioration rate is ranked higher for rehabilitation work. This equation may give some credit to rehabilitating rigid pavements, which generally deteriorate at a slower rate than flexible pavements.

APPLICATION OF THE GOAL PROGRAMMING MODEL

In this section, an application of the goal programming model is presented. To illustrate the use of this model in establishing priorities for rehabilitation work, a set of hypothetical pavement sections was developed as shown in Table 8.2. The equation which was developed in Chapter 8 for this purpose is

$$\begin{aligned} \text{Common Index} = {} & 3.8\ RD + 0.08\ CR \\ & + 0.38\ PO \\ & + 2.86\ (5.0 - SI) \end{aligned} \tag{7.6}$$

where

RD = inches of average rut depth,
CR = percentages of alligator cracking,
PO = number of punchouts,
SI = serviceability index,
PO = 0, for flexible pavement, and
RD = CR = 0, for rigid pavement.

TABLE 8.2. RANKED HYPOTHETICAL PAVEMENT SECTIONS ACCORDING TO COMMON INDEX USING CONDITION SURVEY DATA

Section No.	Pavement Type	Patching (Percent)	Rut Depth (Inches)	Alligator Crack (Percent)	Punchout (Percent)	SI	Common Index	Ranking for Rehabilitation
1	Flexible	0	0	25	---	4.0	4.86	19
2	Rigid	---	---	--	0	4.0	2.86	20
3	Flexible	25	0	25	---	3.5	6.29	16
4	Rigid	---	---	--	5	3.5	6.19	17
5	Flexible	0	0	50	---	3.0	9.72	13
6	Rigid	---	---	--	0	3.0	5.72	18
7	Flexible	0	1.0	25	---	3.0	11.52	9
8	Rigid	---	---	--	10	3.0	9.52	14
9	Flexible	25	0	50	---	2.5	11.15	10
10	Rigid	---	---	--	0	2.5	7.15	15
11	Flexible	25	1.0	25	---	2.5	12.95	7
12	Rigid	---	---	--	10	2.5	10.95	11
13	Flexible	0	0	75	---	2.0	14.58	3
14	Rigid	---	---	--	5	2.0	10.48	12
15	Flexible	50	0.5	25	---	2.0	14.48	4
16	Rigid	---	---	--	10	2.0	12.38	8
17	Flexible	0	1.0	50	---	2.0	16.38	1
18	Rigid	---	---	--	15	2.0	14.28	5
19	Flexible	25	1.0	0	---	1.5	13.81	6
20	Rigid	---	---	--	15	1.5	15.71	2

Using this equation, the common index was calculated for each of the sections listed in Table 8.2. The rankings based on this common index are also listed in the Table 8.2.

In this case the higher common index value represents the higher priority for rehabilitation. The results of this analysis show how this procedure produces a common index using multiple pavement attributes. The ranking numbers seem realistic and applicable in practice.

VERIFYING CONSISTENCY OF THE GOAL PROGRAMMING MODEL

An application of the goal programming model has been illustrated using a set of hypothetical pavement sections, as shown in Table 8.2. However, Eq 7.6, which is used in this example, was developed using only a subset of the entire highway network. Therefore, the consistency of Eq 7.6 needs to be verified against random errors associated with other pavement sections in different conditions. To do this, another Eq 7.9 was developed by conducting a second survey using set of pavement sections with conditions different from those in the first survey. Even though there is no direct statistical test of the hypothesis that the two equations are identical, correlation analysis can be applied if the equations are expressed as ranked data.

The rankings of 20 hypothetical pavement sections using Eq 7.6 were developed in Table 8.2. Now, the consistency of these rankings is to be verified. Another ranking of the same pavement sections, using Eq 7.9, is developed in Table 8.3, together with the rankings by Eq 7.6. The rankings of 20 hypothetical pavement sections using Eq 7.6 can now be compared with the rankings of the same sections using Eq 7.9. The measure of the degree of association between the two rankings can be obtained from a nonparametric method called "rank correlation".

