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SD Department of Transportation
Office of Research

Enhancement of SDDOT's Pavement Management System

Study SD93-14
Final Report

Prepared by
Deighton Associates Limited
112 King Street East
Bowmanville, Ontario, Canada

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DISCLAIMER

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This work was performed under the supervision of the SD93-14 Technical Panel:

Toby Crow	Planning and Programming	Norm Konechne	Pierre Area
Mike Durick	Construction Support	Roger Lehmkuhl	Data Services
Larry Engbrecht	Materials & Surfacing	Blair Lunde	Office of Research
Brett Hestdalen	FHWA	Ben Orsbon	Planning & Programming
David Huft	Research	Johnny Reiff	Sioux Falls Area
Tom Johnson	Aberdeen Area	Larry Schoenhard	Data Inventory

The contribution of the expert group on pavements is gratefully acknowledged:

Don Anderson	Materials & Surfacing	Tom Johnson	Aberdeen Area
Toby Crow	Planning & Programming	Norm Konechne	Pierre Area
Larry Engbrecht	Materials & Surfacing	Dennis Landguth	Rapid City Region
Gil Hedman	Materials & Surfacing	Bob Orcutt	Brookings Area
Jim Hoar	Winner Area	Ben Orsbon	Planning & Programming
Norm Humphrey	Maintenance Support	Tom Week	Yankton Area

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16. Abstract

The consultant provided basic services and software to enhance the South Dakota DOT's (SDDOT) pavement management system (PMS). During the first step, the consultant examined SDDOT's existing support structure for their PMS including their documentation, systems, policies, and data collection procedures. The consultant then made recommendations as to how those should be changed to support an enhanced pavement management process. Next, having concluded there was insufficient historical data to develop the necessary models using statistical procedures, the consultant designed a questionnaire to extract the expert opinion from experienced SDDOT engineers.

With the answers provided on those questionnaires, the consultant developed the following pavement management models and procedures: (a) a distress data collection survey to measure the extent and severity of various distresses important to SDDOT, (b) a set of deduct values necessary to convert the raw condition data to a set of condition indexes, (c) a family of performance curves for each condition index with one family member for each different pavement type, (d) a composite index used to define the overall health of an individual road section, and, when aggregated the overall health of the network, (e) a set of standard rehabilitation treatment types including their unit costs and their effects on the condition indexes, (f) a set of performance curves for the composite index that result after a treatment is applied, (g) a set of trigger limits telling the ranges of each condition index where a treatment is applicable, and a set of economic parameters used when generating a life cycle cost analysis of applying various strategies to all road sections.

The consultant then, configured and installed the following software on the department's micro computers: (a) a database management system loaded with current SDDOT data and capable of becoming SDDOT's historical PMS database, (b) an analysis system capable of evaluating an large number of alternative strategies for each road section and selecting the best strategy using optimization, and (c) an automated mapping system containing a digitized map of the SDDOT highway network which is linked to the historical PMS database and can display any data on the map in different colors or sizes on the map. Finally, the consultant trained SDDOT staff in the use and maintenance of the software.

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Table of Contents

List of Tables

List of Figures

List of Equations

List of Appendices

1. Introduction

'The PMS for the National Highway System (NHS) shall, as a minimum consist of the following components: (1) Data ... (2) Analysis ... (3) Update. ...'[1]

This document is the final report for project SD93-14: Enhancement of SDDOT's Pavement Management System (PMS). Although this report has been published and bound as a complete document, it is important to know that there are several companion documents which accompany it. First, the Executive Summary is a stand alone document published as SD93-14X. Second, the four volumes of report appendices are also published as SD93-14A1 through SD93-14A4. Finally, there are four software manuals: (1) dROAD 5 Technical Guide, (2) dROAD User Manual, (3) dTIMS User Manual, and (4) dMAP User Manual.

1.1 Project Background

This research project was initiated in 1993 when the South Dakota Department of Transportation (SDDOT) issued a Request for Proposals (RFP). The RFP stated that SDDOT's pavement management system (PMS) was a single year prioritization system which was developed in the late 1970's and early 1980's. The RFP went on to say that perhaps more than any other state's pavement management system, this system had developed strong credibility. The credibility, it said, was not only limited to within the Department itself, but, extended to outside organizations such as the state legislature as well.

However, the RFP went on, SDDOT was concerned that despite the success of their pavement management system, it had some limitations. The department's concern was that these limitations might prevent the system from fully supporting decisions that were becoming more difficult to make. The RFP said that SDDOT is facing a problem of rapidly growing construction needs and tightening budgets. And, to head this problem off, SDDOT recognized that research was needed to provide an enhanced pavement management system which more strongly supported decision makers and the Department's pavement management process.

Deighton Associates Ltd. submitted the successful proposal and was awarded the contract on the 29th day of October, 1993. The project finished on the 31st day of December, 1994.

1.2 Project Objectives

To define its overall intention SDDOT listed the following research objectives in the RFP:

1. *To determine how the content and organization of the Department's pavement management database can support a historically based, multi-year optimizing pavement Management System and to identify needed improvements.*
2. *To develop fundamental pavement management components, including historically based pavement performance curves, appropriate strategies for maintenance, rehabilitation and reconstruction, and formal definitions of current pavement management policy objectives.*
3. *To provide operational software incorporating these fundamental components and full pavement management functionality for database management, comprehensive analysis and report generation.*
4. *To recommend policies and procedures and provide training necessary to maintain and operate the system.*

1.3 Project Tasks

The RFP also listed a set of research tasks which the consultant had to perform during the project. This list consisted of a total of eleven tasks. As the project progressed, however, the contract was amended to add another task for conducting a pilot distress survey. The final set of tasks is listed below. The task which was added later is shown as task number eight.

1. *Meet with the project's technical panel to review project scope and work plan.*
2. *Review literature, including other states' experience, pertinent to pavement management art.*
3. *Review information available from documentation, earlier SDDOT studies, and interviews to gain familiarity with SDDOT's existing pavement management system and information processing environment.*
4. *In consultation with SDDOT pavement management and design personnel, develop performance (life-cycle) curves for asphalt and Portland cement concrete pavements and assess the curves' quality. The curves should be expressed in terms of individual and composite condition indexes, and should be based on historical data available within the Department and on expert opinion of Department engineers.*
5. *Construct, by decision trees or other appropriate methods, comprehensive maintenance, rehabilitation and reconstruction strategies based upon history of past performance in South Dakota, proven engineering principles, and expert opinion. Identify costs, selection criteria, and expected improvements for each treatment considered.*
6. *Develop recommendations for pavement management policies, procedures, and software design consistent with SDDOT's technical and organizational requirements.*

7. *Provide an interim report and presentation to the project's technical panel describing findings of Tasks 1-6.*

8. *Design pavement distress survey and check procedures, calibrate raters, create data entry software, train SDDOT staff, collect data on all of I29, I90, I229 and US 281, and enter the data into the enhanced pavement management system.*

9. *Provide and install operational software which incorporates the developed performance curves and treatment strategies, which provides full pavement management functions (including database management, analysis of pavement performance, selection of maintenance, rehabilitation and reconstruction alternatives, optimized investment strategies, and graphic representation of results), and which interfaces to existing data structure. Software should support at least six users via Local Area Network, and should support pavement management on the state's entire 8000 mile highway network.*

10. *Provide training, documentation and a comprehensive user's manual for the enhanced pavement management system.*

11. *Submit a final report and executive summary summarizing relevant literature, research methodology, findings, conclusions, and recommendations.*

12. *Make an executive presentation to the Department's upper management and Research Review Board.*

1.4 Project Summary

Throughout the course of this project, the consultant performed all of the above tasks. The following is a brief summary of how the project was carried out.