A widely used measure of the correlation between ranked series is a coefficient of rank correlation (r_s) developed by C. Spearman in 1904 (Ref 46). This measure is expressed by:

TABLE 8.3. PAVEMENT RANKINGS BY FIRST AND SECOND SURVEYS

	First Survey		Second Survey		Difference in Ranking	
Section No.	Common Index	Ranking	Common Index	Ranking	d	d^2
1	4.86	19	4.21	19	0	0
2	2.86	20	3.43	20	0	0
3	6.29	16	6.32	18	-2	4
4	6.19	17	6.35	17	0	0
5	9.72	13	8.42	15	-2	4
6	5.72	18	6.86	16	2	4
7	11.52	9	10.46	12	-3	9
8	9.52	14	9.26	13	1	1
9	11.15	10	10.53	11	-1	1
10	7.15	15	8.58	14	1	1
11	12.95	7	12.57	8	-1	1
12	10.95	11	10.98	10	1	1
13	14.58	3	12.63	7	-4	16
14	10.48	12	11.49	9	3	9
15	14.48	4	12.90	5	-1	1
16	12.38	8	12.69	6	2	4
17	16.38	1	14.67	2	-1	1
18	14.28	5	13.89	3	2	4
19	13.81	6	13.78	4	2	4
20	15.71	2	15.61	1	1	1
					$\Sigma d = 0$	$\Sigma d^2 = 66$

$$r_s = 1 - \frac{6\Sigma\, d^2}{n\,(n^2 - 1)}$$

where

d = difference in rank between paired items in a series and

n = number of pairs of ranked items in a series.

Using the value of d in Table 8.3,

$$r_s = 1 - \frac{6 \cdot 66}{20\,(20^2 - 1)} = 0.95$$

The coefficient r_s computed from sample data should be tested for significance, since it is subject to sampling error. The value of $r_s = 0.95$ obtained from the sample of 20 paired pavement section rankings is significant at the 0.01 level of significance. This result confirms that the rankings using Eq 7.6 are highly correlated and, therefore, consistent with rankings using Eq 7.9.

CHAPTER 9. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY AND CONCLUSIONS

The research on Project 307 started in 1981 as a five year study to investigate the "Implementation of a Pavement Management System" in Texas. The major findings of various tasks of this project were included in Research Reports 307-1, 307-2, and 307-3. A brief summary of these findings is as follows:

(1) A simplified initial PMS for Texas was recommended, along with an implementation plan and some suggestions for future improvement of the system. This initial PMS was termed "PMS Release 1.0" by the Texas State Department of Highways and Public Transportation.

(2) The recommended Texas PMS Release 1.0 was based on the existing Pavement Evaluation System (PES). It included the following recommendations:

   (a) skid resistance should be omitted from the collective performance index,

   (b) the current mass inventory data collection mode should be modified to allow statistical sampling, and

   (c) analysis techniques for identifying the consequences of different funding levels should be added to the existing system.

(3) The recommendations for future versions of the Texas PMS were also included in Research Report 307-1.

(4) A methodology for formulating a prioritization procedure using a method that will lead to a more realistic and rational way of establishing candidate projects for priority programming at the network level pavement management system was developed. This method was based on a factorial design involving a set of candidate

decision variables, such as distress and present serviceability index. For this reason, it was termed as "the rational factorial rating method". In addition, the actual application of the method to the formulation of a preliminary prioritization procedure was discussed, together with the results obtained. It was felt that the method may provide a better understanding of how decisions on priorities are made in practice. It was expected that the method could be applied in a controlled study by the Texas State Department of Highways and Public Transportation or any other agency to develop a prioritization index which will represent the ideas and experience of the group included in the surveys.

(5) A program level PMS using a method that will lead to a more realistic and efficient way of making decisions concerning pavement rehabilitation was developed. The methodology used in the system was based on the Markovian Decision process, which involved 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 was discussed along with the results. A computer program was also developed to solve a sample problem.

The primary objective of the final phase of this project was to develop a unified ranking system which can be applied to both rigid and flexible pavements on an equitable basis. Although in the past, virtually no effort was made towards developing a unified ranking system, it was felt that this system is an essential component of the total pavement management system. Therefore, an effort was made to investigate the possibility of developing such a system.

Eight different approaches to the development of a unified ranking system were reviewed and discussed. They are listed below:

(1) serviceability index,

(2) rate of loss of SI,

(3) analytical examination of distresses,
(4) economic analysis,
(5) discriminate analysis,
(6) utility theory (value function),
(7) trigger value, and
(8) pairwise comparison.

Several factors were considered in the selection of a suitable approach for use in Texas. As a result of this analysis two methodologies were selected to develop a common prioritization index for rehabilitation. Application of the univariate time series of serviceability index method was considered useful in establishing an objective way to assign priorities by taking the past history of the pavement into consideration.

The univariate time series model was solved using an ordinary regression technique. This regression equation was tested against basic assumptions of regression theory using available statistics:

(1) normality of errors,
(2) independence of errors,
(3) common variance of errors, and
(4) multicollinearity between independent variables.

The equation satisfied all these assumptions. As expected, the deterioration rate was shown to be a significant factor in the model. However, this empirical result is by no means definitive. The equation was generated using a rather small sample of data collected from flexible pavements in Austin. The model should be tested with more data obtained under different conditions such as cold weather, rigid pavement, etc.

A goal programming model using pairwise comparison data also appeared to be a useful methodology in explaining the process of how decisions are made. This model used paired comparison judgements on the global criterion directly and estimated the set of weights simultaneously. This method does not place significant judgemental requirements on the decision maker, as do other methods. The procedure is generalized to estimate a set of weights using the paired comparison judgements of a group of highway engineers. Two different types of pavement with different pavement attributes were used for this purpose.

Only five out of eight pavement attributes were found to be significant for comparing rigid pavements with flexible pavements. This could be due to the limited capability of human beings in aggregating numerous factors into the final decision. However, this method can help highway engineers to focus their limited, information-processing capabilities, and resources on essential elements of the pavement evaluation, thereby improving the efficiency and effectiveness of the decision making process.

The goal programming formulation is extremely flexible so that many additional features can be built into the basic model, as indicated below:

(1) Additional constraints on weights can be readily imposed. For example, if it is known from a previous analysis that Serviceability Index is more important than the number of spalled cracks, such a constraint can be added.
(2) The quadratic utility concept can be used instead of the linear utility function used in the model developing procedure.
(3) An individual highway engineer can state his confidence in comparing a given pair of pavement sections.

The application of this method to developing a common index will be helpful in understanding the decision makers' behavior in aggregating information across the attributes, and in improving their decision making ability.

In general, the prioritization analysis shows the equivocal nature of the phenomenon. The different rankings resulting from different prioritization analyses could be thought of as a strength rather than a weakness. It should be noted that each prioritization procedure is based on some rational strategy and that each different strategic approach affords a different view of the phenomenon.

The time series model may be considered as a "quick and dirty" solution to comparing rigid and flexible pavements. But the model is a good start to the development of a unified ranking system. The model produces a reasonable answer and it can be easily applied in practice.

The pairwise comparison approach is recommended for collecting subjective opinions about two different types of pavements with different pavement attributes because highway engineers can provide the information with higher confidence through this method than through others, such as the utility theory and the scaled rating method. Pairwise comparison is simpler and easier than probabilistic assessment of values for utility function development or direct rankings of pavements in different types and conditions.

Finally, it is recommended that future research efforts be directed towards verifying these models with different sets of serviceability index data and different groups of highway engineers. As mentioned earlier, the univariate time series model was developed using a small sample of data collected from flexible pavements in Austin for three years. Therefore, the model should be tested with a broad range of data for different environmental conditions, various traffic conditions, different types of pavement structures, etc. Historical serviceability index data should be collected for a longer time. This would allow us to test the model over different points in time.

RECOMMENDATIONS

It is recommended that the goal programming model based on pairwise comparison data should be tested and implemented using a group of highway engineers in the state of Texas. The group of raters should be composed of one engineer from each district. Then the equation developed, using their data could can be considered as a consensus of their different views of pavement rehabilitation programming. This would also allow us to test the model developed in this report with a different group of people. The involvement of highway engineers from the districts in the modelling process would facilitate the implementation of results. It is recommended that these two models for developing a unified ranking system be implemented by the Texas State Department of Highways and Public Transportation at an early date.

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APPENDIX A

PAIRWISE COMPARISON METHOD FOR DEVELOPING A COMBINED INDEX

APPENDIX A. PAIRWISE COMPARISON METHOD FOR DEVELOPING A COMBINED INDEX

A model for estimating the parameters of a combined index is described in Chapter 7. The data needed for determining these estimates were collected by conducting a survey. This appendix includes a brief description of the survey procedure and the data recording and other associated forms used in the survey.

A group of highway engineers who attended a special course in Pavement Management at The University of Texas at Austin were requested to participate in the survey. The survey was designed as a laboratory exercise for the class.

PAIRWISE COMPARISON METHOD FOR
DEVELOPING A COMBINED INDEX

NAME ______________________________

MAJOR WORK AREA ________________

STATE ______________________________

DATE ______________________________

PAIRWISE COMPARISON METHOD FOR DEVELOPING A COMBINED INDEX

The objective of this lab is to familiarize the students with a method for selecting pavement sections for rehabilitation based on pavement attributes, such as roughness, cracking, etc. A survey will be conducted to obtain a set of forced choices between pairs of pavement sections. It is expected that the set may contain inconsistent choices. This inconsistency is allowed and is minimized by assigning smaller weights to the attributes involved in inconsistent choices.