The bulk of the consultant's effort went into four areas: (1) investigate SDDOT's pavement management process, (2) make recommendations regarding the non-computerized part of it, (3) use expert opinion to develop a set of engineering models which represent SDDOT's current pavement management practice, (4) put SDDOT's data and these new models in the consultant's three software packages, dROAD, dTIMS and dMAP.

dROAD is a database management system designed exclusively to integrate roadway data. dTIMS is a pavement management analysis system which analyzes the life cycle cost for various treatments on each road section and performs optimization to select the best. dMAP is an automated mapping system which allows the data in the database to be depicted and accessed through an electronic map. The hallmark of all three of these systems is their flexibility. Typically, they can be configured to handle the pavement management system needs of any road department.

The project began when the consultant met with SDDOT staff and developed a workplan. Following this, the consultant gathered and reviewed SDDOT's literature which included documentation of existing systems. The consultant also performed a TRIS literature search to find information from other agencies which may help. Appendix A lists the results of this TRIS search.

After this investigation, it became apparent to the consultant that SDDOT did not have historical data. The RES file: (a) required too much effort to extract data from, (b) only had the most current values of that data, and (c) contained distress data whose reliability was unknown. The Planning File had current and historical data, but (a) the historical data turned out to be old copies of the file saved on tape with no integrity from year to year, (b) the long sections meant characteristics were not always homogeneous throughout the length, and (c) did not have distress data.

At this point, the focus of the project switched. Rather than gathering and analyzing hard historical data, developing performance curves and verifying them with expert opinion, the consultant now had to develop the performance curves using only expert opinion. Many DOT's develop models through expert opinion, but, not many wrote about how they did it.

SDDOT formed an PMS Advisory Team and called them to a meeting. The PMS Advisory Team consisted of experienced engineers from all parts of the Department. The purpose of the meeting was to help the consultant understand why pavements fail in South Dakota, why the department fixes pavements, and what treatments were employed to do the fixes. The consultant used this information to develop a set of condition indexes which were unique to SDDOT. While developing these condition indexes, the consultant also relied heavily on experience from other projects and the distress identification manual published by the Strategic Highway Research Program (SHRP).

Following this, the consultant designed a questionnaire to gather: (a) performance data about SDDOT's condition indexes, and (b) data regarding how these indexes were used to trigger treatments. After two attempts, each member of the PMS Advisory Team completed a questionnaire and returned it to the consultant. The consultant then summarized the data from these questionnaires and developed a set of performance curves and trigger mechanisms.

At the same time the consultant was developing the above analysis parameters, two other tasks were being completed, (1) software set up and (2) distress data collection.

With respect to software setup, the consultant obtained data files from several of SDDOT's existing systems. Then, the consultant designed a database structure, set up the database software, and loaded the data. After several iterations, the database was finally loaded. Several custom programs were developed to help format the data so it could be imported into the software. In addition, the consultant began formulating a design for the analysis software. And, following the development of the other parts of the project, this software was also set up and loaded. Finally, the mapping software was set up by obtaining an electronic map from SDDOT's Intergraph system. This map was prepared and connected to the roads in the database.

With respect to the distress data collection, the consultant recommended that SDDOT collect the data to support the condition indexes derived from the PMS Advisory Team. In an effort to demonstrate the system's capability, SDDOT agreed to perform this survey on all Interstates and on one non-interstate. SDDOT made an addendum to the contract so the consultant could collect this data. The consultant hired a subcontractor who performed the survey. Then, the consultant entered the data into the database.

After the database software was set up, the consultant brought it to the department and had a training session which lasted about a week. As well, after the analysis and mapping software was set up, the consultant held another week long training session.

In the end, the consultant provided SDDOT with the following deliverables:

1) An interim report describing the questionnaire used to gather the expert opinion.
2) An interim report describing the data collection survey required to collect the distress data required by the recommended system.
3) A Final Report summarizing the project which includes a description of the findings, such as the set of performance curves, and all the recommendations related to pavement management systems, procedures and policies in the department.
4) A database management system configured to store all current and future relevant and reliable pavement management historical data in SDDOT,

and, capable of being modified to add any more data as it becomes available.

5) A complete user manual and technical guide for the above software.

6) A set of training videos for the above software.

7) A pavement management analysis system configured to analyze the future needs of all road sections in SDDOT which have distress data, and, capable of being modified to accommodate changes to any models as necessary.

8) A complete user manual and technical guide for the above software.

9) An automated mapping system configured to represent any characteristics of any and all roads in South Dakota in different colors, and, capable of allowing the user to view the data for any road by selecting it from the map.

10) A complete user manual and technical guide for the above software.

The remainder of this report elaborates on all of the above tasks.

1.5 Report Layout

This report has been organized so each chapter represents one task in the project. Consequently, the respective task described in the RFP is repeated in italics as the first paragraph following the heading of each chapter.

Also, Chapter 0,

Configuring the Software, may seem repetitive in places. The reason for this is that the consultant tried to write that chapter as a stand-alone reference to the software. The preceding chapters explain all the engineering that went into designing and developing the models for the SDDOT pavement management system. Chapter 0 then focuses on how the software was set up to accommodate these models. This will allow anyone making future modifications to the software to get immediate and direct reference, without having to sift through the entire report to get the information.

Finally, Table 1 is provided to help the reader visualize not only how the report corresponds to the project tasks, but, how the tasks correspond to the project objectives. Each row in Table 1 shows one of the tasks. The columns show: (a) which chapter discusses the task, and (b) the objectives the project was intended to achieve. A dot in a cell indicates that the task helped achieve the objective.

Task	Chapter in this report explaining task	Objective 1 Develop Historical Database	Objective 2 Develop Fundimental PMS Components	Objective 3 Provide Operational Software	Objective 4 Provide Recommen dations to operate System
1. Conduct inception meeting	Chapter 2	•	•	•	•
2. Review literature	Chapter 3	•	•	•	•
3. Review SDDOT documentation and systems	Chapter 4	•	•	•	•
4. Develop performance curves	Chapter 5		•		
5. Develop treatments and triggers	Chapter 6		•		
6. Develop recommendations	Chapter 12	•	•	•	•
7. Prepare interem report	Chapter 7	•	•	•	•
8. Implement pilot distress survey	Chapter 8			•	•
9. Install and configure software	Chapter 9			•	
10. Provide training and documentation	Chapter 10			•	
11. Submit Final Report	N/A	•	•	•	•
12. Make executive presentation	Chapter 11				•

Table 1: Project tasks, where they are discussed in this report, and the objectives they help achieve.

2. Conduct Inception Meeting

Meet with the project's technical panel to review project scope and work plan.

The first task the consultant performed was a project inception meeting. This two day meeting was held in November, 1993. The main purpose of the meeting was to review the scope of the work and to develop a work plan.

The meeting was chaired by the consultant and began by him outlining the software (dROAD and dTIMS) and the data required to make these systems work. The discussion made the consultant aware that the main source of raw roadway related data in SDDOT is the database for a system called **RES** (**R**oadway **E**nvironmental **S**ubsystem). The consultant also became aware of data contained in the Planning File and the PCI data file. SDDOT agreed to provide the consultant with information relating to these three systems.

More specific discussion about these systems made the consultant aware of the fact that there was essentially no historical road condition or repair data available in SDDOT in electronic format. This realization caused the nature of task 4 (develop performance curves) and task 5 (develop treatments and triggers) to change drastically. The change came about because originally both the consultant and the SDDOT PMS Task Force thought the two tasks would consist of: (a) a statistical computer exercise involving historical data, and (b) a review and verification of the results by an panel of experts. In the absence of historical data, however, the nature of the tasks had to be changed to focus exclusively on obtaining and evaluating expert opinion. As a result, the consultant asked that the PMS Task Force assemble a group of engineers who was to supply the necessary expert opinion. This group is referred to throughout this report as the PMS Advisory Team. Later, the report elaborates on what the PMS Advisory Team did to assist in developing the required PMS models.