Attached is a set of forms which will be utilized in the development of the weights to be assigned to the pavement attributes for application in the combined index. The four flexible pavement attributes which have been selected for this purpose are SI (based on roughness), rutting, patches, and alligator cracking. The four attributes selected for rigid pavements are SI (based on roughness), spalled cracks, punchouts, and patches. The selected pavement attributes are described below.

SI (BASED ON ROUGHNESS)

The serviceability of a pavement is defined by the Present Serviceability Rating (PSR) established by the public (user). However, it is impractical and expensive to evaluate serviceability on every pavement section using the rating panel method. Consequently, considerable effort has gone into correlating various mechanical measurements with these subjective ratings. The SR was correlated with a set of physical measurements, called Present Serviceability Index (PSI). PSI calculated from physical measurement data it is only an estimate of PSR; that is,

$$PSI = PSR + Error$$

Although these physical measurements include condition or distress data, it is the roughness that provides that major correlation variable. The correlation coefficients between PSR and PSI are increased by only about 5 percent after including the condition data in the serviceability equation. The major use of roughness measurements, which are objective, is for estimating pavement serviceability, which is subjective.

The roughness is a common attribute, one which exists in both flexible and rigid pavements. A serviceability index based solely on roughness measurements should be commensurable (directly comparable) among all types of pavements.

FLEXIBLE PAVEMENT

Rutting

A rut is a surface depression in the wheel paths. It stems from a permanent deformation in any of the pavement layers or subgrade. Rutting is caused by consolidation or lateral movement of the materials due to traffic loads. Significant rutting indicates that one of the pavement layers is inadequate and it often leads to a major structural failure. Rutting is measured as the average rut depth over a one-mile section.

Patching

Patches are corrections made to surface defects including surface and deep asphalt patches and sporadic seal coating. All patches are to be recorded except full roadway treatments greater than 500 feet (i.e., full width seal coats or overlays). Condition of patch is not considered in the determination of patched area. Patch is measured as percent of the total lane surface area.

Alligator Cracking

Alligator cracking is interconnected cracks forming a series of small blocks resembling an alligator's skin or chicken wire. They are often associated with pavements that deflect excessively under traffic loads. The excessive deflection is due to improper design, weak base, subbase or subgrade pavement layers in relation to traffic loads imposed on the facility. Alligator cracking is measured as percent of total wheel paths, and all alligator cracks, whatever the crack width, are counted.

RIGID PAVEMENT

Spalled Cracks

Spalling is defined as the widening of existing cracks by secondary cracking or breaking of the crack edges. To be considered in the survey, the crack must have spalling an inch wide or more for a length of at least one foot.

Punchouts

When closely spaced transverse cracks are linked by longitudinal cracks to form a block, the block is called a punchout. A punchout should be counted when a block has formed and the cracks surrounding the block show signs of spalling or faulting. Punchouts are caused by load repetition combined with loss of support. Punchouts are measured by counting the number of punchouts for a one-mile-long highway segment.

Patches

A repaired patch is defined as a repaired section of the pavement where the repair work has been carried out to the full depth of the concrete. It is understood that the depth of repair cannot be determined by visual inspection; therefore, all patches should be counted. Patches are measured by counting the number of patches for a one-mile long highway segment.

INSTRUCTIONS

Please fill the blanks in the survey form, with 1 or 2 according to the following instructions:

(1) Imagine the hypothesized pavement sections with the given combinations of pavement attributes.

(2) Assume that the pavements under consideration are in the same environmental zone and same traffic level.

(3) Consider only four attributes described previously for the comparison of pavements.

(4) Compare two pavement sections based on their selected attributes, and determine which pavement section is worse than the other.

(5) Write down the selected worst pavement section number (1 or 2) in the blank.

(6) Proceed to the next pairwise comparison set.

(7) Make a choice in the pairwise comparison set independently without relating the current selection with the previous selections.

A. Data Recording Sheet for Flexible Pavements

1	________	13	________	25	________
2	________	14	________	26	________
3	________	15	________	27	________
4	________	16	________	28	________
5	________	17	________	29	________
6	________	18	________	30	________
7	________	19	________	31	________
8	________	20	________	32	________
9	________	21	________	33	________
10	________	22	________	34	________
11	________	23	________	35	________
12	________	24	________	36	________

B. Data Recording Sheet for Rigid Pavements

1 __________	13 __________	25 __________
2 __________	14 __________	26 __________
3 __________	15 __________	27 __________
4 __________	16 __________	28 __________
5 __________	17 __________	29 __________
6 __________	18 __________	30 __________
7 __________	19 __________	31 __________
8 __________	20 __________	32 __________
9 __________	21 __________	33 __________
10 __________	22 __________	34 __________
11 __________	23 __________	35 __________
12 __________	24 __________	36 __________

C. Data Recording Sheet for Flexible vs. Rigid Pavements

1 ____________
2 ____________
3 ____________
4 ____________
5 ____________
6 ____________
7 ____________
8 ____________
9 ____________
10 ____________
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28 ____________
29 ____________
30 ____________
31 ____________
32 ____________
33 ____________
34 ____________
35 ____________
36 ____________

1.

SECTION / ATTRIBUTE	Section 1	Section 2
Patching	50 %	0 %
Rutting	0 in	0.5 in
Alligator Cracking	0 %	30 %
Serviceability Index	2.5	3.0

2.

SECTION / ATTRIBUTE	Section 1	Section 2
Patching	0 %	20 %
Rutting	1.0 in	0 in
Alligator Cracking	0 %	30 %
Serviceability Index	3.0	2.0

3.

SECTION / ATTRIBUTE	Section 1	Section 2
Patching	0 %	30 %
Rutting	0 in	0.5 in
Alligator Cracking	50 %	0 %
Serviceability Index	2.0	1.5

Examples of typical pairs of flexible pavement sections used in the surveys

SECTION / ATTRIBUTE	Section 1	Section 2
Patches (#/mile)	10	0
Spalled Cracks (#/mile)	5	0
Punchouts (#/mile)	0	5
Serviceability Index	2.0	3.0

SECTION / ATTRIBUTE	Section 1	Section 2
Patches (#/mile)	0	5
Spalled Cracks (#/mile)	15	0
Punchouts (#/mile)	0	10
Serviceability Index	2.5	3.0

SECTION / ATTRIBUTE	Section 1	Section 2
Patches (#/mile)	15	0
Spalled Cracks (#/mile)	10	0
Punchouts (#/mile)	0	15
Serviceability Index	2.0	2.5

Examples of typical pairs of rigid pavement sections used in the surveys.

Flexible Pavement

Attribute \ Section	Section 1
Patching	0 %
Rutting (inches)	1.0 in
Alligator Cracking	20 %
Serviceability Index	2.5

Rigid Pavement

Attribute \ Section	Section 2
Patches (#/mile)	10
Spalled Cracks (#/mile)	5
Punchouts (#/mile)	0
Serviceability Index	2.0

Example of a typical pair of flexible and rigid pavement sections used in the surveys.

APPENDIX B

SUMMARY OF ATTRIBUTE WEIGHTS FOR 27 HIGHWAY ENGINEERS

TABLE B.1. WEIGHTS OF FLEXIBLE PAVEMENT ATTRIBUTES FOR EACH HIGHWAY ENGINEER (FIRST SURVEY)

No.	State	Work Area	Patching (Percent)	Rutting (Inches)	Cracking (Percent)	S.I.
1	Michigan	Administration	0.06	6.21	0.10	3.62
2	Wyoming	Administration	0	5.56	0	4.44
3	North Carolina	District Engineer	0.15	4.43	0.21	5.22
4	Georgia	District Engineer	0	9.52	0.20	0.27
5	Alabama	District Engineer	0.09	5.02	0.13	4.77
6	Utah	Traffic	0.09	5.09	0.11	4.71
7	Texas	Pavement Management	0.10	6.12	0.10	3.67
8	Florida	Pavement Management	0	4.44	0.02	5.53
9	Kentucky	Pavement Management	0.07	5.92	0.08	3.93
10	Minnesota	Soil	0.07	5.64	0.09	4.20
11	Australia	Soil	0.07	5.48	0.09	4.35
12	Virginia	Material	0.10	4.70	0.11	5.09
13	Minnesota	Material	0.09	5.48	0.10	4.34
14	Alabama	Material	0.14	5.20	0.16	4.51
15	Virginia	Research	0.07	5.62	0.09	4.22
16	California	Area Engineer	0.03	5.81	0.07	4.09
17	New York	Area Engineer	0.11	4.68	0.11	5.11
18	Colorado	Construction	0.10	5.54	0.11	4.25
19	Colorado	Construction	0.12	4.97	0.11	4.81
20	South Dakota	Construction	0	5.72	0.06	4.22
21	FHWA	Construction	0.09	6.71	0.08	3.12
22	Puerto Rico	Construction	0.11	4.85	0.14	4.90
23	Arizona	Construction	0.10	5.01	0.10	4.79
24	Texas	Design	0.07	5.25	0.08	4.60
25	Florida	Design	0.11	4.61	0.11	5.17
26	Kansas	Design	0.09	5.87	0.15	3.88
27	Ohio	Design	0.10	5.01	0.12	4.76
	Group		0.07	5.62	0.09	4.22