During the meeting, it also became apparent that the prime motivater behind this project was PCC pavements in South Dakota. The issue was not so much that these pavements were a problem, rather, it was that they were all getting old and would become a problem in the near future. The PMS Task Force expressed that they saw the enhanced PMS as providing some help with this impending problem.

The final product of this inception meeting was a project work plan including a schedule of meetings, and a list of material that SDDOT was to provide the consultant. Throughout the project, the work plan and original schedule was maintained fairly well. The three exceptions were: (a) a misunderstanding regarding how to answer the expert opinion questionnaire forced a supplementary meeting and a slight delay (the consultant eventually recovered from this delay and did not require a contract extension), (b) the contract was amended to add an additional task to collect distress data causing a two month extension, and (c) SDDOT asked for a substantial reorganization of the final report causing the consultant to request a further two week extension.

3. Review Literature

Review literature, including other states' experience, pertinent to pavement management art.

3.1 General Literature

Appendix A lists the results of a TRIS search the consultant performed on pavement management. The consultant was specifically using this TRIS search to find new innovative ways to obtain expert opinions on performance curves and trigger limits; a topic which would be valuable to this project. Since none of the literature pertained directly to this topic, the consultant did not find anything particularly new or relevant. The list is included in Appendix A so that readers interested in pavement management systems may find some useful papers on the topic.

The list of references at the end of the body of this report are specifically related to this project. Each reference is identified throughout the report with the particular topic or citation it pertains to.

3.2 Other Agency's Experiences

Throughout the project the consultant relied heavily on experience gained from numerous other pavement management implementation projects. Although these other projects are not specifically referenced in this report, undoubtedly the experience gained has had some influence. The implementations include installing pavement management systems in the following states, provinces and foreign countries: Ontario, Saskatchewan, North Dakota, Utah, Washington, West Virginia, Rhode Island, Louisiana, Michigan, Arkansas, Indiana, Switzerland, Botswana, South Africa, India, Indonesia, Thailand, and Australia.

In general, all of these implementations required the consultant to load data similar to that he assembled and loaded in this project, and to develop pavement management models similar to those developed in this project. Therefore, since this project required the use of expert opinion to develop the models, the consultant included his expert opinion as required to develop the deliverables in the project.

3.3 ISTEA Requirements

As part of this task (literature review), the consultant examined the ISTEA legislation[1]. Pronounced as *ice tea* , the acronym ISTEA stands for Intermodel Surface Transportation Efficiency Act. The part of this legislation which defines the requirements for a PMS on National Highway System (NHS) roads is paragraph P500.207 PMS Components. In the following discussion, the consultant repeats (in bold lettering) each subparagraph of 500.207 which relates to NHS roads. Then, immediately following each citation, the consultant presents his understanding of it. It is important that all agencies, including SDDOT, evaluate their own understanding of paragraph 500.207, and what they want to do to about each requirement[2].

Some of the remarks made below make reference to systems of both the consultant and SDDOT which may not have been discussed in this report yet. The interested reader is therefore requested to search forward in later sections of this report to find their explanations.

P500.207 PMS Components

(a) The PMS for the National Highway System (NHS) shall, as a minimum consist of the following components

(1) Data collection and management

(i) An inventory of physical pavement features including the number of lanes, length, width, surface type, functional classification, and shoulder information.

This is a standard minimum road inventory. Most configurations of dTIMS require some or all of it. The raw values can be managed in dROAD (the recommended PMS historical database).

(ii) A history of project dates and types of construction, reconstruction, rehabilitation, and preventative maintenance.

This is much more difficult to capture and manage. Although most PMS's require some knowledge of age and structure, this kind of information is usually derived before hand from a historical database similar to the one recommended by this subparagraph. dTIMS does not require this raw data, however, it does require the summary data like age and structure. This type of detailed data can be kept in dROAD, summarized, and supplied to dTIMS regularly.

(iii) Condition surveys that include ride, distress, rutting, and surface friction.

These surveys are standard to road condition evaluation. The questions to be answered for each survey are: 'What should be collected?', 'How should it be collected?', 'How much of the network should be covered?', 'How often should it be collected?', and 'How should the correctness of the collected data be verified?'. Answering these questions requires a trade-off between the cost of making bad decisions based on incorrect data versus the cost to collect accurate and precise data.

(iv) Traffic Information including volumes, classification, and load data.

The comment given above applies to this subparagraph as well.

(v) A database that links all data files related to the PMS. The database shall be the source of pavement related information reported to the FHWA for the HPMS in accordance with the HPMS Field Manual.

Building and maintaining a database such as the one described in this subparagraph would require *dynamic segmentation* capabilities. dROAD has such capabilities, and has been used elsewhere to manage HPMS data.

(2) Analysis, at a frequency established by the State consistent with its PMS objectives.

(i) A pavement condition analysis that includes ride, distress, rutting, and surface friction.

This subparagraph requires that the agency process the raw condition survey data into some form of individual and composite indexes. dROAD is capable of performing transformations like those required to do this. dTIMS makes use of the condition indexes in the analysis procedures for treatment triggering, costing, and evaluating effectiveness.

(ii) A pavement performance analysis that includes an estimate of present and predicted performance of specific pavement types and an estimate of the remaining service life of all pavements on the network.

This subparagraph requires the agency to develop deterioration curves for each of the condition indexes identified in the previous subparagraph. Ideally, these curves should be based on a statistical analysis of historical observations, and verification by expert opinion. This historical observation requires the work history database described in an earlier subparagraph as well as a condition history data. In the absence of either historical database, expert opinion can be used. dROAD has all the tools necessary to analyze historical data for performance trends. And, dTIMS has all the required flexibility to use these curves in a remaining service life analysis.

(iii) An investment analysis that includes:

(A) A network-level analysis that estimates total costs for present and projected conditions across the network.

This is a the first step to a standard life cycle cost analysis of pavement strategies. A strategy is defined as a series of treatments applied over a period of time. This period of time is called[3] the *treatment application period*. The calculation and inclusion of benefits is not mentioned in this subparagraph. Therefore, one could assume the costs referred to are the agency costs and not the vehicle operating costs. dTIMS has this capability.

(B) A project level analysis that determines investment strategies including a prioritized list of recommended preservation treatments that span single-year and multi-year periods using life-cycle cost analysis.

This is the second step to a standard life cycle cost analysis of pavement strategies. This subparagraph, however, requires the agency to calculate and compare the benefits for a strategy. The benefits are accrued over a period of time called[3] the *analysis period*. This subparagraph makes no reference to a network level comparison of the strategies such as would be achieved with optimization techniques. dTIMS has this capability as well.

(C) Appropriate horizons, as determined by the State, for these investment analyses.

This subparagraph allows the state to define its own *treatment application period* and *analysis period*.

(iv) For appropriate sections, an engineering analysis that includes the evaluation of design, construction, rehabilitation, materials, mix designs, and preventive maintenance as they relate to the performance of pavements.

When this subparagraph says 'appropriate sections', it appears to be referring to road sections from the upper levels of functional classification. This is a very detailed type of project level analysis which is seldom carried out for individual road sections belonging to the lower classifications. In any case, dTIMS can evaluate each of these different areas provided the proper performance curves are supplied for the various options in each area.

(3) Update. The PMS shall be evaluated annually, based on the agency's current policies, engineering criteria, practices, and experience, and updated as necessary.