TABLE B.2. WEIGHTS OF RIGID PAVEMENT ATTRIBUTES FOR EACH HIGHWAY ENGINEER (FIRST SURVEY)

No.	State	Work Area	Patches (Number)	Cracks (Number)	Punchouts (Number)	S.I.
1	Michigan	Administration	0.68	0.79	1.00	7.52
2	Wyoming	Administration	0.68	0.78	0.78	7.76
3	North Carolina	District Engineer	0.30	0.39	1.10	8.22
4	Georgia	District Engineer	0.81	0.69	0.68	7.82
5	Alabama	District Engineer	0.74	0.84	0.96	7.47
6	Utah	Traffic	0	0	0.32	9.68
7	Texas	Pavement Management	0.67	0.44	1.33	7.56
8	Florida	Pavement Management	0.55	0.55	0.91	5.00
9	Kentucky	Pavement Management	0.62	0.83	0.66	7.90
10	Minnesota	Soil	0.65	0.65	0.70	8.00
11	Australia	Soil	0	0.93	2.06	7.01
12	Virginia	Material	0.65	0.66	0.91	7.78
13	Minnesota	Material	0.69	0.84	0.84	7.63
14	Alabama	Material	1.02	0.65	1.12	7.21
15	Virginia	Research	0.73	0.77	0.90	7.60
16	California	Area Engineer	0.80	0.62	1.01	7.57
17	New York	Area Engineer	0.60	0.70	0.96	7.74
18	Colorado	Construction	0.87	0.91	0.97	7.25
19	Colorado	Construction	0.69	0.79	0.99	7.52
20	South Dakota	Construction	0.63	0.62	0.79	7.97
21	FHWA	Construction	0.91	1.17	0.93	6.99
22	Puerto Rico	Construction	0.83	0.93	1.26	6.98
23	Arizona	Construction	0.86	0	0.17	8.97
24	Texas	Design	0.94	0.60	1.37	7.08
25	Florida	Design	0.28	0.83	0.56	8.33
26	Kansas	Design	1.13	0.75	1.32	6.79
27	Ohio	Design	0	0.70	4.04	5.26
	Group		0.67	0.72	0.98	7.63

TABLE B.3. WEIGHTS OF FLEXIBLE AND RIGID PAVEMENT ATTRIBUTES FOR EACH HIGHWAY ENGINEER (FIRST SURVEY)