This subparagraph reminds the agency that the PMS models must be kept as up to date and as accurate as possible, and they must reflect current policy.

4. Review SDDOT Information

Review information available from documentation, earlier SDDOT studies, and interviews to gain familiarity with SDDOT's existing pavement management system and information processing environment.

4.1 Introduction

During the first visit to SDDOT the consultant obtained the literature listed below and reviewed it thereafter. In fact, the consultant relied heavily on these documents throughout the entire project. The first two of these documents are so applicable to this project that the consultant provides a summary in the following two sections of this chapter.

1 <u>Information Systems Plan</u>[4]

This report is a long term strategic plan identifying the information systems needs in SDDOT.

2 <u>Historical Database Feasibility Study</u>[5]

This report is an excellent account of; (1) the current central database capabilities in SDDOT, (2) the need for a more historical-based database, (3) a review of other states' central databases, and (4) a conceptual design of a central historical based database.

3 **Database Item Analysis for Pavement Management Historical Database (internal document)**

A list of data items to be included in a pavement management historical database. This list shows for each data item: (a) its importance, (b) where it is collected, (c) the cost to collect it, and (d) the level of PMS where it is applicable.

4 **Flowchart describing data flows from RES to Planning File to Project Master File.**

This flowchart shows the source files used to create the Planning File, as well as, some of the places this file is used.

5 **Excerpt from the RES - MRM File**

This list gives an example of the layout of the RES-MRM file.

6 **Highway Mileage Reference Marker Policy Manual, March 1974, revised April 1991.**

This report presents the policy and procedures relating to the installation and maintenance of mileage reference markers on the state highway system.

7 **Planning File layouts**

This shows the contents and structure of the Planning File.

8 **<u>Highway Planning Update Instructions</u>, Number HR46JS02, (description of each field in the Planning File)**

A set of instructions for adding or altering user coded data in the Planning File. It also gives a more detailed description of each data item in the Planning File.

9 **List of codes describing improvement types**

This list gives the codes and descriptions of the reconstruction and resurfacing treatments used in SDDOT.

10 **Description of Concrete and Asphalt distress codes**

Description of the codes used to describe the distresses which are collected during the Dynaflect survey.

11 Description of Pavement Serviceability Rating Formula

This collection of papers describe the formula used to calculate the Pavement Serviceability Rating (PSR).

12 Description of the Sufficiency Rating

Describes the sufficiency rating and some other related indicators used in the existing SDDOT pavement management process.

13 1993 Highway Needs Analysis and Project Analysis Report for State Administered Highways, 1993, SD DOT Planning Department.

Shows an example of the information presented in the above book.

14 Correspondence regarding pavement Deterioration Curves, 1980, between Glenn Kietzmann and Mark Hanson

Describes a PSR performance curve for concrete and bituminous pavements.

15 Enhancement of the Project Ranking Methodology

Describes the modification to the project ranking methodology.

16 RES: Roadway Feature Coding Manual

Gives the instructions to be followed when completing the SDDOT Roadway Features Input Data Sheets.

17 Distress Identification Excerpt from the <u>Distress Identification and Recording Manual</u>

Describes the survey procedure and the distresses for both concrete and flexible pavements.

18 PCC pavement Evaluation Form

A data collection form used for evaluating the condition of PCC pavements.

19 Pavement Evaluation Guide (Pictures)

A pictorial description of the distresses which are collected during the Dynaflect survey.

20 South Dakota Sufficiency Rating Process

Describes the sufficiency rating process used in the existing SDDOT pavement management process.

21 HR460200 Program Narrative (Reconstruction vs Resurfacing decision)

Describes the computer program used to make the reconstruction versus resurfacing improvement type decisions.

22 Highway Accomplishment Report (program description and file layout)

Describes the computer program used to generate the highway accomplishment reports.

23 Annual Sufficiency Order of Work

Describes the order in which the computer programs are executed to produce the annual sufficiency rating values.

24 DRS File Definition

Describes the data structure of the RES-DRS file.

25 Standard Bid Item Report

Describes the SBI booklet and the work sheets which show how the costs for various improvements were developed.

4.2 SDDOT Literature

4.2.1 Information Systems Plan

The Information Systems Plan[4] report gives a rationalized approach to Information Systems at SDDOT. This report specifically mentions a pavement management historical database, an enhanced pavement management system, and a geographic information system. These three systems relate to this project in some way or another.

The report says that the pavement management historical database would provide for the creation of a historical database which would include RES data, soil properties data, pit information, lane identification data, material test results, and additional design, as-built and construction information. The report stated that the development of this historical database was paramount because developing it would "prevent the further loss of historical data".

The report said that the enhanced pavement management system project would add "additional components that would improve the Department's capability to analyze pavements and produce a more comprehensive program, addressing future reconstruction/rehabilitation strategies and cash flows associated with those strategies."

Finally, the report endorsed the development of a Geographical Information System (GIS) for the department. The report said that: "Ties to existing computerized databases provided by a GIS will allow powerful querying of data not allowed by the current systems." The report also said that "Automated Mapping will provide significant cost savings over current mapping methods."

According to the report, the systems it mentioned appear to satisfy the objectives for this project. Indeed, the deliverables of this project are a historical database, an enhanced pavement management analysis system, and an automated mapping system. It is important, however, to distinguish these deliverables from the systems in the report. Under no circumstances should anyone assume that the deliverables of this project are the three systems mentioned in the report. On one hand, for example, the scope of this project is specifically geared toward satisfying only the pavement management needs of SDDOT. On the other hand, two of the three systems mentioned in the report, the historical database and the GIS, satisfy a much broader scope than just pavement management.

4.2.2 Historical Database Feasibility Study

The Historical Database Feasibility Study[5] report is an excellent account of; (1) the current central database capabilities in SDDOT, (2) the need for a more historically based database, (3) a review of other states central databases, and (4) a conceptual design of a central historical based database. Anyone in SDDOT needing information regarding highway databases should definitely start with this report.

It is worth noting that the scope of the database described in this reference is much broader than the scope of the database delivered under this project. In no way should the two be confused. However, even though the scope of the database described in this reference is much broader, it is important to point out that the reference did not highlight the absolute necessity that SDDOT have a person to administer this database. Even with the modest scope of the database delivered for this project, the consultant absolutely recommends that a position called PMS System Administrator be regarded as essential, and, that SDDOT make such provisions.

4.2.3 Priority Ranking Number

The following is a review of the references relating to the project priority ranking process used at SDDOT.

SDDOT has developed and uses a project priority ranking process to identify candidate projects for resurfacing. The earlier version of the process combined eleven items to produce a composite ranking index for flexible pavements and twelve items to produce a composite ranking index for rigid pavement.

That process was modified somewhat by: (a) adding two more items for flexible pavements, and (b) changing the relative element weighting values of various items for both flexible and rigid pavements. Table 2 on page 36 shows the original list and the enhanced list of items for flexible pavement in a spread sheet form. The two pie charts below the spread sheet show the relative impact of each item on the composite index before and after the enhancement to the prioritizing index. Clearly, the relative weightings for truck traffic, surface maintenance, and roadway strength were increased, while surface condition, remaining life, and rideability were reduced somewhat.

The most important characteristic of a prioritizing index is how sensitive it is to change. To get an idea of this sensitivity one could examine what factors influence the range in possible values of the index. Theoretically, the SDDOT's prioritizing index could range from zero to ten. A zero would occur if all the individual items were very bad with each one having a zero. This situation is very unlikely. On the other hand, a ten would occur if all the individual items were very good with each item having a ten; another unlikely occurrence. In fact, the numerical value for many of the individual items probably changes very little over time. It is most likely that on a single pavement section only a very few items change markedly over time. If one also considers the fact that the composite effect of this large a number of items most likely reduces the functional range of the index from a high value in the eight's to a low value in the three's, one is left realizing that the priority ranking number has a range of about five points. The consequence of having this small a range to distinguish between all of the paving projects is that there would be an even smaller range for the very critical list of candidate projects. From this analysis, the consultant suspected that the difference in index values for the list of critical projects in SDDOT would be half a point at best. This suspicion was confirmed through discussion with SDDOT personnel.