			Attributes							
No.	State	Work Area	Patching (Percent)	Rutting (Inches)	Cracking (Percent)	S.I.	Patches (Number)	Cracks (Number)	Punchouts (Number)	S.I.
1	Michigan	Administration	0.06	3.91	0.07	2.46	0.21	0.29	0.29	2.73
2	Wyoming	Administration	0	3.26	0.07	3.01	0	0.33	0.33	3.01
3	North Carolina	District Engineer	0.11	0.84	0.27	3.85	0.08	0.08	0.91	3.85
4	Georgia	District Engineer	0.07	3.38	0.10	2.54	0.29	0.29	0.29	3.06
5	Alabama	District Engineer	0.06	3.73	0.07	2.56	0.26	0.28	0.30	2.74
6	Utah	Traffic	0.04	0	0.04	4.97	0	0	0	4.97
7	Texas	Pavement Management	0.05	3.94	0.08	2.54	0	0.23	0.37	2.78
8	Florida	Pavement Management	0	1.85	0.05	3.95	0	0	0.19	3.95
9	Kentucky	Pavement Management	0	3.96	0.02	2.97	0	0	0.08	2.97
10	Minnesota	Soil	0	3.97	0.07	2.98	0	0	0	2.98
11	Australia	Soil	0.06	3.59	0.07	2.70	0.22	0.31	0.36	2.70
12	Virginia	Material	0	2.94	0	3.69	0.08	0	0.40	2.89
13	Minnesota	Material	0	3.99	0.02	2.99	0	0	0	2.99
14	Alabama	Material	0.05	0.37	0.13	4.45	0	0	0.17	4.83
15	Virginia	Research	0.05	1.94	0	4.12	0.11	0.11	0.66	3.01
16	California	Area Engineer	0.08	3.66	0.08	2.73	0.36	0	0.37	2.74
17	New York	Area Engineer	0	0.90	0.03	4.60	0	0.22	0.72	3.55
18	Colorado	Construction	0.15	3.34	0.54	1.60	0	0.12	0.50	3.74
19	Colorado	Construction	0.02	0	0.18	4.36	0	0	0	5.44
20	South Dakota	Construction	0.02	3.84	0	2.88	0	0	0.38	2.88
21	FHWA	Construction	0	9.58	0	0	0.18	0.24	0	0
22	Puerto Rico	Construction	0.17	0	0.23	3.34	0.30	0.50	0.64	4.82
23	Arizona	Construction	0.06	1.79	0.04	3.93	0.18	0	0.08	3.93
24	Texas	Design	0	0	0	0	0	0	10.00	0
25	Florida	Design	0	0.94	0.07	4.11	0	0.35	0.43	4.11
26	Kansas	Design	0.32	4.51	0.32	3.05	0	0	1.80	0
27	Ohio	Design	0.01	4.59	0.04	2.33	0	0	0.43	2.60
	Group		--	3.80	0.08	2.86	0	0	0.38	2.86

TABLE B.4. WEIGHTS OF FLEXIBLE PAVEMENT ATTRIBUTES (SECOND SURVEY)

No.	State	Work Area	Patching (Percent)	Rutting (Inches)	Cracking (Percent)	S.I.
1	Michigan	Administration	0.01	8.67	0.10	1.22
2	Wyoming	Administration	0.06	6.35	0.15	3.44
3	North Carolina	District Engineer	0.13	4.84	0.18	4.84
4	Georgia	District Engineer	0	3.33	0	6.67
5	Alabama	District Engineer	0.06	6.91	0.19	2.85
6	Utah	Traffic	0	1.46	0.10	8.44
7	Texas	Pavement Management	0.07	7.04	0.07	2.82
8	Florida	Pavement Management	0.08	2.11	0.20	7.61
9	Kentucky	Pavement Management	0.02	5.24	0.03	4.71
10	Minnesota	Soil	0.02	6.88	0	3.10
11	Australia	Soil	0	2.97	0.19	6.84
12	Virginia	Material	0	4.75	0.02	5.23
13	Minnesota	Material	0	10.00	0	0
14	Alabama	Material	0.10	5.38	0.17	4.35
15	Virginia	Research	0	6.81	0.08	3.11
16	California	Area Engineer	0	4.50	0.09	5.41
17	New York	Area Engineer	0.09	6.09	0.16	3.65
18	Colorado	Construction	0.14	4.83	0.19	4.83
19	Colorado	Construction	0.15	6.48	0.23	3.13
20	South Dakota	Construction	0	4.75	0.02	5.23
21	FHWA	Construction	0.08	9.83	0.09	0
22	Puerto Rico	Construction	0	2.11	0.27	7.61
23	Arizona	Construction	0.01	5.98	0.04	3.97
24	Texas	Design	0.04	6.19	0.11	3.65
25	Florida	Design	0.14	4.45	0.20	5.21
26	Kansas	Design	0.03	7.02	0	2.95
27	Ohio	Design	0.08	6.23	0.11	3.58
	Group		0.05	5.61	0.10	4.24