To provide better insight into which items might have the most impact on identifying the critical list of candidate projects, the consultant performed a fairly simple sensitivity analysis. To do this the consultant envisioned a typical project that would represent an average principal arterial road section in South Dakota. The road section consisted of 4 in. of ACP on 12 in. of gravel, with an average daily traffic of 2,000 vehicles per day of which 5% are classed as trucks. This project was last overlaid 8 years ago and was half way through its expected service life. There were no unusual problems with the pavement. It typically had moderate thermal cracking, was experiencing some rutting, and had some patching. These conditions gave average condition values and resulting importance values as shown in Table 2 on page 38.

The fairly average condition of this pavement segment resulted in a priority ranking number of "6.70". Given these conditions, the consultant then estimated the changes that would probably occur in each of the individual items over the next 6 years before that project was identified for rehabilitation. Clearly the changes were over exaggerated, most likely only a few of the characteristics would have changed to the extent shown, with most of them changing very little. However, the consultant treated each item considering its maximum potential to change.

The relative absolute value of the ranking elements for flexible pavements are shown on the pie chart on the right of Table 3. In this case rideability, remaining life, surface condition, roadway strength and drainage adequacy make up almost three quarters of the total index. The elements that potentially could be affected with time on an average project are shown on the pie chart on the left of Table 3. Here only remaining life, surface condition, rideability and traffic make up almost three quarters of the total index.

This analysis indicates that rideability, remaining life, surface conditions, and traffic are still the primary factors that contribute to identifying the critical resurfacing timing for a typical flexible pavement project. Surface maintenance and roadway strength are secondary factors that may have some effect on the timing. Traffic was included in the primary list because it is a significant factor in the values for strength, drainage, surface condition, and remaining life as well as having its own value in two categories of traffic. Since remaining life is determined from an effective PSR value which is computed from ride and surface conditions the primary items really end up consisting of only ride, traffic and surface condition in that order.

Though the composite index includes many elements that are of concern when selecting a candidate project for rehabilitation, the inclusion of such a large list makes the index fairly insensitive to typical changes in many of those items. It effectively compresses the index value down to a very narrow scale. This narrow scale most likely makes it very difficult to determine the value of any particular project relative to the rest of the projects on the list. In addition, the narrow scale does not provide any particular knowledge of what may be the predominate problem on the project that needs correction. This information is necessary to help provide a better estimate of the likely scope of the project in the project selection procedure.

It appears that ride may make up a large part of the relative change in the prioritizing index value for most flexible pavements over time. Although everyone agrees that a smooth ride is the ultimate service a pavement provides those who travel on it, roughness is nevertheless a very inefficient indicator of pavement rehabilitation timing. This is so because in most cases roughness identifies the candidate project too late in the deterioration cycle to use earlier and more cost effective treatments.

Considering all of these issues there is little doubt why one of the early tasks in this research project was to develop performance curves for flexible and rigid pavements. These curves were to be expressed in terms of individual and composite pavement condition indexes. The individual pavement condition indexes will provide earlier and more efficient identification of projects. This will benefit by helping identify earlier, less costly, rehabilitation treatments, with better identification of project scope in the planning processes.

Table 2: Relative sensitivity analysis showing both the original and the enhanced priority ranking number.

Table 3: Relative sensitivity of priority ranking for a typical road section.

4.3 Existing Data Systems

4.3.1 Introduction

The primary source of data for the project was: (a) the RES database, (b) the Planning File, and (c) the PCI data files. This section of the report explains the results of the consultant reviewing each of these data sources. Chapter 0

Configuring the Software, gives an account of the exact data extracted from these files and the procedures used to load it into dROAD.

4.3.2 The RES Database

The Historical Database Feasibility Study[5] refers to the RES database as SDDOT's 'current central database'. According to the general terminology of highway information professionals, the implied meaning of the term "central database" in a highway agency is: a head-office database which automatically integrates all roadway data and gives users easy query access to it. In this sense, the term central database does not describe RES very well.

RES is a collection of nine *loosely* related database files. The term *loosely* means that data integrity and integration is not treated as paramount between the files. In fact, any change to a location reference address in one file is not automatically cascaded through any of the other files for the current year. According to the consultant's study, these address changes must be carried out on each file individually and are only guaranteed by human administration. Furthermore, any address change in one year's RES database is never cascaded back through the historical copies of the RES database; if indeed these historical copies even exist (more on this later). Therefore, if the term 'integrated' is used to describe the RES files, the term integrated is not being used properly.

The term "easy query access" is equally inapplicable to RES. Most access to RES must be done in a batch environment through "user" written custom programs. The Historical Database Feasibility Study makes the following statement in this regard:

> *If a user has a requirement for a data operation that is outside the scope of the set of pre-written computer programs for a particular RES file, a request for writing a new computer program is sent to the data services department. This process historically requires a substantial amount of turn-around time.*[5]

The following list shows the database files which are part of RES. This project only required some of the data from these files. Later in the report the consultant lists the specific instances where data was extracted from RES to be loaded into dROAD. The contents and format of the extracted files is listed later when the specific file is mentioned.

1 Traffic Inventory;
2 Roadway Features Inventory;
3 Intersection Inventory;
4 Sufficiency Inventory;
5 Dynaflect, Roughometer, and Pavement Friction (DRS) Inventories;
6 Maintenance Cost Inventory;
7 Bridge System Inventory;
8 Railroad Crossing Inventory;
9 Mileage Reference Marker Inventory.

From conversation with appropriate personnel, the consultant learned that each year the computer services department makes a tape copy of RES and places the tape in storage. Then, throughout the next year, all new data entered into RES overwrites the data from the previous year. This process leads to the Historical Database Feasibility Study report making the following statement:

> *The current central database that is used in the management of South Dakota's pavement system is nonhistorical and primarily reflects the current status of South Dakota's highway system.*

This statement confirmed earlier discussions regarding the fact that there was no historical data in SDDOT from which to develop performance curves. Having established this conclusively, the consultant was faced with a dilemma. On one hand, task number four of the contract specifically requested the consultant to "use historical data". On the other hand, access to historical data was extremely difficult. To satisfy this request, the consultant would have had to: (1) obtain the old RES tapes, (2) dump them on-line, (3) find and resolve all the cumulative historical location reference address changes, and (4) integrate the data to a meaningful format. The estimated resources required to do this was more than ten-fold greater than the resources available in the entire project. Indeed, even when the consultant tried to find these historical tapes, they were impossible to track down.

In any case, data is stored in the RES databases as either point or section data. The term *point data* usually refers to the fact that the object being described occurs at a point along the road[6], like a traffic accident or a sign for instance. In the case of the Roadway Features Inventory Master File of RES, however, the term *point data* also means that the data described at the point is valid until another point is encountered on the same road. In other words, data such as pavement width exists in RES as point data. Writing programs to extract, summarize or integrate point data is very difficult.

The MRM (Mileage Reference Marker) file of RES is a point data file. It describes the location and number for each MRM post in the state. The location of each MRM is given in terms of the mile point[7] which is the distance from the beginning of the road. Although assumed by many to be so, in some cases the number on the MRM is not the same as the distance from the beginning of the road. In any case, whenever the two numbers are not the same, dROAD requires a table showing the locations (i.e., the mileage) for every marker. The MRM file provides this information precisely.

4.3.3 The Planning File

SDDOT has at least one set of programs which go through all the RES data files and performs *dynamic segmentation* on them. Dynamic segmentation is a term used to describe the process of transferring data which describes one set of sections into data which describes another set of sections[6]. The end result of running this set of programs is a file commonly referred to in SDDOT as the Planning File.

The Planning File consists of data describing a set of planning sections. The data is composed of more than one hundred individual fields describing an exhaustive collection of characteristics. The headings used in the Planning File within which these data fields reside are shown in Table 4. This data was originally assumed to be sufficient to supply all the information required for the pavement management system analysis. This assumption would later prove to be incorrect, however.

Part	Heading
A.	Identification
B.	Geometrics
C.	Traffic
D.	Structural
E.	Railroad Crossings
F.	Structures
G.	Deficiency Analysis
H.	Improvement Description
I.	Improvement Costs
J.	Average Cost Per Mile Per Year
K.	Project Description

Table 4: Headings showing the kind of data contained in the Planning File.

To understand the Planning File requires discussion about the nature of the road sections it describes. The limits of the sections in the Planning File are remarkably stable over time. Unfortunately, however, section limit stability is bad in a historical database. The location of the section limits in the Planning File are influenced more by the location of the original construction projects than anything else. Figure 1 demonstrates this point. The top line shown in Figure 1 is a road with two Planning File sections. The line below it shows how an overlay covers the entire length of the first Planning File section and a part of the next. The two lines below these show two options for how the Planning File sections should have been changed. Unfortunately, in SDDOT the Planning File sections were not changed.

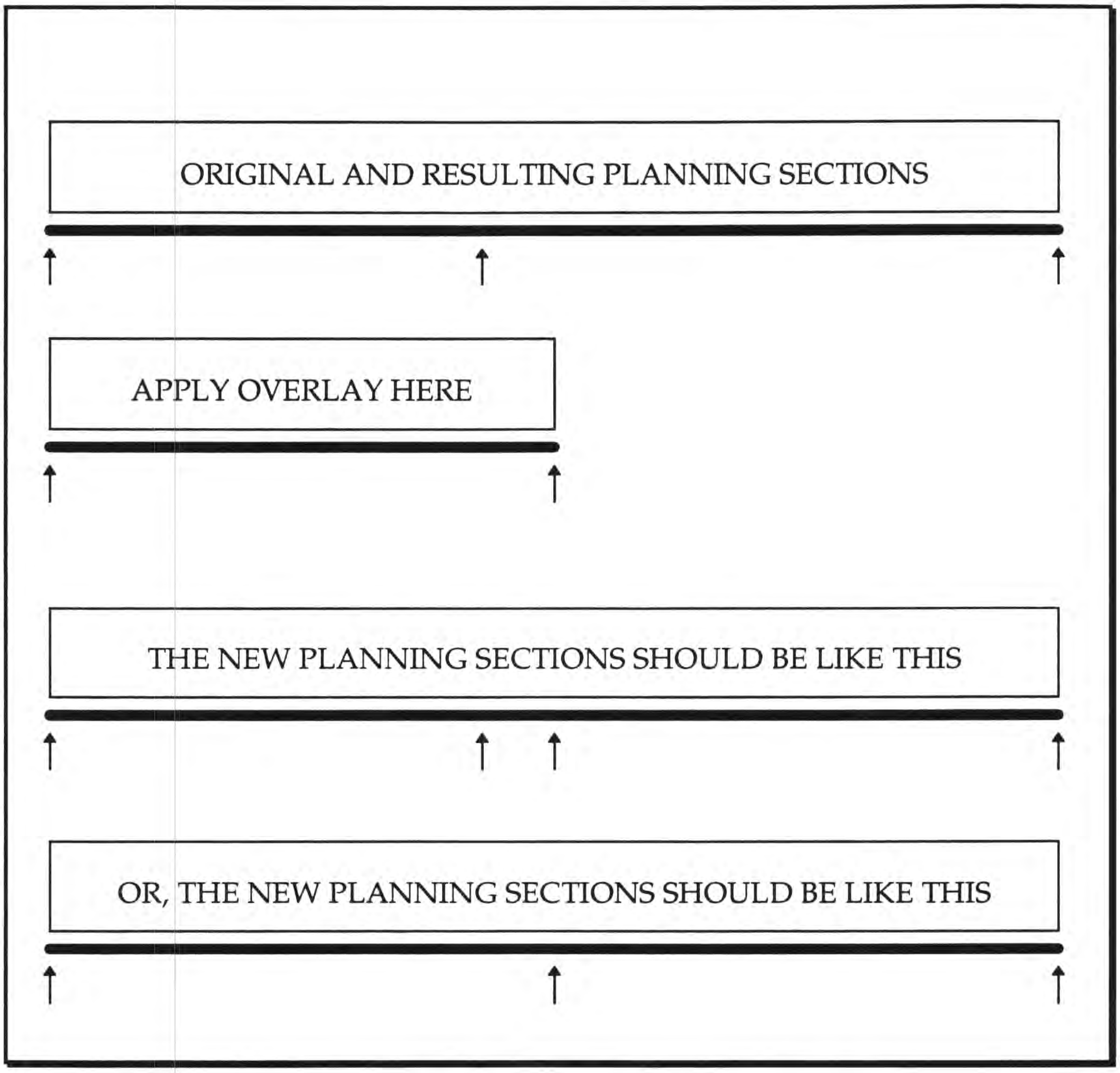

Figure 1: Planning File section locations seldom change, even after an overlay.

This means that over a period of time, the sections in the Planning File have come to be non-homogeneous. For example, consider Portland cement concrete (PCC) as the original pavement type of the top road in Figure 1. The overlay would cause the PCC pavement type to change to asphalt on concrete (AonC). If the Planning File section limits were not changed, then the second section's pavement type would still be PCC because that's the pavement type for the majority of its length.

Later, the consultant will show that the pavement management models were developed for different pavement types. The stability of the Planning File sections became apparent when collecting data for the development of those models. An independently collected set of distress data showed pavement types which were inconsistent to those listed in the Planning File. This ended up causing a problem which had to be corrected later in the project. Therefore, the problem and its solution will be discussed later in this report.

Both the consultant and SDDOT originally decided that the majority of data required for pavement management would come from the Planning File. Without prior knowledge of the size or significance of the pavement type description problem in the Planning File, this conclusion made a great deal of sense at the time. The only other source of pavement management data is RES. To get pavement management data from RES by road section would have required the SDDOT computer department to build a complicated set of computer programs. According to a citation made earlier from the historical database feasibility study report, this would have taken a great deal of time. After all, the set of programs used to generate the Planning File is considerable in size, and requires significant maintenance.

Now, it appears that the pavement management data should come from RES. However, since the problem was discovered so late, for the purposes of this project most of the required data was acquired from the Planning File and was supplemented with the distress survey data and data from other internal sources (see section 4.3.5 below).

4.3.4 The PCI Database

In 1990 and again in 1993, SDDOT did a special condition survey on selected interstate highways. This survey gathered the distress data required to calculate the Pavement Condition Index (PCI) on these sections. The data from these surveys was placed on two computer files located in the research department of SDDOT. The consultant obtained these files and loaded them into dROAD (the database) for completeness.

4.3.5 Other Systems and Data Sources

In addition to the above data and systems in SDDOT, the consultant obtained data from two other sources. First, as already mentioned above, the consultant obtained data from the pilot distress survey. The data in these files was collected during the pilot study of the new distress data survey procedure. The only place this data exists in SDDOT is in dROAD. Second, as also mentioned earlier, the consultant required more precise pavement type data. A file containing the pavement type by location was provided by the data services department on a verbal request. This file contained data for the pilot roads only.