TABLE B.5. WEIGHTS OF RIGID PAVEMENT ATTRIBUTES FOR EACH HIGHWAY ENGINEER

No.	State	Work Area	Patches (Number)	Cracks (Number)	Punchouts (Number)	S.I.
1	Michigan	Administration	0.06	0.23	0.50	9.21
2	Wyoming	Administration	0.19	0.40	0.60	8.81
3	North Carolina	District Engineer	0.13	0.43	0.87	8.56
4	Georgia	District Engineer	0.32	0.56	0.86	8.27
5	Alabama	District Engineer	0.13	0.56	0.78	8.52
6	Utah	Traffic	0.29	0.36	0.64	8.71
7	Texas	Pavement Management	0.10	0.36	0.99	8.55
8	Florida	Pavement Management	0.11	0.26	0.60	9.03
9	Kentucky	Pavement Management	0.41	0.63	0.59	8.37
10	Minnesota	Soil	0	0	0	10.00
11	Australia	Soil	0.34	0.63	1.00	8.04
12	Virginia	Material	0	0.33	0.79	8.88
13	Minnesota	Material	0	0	0	10.00
14	Alabama	Material	0.82	0.25	1.76	7.18
15	Virginia	Research	0.17	0.41	0.82	8.60
16	California	Area Engineer	0.36	0.31	0.71	8.62
17	New York	Area Engineer	0	0.45	0.94	8.62
18	Colorado	Construction	0.38	0.63	0.86	8.13
19	Colorado	Construction	0.25	0.46	0.83	8.45
20	South Dakota	Construction	0	0.18	0.51	9.32
21	FHWA	Construction	1.30	2.10	0.96	5.64
22	Puerto Rico	Construction	0.50	0	2.00	7.50
23	Arizona	Construction	0.32	0.32	0.75	8.62
24	Texas	Design	0.71	0.38	1.56	7.35
25	Florida	Design	0.24	0.63	0.54	8.59
26	Kansas	Design	0.42	0.51	0.79	8.28
27	Ohio	Design	0.22	0.08	0.96	8.74
	Group		0.19	0.46	0.74	8.61

TABLE B.6. WEIGHTS OF FLEXIBLE AND RIGID PAVEMENT ATTRIBUTES FOR EACH HIGHWAY ENGINEER (SECOND SURVEY)

			Attributes							
No.	State	Work Area	Patching (Percent)	Rutting (Inches)	Cracking (Percent)	S.I.	Patches (Number)	Cracks (Number)	Punchouts (Number)	S.I.
1	Michigan	Administration	0	3.85	0	2.80	0	0	0	3.36
2	Wyoming	Administration	0.02	0.67	0.02	4.87	0.06	0.02	0.07	4.29
3	North Carolina	District Engineer	0.04	2.15	0.10	3.48	0.14	0	0.38	3.72
4	Georgia	District Engineer	0.05	1.75	0.10	3.40	0	0.43	0.44	3.87
5	Alabama	District Engineer	0.02	3.31	0.13	2.86	0.16	0.07	0.53	2.91
6	Utah	Traffic	0.03	1.02	0.05	4.44	0.12	0.12	0.13	4.10
7	Texas	Pavement Management	0	4.0	0	3.97	0.43	0.04	1.17	0.03
8	Florida	Pavement Management	0.04	0.20	0.09	4.80	0.20	0.02	0.38	4.28
9	Kentucky	Pavement Management	0.03	5.46	0.02	1.79	0.05	0.11	0	2.54
10	Minnesota	Soil	0	4.65	0	2.52	0.03	0.06	0	2.75
11	Australia	Soil	0.06	2.62	0.16	2.39	0	0.28	0.80	3.71
12	Virginia	Material	0.03	3.34	0.07	2.79	0.08	0.17	0.22	3.30
13	Minnesota	Material	0.01	4.81	0	2.56	0.08	0	0.26	2.28
14	Alabama	Material	0.07	2.27	0.09	3.55	0.31	0.17	0.51	3.01
15	Virginia	Research	0	3.60	0.03	3.42	0.20	0.14	0.54	2.08
16	California	Area Engineer	0.02	4.04	0.05	2.78	0.23	0.11	0.41	2.37
17	New York	Area Engineer	0.01	3.82	0.04	2.93	0.08	0.24	0.55	2.32
18	Colorado	Construction	0.08	5.37	0.16	1.23	0.17	0.03	0	2.97
19	Colorado	Construction	0.14	3.29	0.26	1.26	0.03	0	0.43	4.59
20	South Dakota	Construction	0	3.85	0	2.80	0	0	0	3.36
21	FHWA	Construction	0	5.38	0.03	1.76	0	0.28	0	2.54
22	Puerto Rico	Construction	0.04	1.61	0.12	3.82	0.12	0	0.45	3.85
23	Arizona	Construction	0.02	3.68	0	3.23	0.08	0.13	0.47	2.41
24	Texas	Design	0.05	4.46	0.08	1.86	0.01	0.02	0.47	3.04
25	Florida	Design	0	0	0	4.71	0.13	0.11	0.09	4.98
26	Kansas	Design	0	4.64	0.02	2.93	0.25	0	0.56	1.61
27	Ohio	Design	0.03	5.00	0.05	1.97	0.15	0	0.18	2.62
	Group		0.03	3.54	0.06	2.71	--	--	0.24	3.43