4.4 Existing Data Collection

4.4.1 Location Reference

During the investigation stage of the project, the consultant became aware that the location reference method used by SDDOT was the mile post method. The posts used in this location reference method are called MRM's (Mileage Reference Markers). A location reference method involving posts or fixed reference points is preferable to other methods. However, others have shown that problems result if the address of those posts ever changes[7].

One of the first files the consultant required to load into dROAD was the MRM file. The MRM file is the foundation for data integration (the importance of data integration was pointed out earlier). During a meeting to discuss this data, the consultant had to decide between accepting the data in the file as it was, or, waiting until an update survey was complete to get the most up to date addresses for the MRM posts. Both choices below have significant consequences.

1. If the consultant loaded the existing MRM data, all existing data would relate well, and any data collected according to the new addresses would not relate well. dROAD is currently loaded with this data.
2. If the consultant waited for the new MRM data, all existing files would not relate well, and any data collected according to the new addresses would relate well.

SDDOT manages its location reference method extremely well. Unfortunately, the location reference method is an outdoor process. The indoor process is called a location reference system. SDDOT's location reference system lacks the necessary coordination to ensure address changes are cascaded through all files simultaneously. The difference between location reference *method* and location reference *system* must be appreciated and accomodated[7]. Doing this is not only recommended, it is essential to maintain a historical database.

4.4.2 Pavement Deflection

SDDOT used a Dynaflect to collect deflection data for many years. This deflection data provided an indication of "Roadway Strength" in the existing pavement management system. It was collected at each MRM throughout the entire highway network. The strength of the highway was indicated by taking the maximum deflection from the Dynaflect readings and subtracting it from a value of five. Recently, SDDOT switched to a Falling Weight Deflectometer (FWD) to collect this deflection data. The procedure still involves doing a test at each MRM. To make the FWD data compatible with the older Dynaflect data, the FWD readings have been correlated to the older Dynaflect readings.

A value of five (5/1000 inch, or 5 mils) is a fairly high deflection reading from a Dynaflect. Values that high generally indicate a weak pavement structure. Subtracting the maximum deflection from five means that the resulting Roadway Strength index ranges on a scale from 0 to 5, where the higher the index the stronger the roadway. Earlier in this report the project ranking methodology showed the Roadway Strength index provided as much as 10% of the priority ranking number for any road section (see section 4.2.3 Priority Ranking Number).

This approach to calculating roadway strength is quite simple and easy to understand. However, it is also very limited in characterizing the stiffness of the pavement; let alone distinguishing between the stiffness of the pavement versus the stiffness of the subgrade. Most of the Dynaflect analysis processes were developed over 20 years ago and most do not relate well to current design methodology. In addition, it is doubtful whether SDDOT can even use the procedures developed for Dynaflect output to analyze the output from an FWD.

There have been many attempts to correlate FWD and Dynaflect readings, but, they have been unsuccessful over a reasonable range of pavement and subgrade conditions. The Dynaflect applies a relatively light vibrating load to the pavement while the FWD applies a much heavier impact load similar to a truck tire load. Since most subgrade soils and granular surfacing materials are stress sensitive they respond quite differently to these variable loading conditions. Considering these primary differences, the only possibility of getting a reasonable correlation between the readings from these two deflection test methods would be at locations where there are no differences between the pavement sections and the subgrade soils. If this were the case, there would also be no reason to perform the deflection measurements.

There have been quite a few deflection basin parameters developed to help interpret the deflection basin data from various deflection measuring devices. A list of the more common deflection basin parameters is shown in Table 5.

Parameter	Formula	Measuring Device
Maximum deflection	D_0	Benkelman Beam, Lacroux deflectometer, FWD
Radius of curvature	$R = r^2 / (2D_0(D_0/D_r - 1))$ where $r = 127$ mm	Curvaturemeter
Spreadability	$S = [(\{D_0 + D_1 + D_2 + D_3\}/5)100]/D_0$ $D_1 \ldots D_3$ spaced at 305 mm	Dynaflect
Area	$A = 6[1 + 2(D_1/D_0) + 2(D_2/D_0) + D_3/D_0]$	FWD
Shape factors	$F1 = (D_0 - D_2) / D_1$ $F2 = (D_1 - D_3) / D_1$	FWD
Surface curvature index	$SCI = D_0 - D_r$ where $r = 305$ mm, or $r = 500$ mm	Benkelman Beam Road Rater FWD
Base curvature index	$BCI = D_{610} - D_{915}$	Road Rater
Base damage index	$BDI = D_{305} - D_{610}$	Road Rater
Deflection ratio	$Q_r = D_r/D_0$, where $D_r = D_0/2$	FWD
Bending index	$BI = D/a$, where a = deflection basin	Benkelman Beam
Slope deflection	$SD = \tan^{-1}(D_0 - D_r) / r$, where $r = 610$ mm	Benkelman Beam

Table 5: Summary of deflection basin parameters

All of the parameters in Table 5 tend to focus on the following four major areas:

1. Plate or center load deflection which represents the total deflection of the pavement. This was obviously the first deflection parameter that came from the Benkelman Beam. It has been used for many years as the primary input for several overlay design procedures.

2. The slope or deflection differences close to the load such as Radius of Curvature (R), Shape Factor (F_1), and Surface Curvature Index (SCI). These parameters tend to reflect the relative stiffness of the base or lower regions of the pavement section.

3. The slopes of deflection differences in the middle of the basin about 11.8 in. (300 mm) to 35.4 in (900 mm) from the center of the load. These parameters tend to reflect the relative stiffness of the base or lower regions of the pavement section.

4. The deflections toward the end of the basin. Deflections in this region relate very well to the stiffness of the subgrade below the pavement surfacing.

The issue here is which deflection parameters will provide the most meaningful information to include in a pavement management system. Most of the parameters described came from pavement design analysis. Many of the parameters tend to superimpose the effects of both the pavement and subgrade stiffness. The deflection parameter that would be most useful for pavement management processes would be one that quantified the structural condition of the pavement separate from the stiffness of the subgrade. It would also be helpful to have it be in terms that related easily to the structural needs of the specific highway. Of all the parameters listed in the table, the Area parameter provides the best interpretation of the structural stiffness of the pavement section separate from the stiffness of the subgrade. Unfortunately, this parameter does not relate easily to the structural needs of any specific highway.

Because of the limitations of the various parameters discussed above, SDDOT would be wise to investigate the new parameter that comes from AASHTO[8]. The major change in this 1993 AASHTO Guide is revisions in the procedures for the design of pavement overlay thickness'. The most significant of these changes was the further development of the effective modulus of the pavement (E_p) that could be determined from deflection testing. A deflection based overlay design procedure was developed using the effective modulus of the existing pavement to estimate the effective structural number of the existing pavement using Equation 1.

$$SN_{eff} = 0.0045D \quad E_p$$

Equation 1: Effective Structural Number

where:

D	= total thickness of surface, base and subbase in inches.
E_p	= effective modulus of the pavement in psi.

The effective modulus of the pavement can be determined by an iterative process if the following are known: (i) the total thickness of the pavement (D), (ii) the maximum deflection D_0, (iii) the pavement temperature during the test, (iv) the subgrade resilient modulus M_R, and (v) the load P on the FWD plate. All of this information is available from the FWD tests and the construction history in the PMS.

The total thickness of the pavement (D) should be determined from past construction records. This data will eventually come from a historical database. In the mean time, however, it can also be estimated through expert opinion from the basic classification and pavement type.

The subgrade resilient modulus M_R can be estimated from the FWD data using Equation 2. This equation also comes from the AASHTO Guide.

$$M_R = P(1 - m^2)/(\ p\ )(dr)(r)$$

Equation 2: General equation for the subgrade resilient modulus

where

P	= applied load (lb.)
m	= Poisson's ratio
dr	= pavement surface deflection at r distance from center of load.
r	= distance from center of load to dr.

The distances to the deflection sensors on most FWDs used in the US are 0 in., 8 in., 12 in., 18 in., 24 in., 36 in., and 48 in.. The consultant recommends that the sensor used to estimate M_R should be as close to the stress bulb caused by the plate load as possible. In other words, SDDOT should use the 24 in. Sensor for thin flexible pavements and the 36 in. sensor for thick ACP pavements and ACP over PCC pavements.

Assuming that the Poisson's ratio for the average subgrade soil found in South Dakota is 0.45, the consultant recommends using Equation 3 or Equation 4 to estimate the M_R for each FWD test at each MP:

$$M_R = 0.01058(P/d_{2\,ft})$$

Equation 3: Subgrade resilient modulus for thin flexible pavements.

$$MR = 0.00705(P/d_{3\,ft})$$

Equation 4: Subgrade resilient modulus for thick pavements.

where:

P	= the FWD plate load (lb.)
$d_{2\,ft}$	= the deflection (mils) at 24 in.
$d_{3\,ft}$	= the deflection (mils) at 36 in.

To determine the effective pavement modulus E_p for each FWD site requires an iterative solution approach to Equation 5.

$$d_0 = \quad 1.5pa\ [1/(M_R(1+((D/a)(E_p/M_R)^{1/3})^2)^{1/2}) + (1-(1/(1 + (D/a)^2)^{1/2})/E_p)]$$

Equation 5: Deflection equation used to find the effective pavement modulus.

where

p	= contact pressure (psi) from plate load
a	= circular load radius which is 5.94 in. for most FWDs
D	= total thickness of all pavement layers,
M_R	= subgrade resilient modulus
E_p	= effective pavement modulus
d_0	= maximum deflection at center of plate adjusted for test pavement temperature.

The maximum deflection d_0 may be corrected for the pavement temperature at the time of the test using the charts in the AASHTO guide. Alternatively, Equation 6, Equation 7, or Equation 8 could be used for 4, 8, and 12 inch ACP, respectively. These equations were developed by the consultant from the AASHTO charts.

$$F4 = 1.43 - 0.00635T$$

Equation 6: 4 inch ACP maximum deflection temperature correction equation.

$$F8 = 1.65 - 0.00962T$$

Equation 7: 8 inch ACP maximum deflection temperature correction equation.

$$F12 = 1.78 - 0.01154T$$

Equation 8: 12 inch ACP maximum deflection temperature correction equation.

where:

F4,	= adjustment factor for 4 inch ACP
F8	= adjustment factor for 8 inch ACP
F12	= adjustment factor for 12 inch ACP
T	= pavement temperature at the time of the deflection test.

The iterative solution for E_p consists of estimating a value for E_p and solving for d_0. The d_0 calculated is then compared to the d_0 measured. The process is repeated until the calculated values for d_0 comes reasonably close to the measured d_0 which then provides a reasonable estimate of E_p. This value may be used by itself in the PMS or it can be used to estimate the effective structural number SN_{eff} for the FWD test section. The SN_{eff} value would probably be the easiest value to relate to. It could also provide some basic estimate of overlay thickness needs.

Assuming the paving materials in South Dakota are similar to those used in the AASHTO test track, SDDOT should expect SN values from their basic pavement types similar to those shown in Table 6. If SN values were obtained which were significantly lower than these values it would be a very good indication of structural deterioration either from fatigue cracking or stripping.

PAVEMENT TYPE	Range of SN
Thin ACP on weak base	2.2 to 2.5
Thin ACP on strong base	3.0 to 3.5
Thick ACP	4.0 to 5.5
Full Depth	4.0 to 5.0

Table 6: Typical SN values for South Dakota pavements.

For the time being, the consultant recommends that SDDOT use the resulting SN_{eff} values for general information only. If after some field review the SN_{eff} values look likely they reasonably represent the pavement stiffness, then, the values may be used as additional guidelines in the pavement treatment selection processes.

4.4.3 Pavement Condition

SDDOT has been conducting a pavement distress survey in conjunction with the deflection survey. The raters, who were also performing the deflection survey, were instructed to evaluate and record the distress of the pavement immediately adjacent to the MRM. It was assumed that this distress data was a reasonable representation of the distress on the piece of road from this MRM to the next, even though no statistical evidence was provided to support this assumption. The consultant searched for other work which would substantiate the assumption. And, although it appears to be common practice, no studies were found which showed how repeatable or reliable this data would be.[9,10,11,12]

4.5 Institutional Issues

The consultant reviewed SDDOT from a perspective of what is commonly called Institutional Issues. These issues represent the non-technical side of a pavement management system. The following discussion represents the consultant's observations, and precautions regarding them.

To discuss the basic issues regarding pavement management system implementation, it is important to keep in mind what a pavement management system is. The AASHTO Task force on pavement management systems (PMS) considered a large list of definitions as they began the development of the current AASHTO guidelines for pavement management systems[13]. After considerable deliberation they settled on the Federal Highway Administration's:

> *'A set of tools or methods that can assist decision makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in a serviceable condition.'*[13]

In addition, the task force provided a basic list of the elements and products that a pavement management system could include, which was:

1. An inventory of pavement in the network.
2. A database of information pertinent to past and current conditions of pavements.
3. Budget requirements needed to preserve the pavement network to acceptable levels of performance.
4. Methods of prioritizing expenditures.
5. A basis for communications of agency plans, both within the agency and to groups and organizations not an integral part of the agency, but who might be interested in such plans.

It should be emphasized here that this is not the definition nor products of a pavement management system that makes decisions. What is described is a ***Tool*** that provides technical information, analysis, and models to aid engineers and administrators in making more systematic and informed decisions in developing their Agency's pavement preservation program.

The basic technical features for a pavement management system are fairly straight forward. These technical capabilities are easily developed by most State Transportation Agencies who are willing to invest adequate funds and workforce to the process. SDDOT has made a continuing commitment over the years to the pavement management processes in their development and use of their own system. This commitment is demonstrated by this very pavement management research project. Indeed, the original RFP for this project correctly pointed out that SDDOT is in an enviable position because of the positive reputation their pavement management system has.

4.5.1 Hard Boundaries

The primary difficulty in full implementation of a pavement management system deals with the very nature of the both the data and the information. Data is raw facts, and information is the users interpretation of those facts[14]. Pavement management systems assemble data which is collected by many different departments in the agency. They also provide information to several departments who do not normally work together, such as Planning, Regions, Construction, Programming, Maintenance, Information Services, Design, Materials, etc[15]. In many agencies, these different departments, though sharing a common agency goal, often have competing individual department goals and authority.

In many agencies, these unique and separate department goals and areas of authority resulted in the formation of very hard boundaries throughout the agency. In agencies where these organizational boundaries have become quite hard, it is very difficult to implement a full functioning pavement management system. For example, those in individual organizations such as Design, Regions, Information Systems, etc. typically view the pavement management system, and the department in which it is based, as competing with their products or process and particularly their authority.

Agency wide corporate databases are a very good example of how conflicts arise. It is common to have an information systems project underway to produce a corporate database which integrates all pavement data together. In the mean time, however, the pavement management department needs to integrate road data to perform the pavement management analysis. It is not uncommon for the pavement management department to develop and manage their own database because they simply cannot afford to wait until the corporate database is completed. This often causes turmoil.

In the consultant's experience, these hard departmental boundaries are more the rule than the exception in large Transportation Agencies. Fortunately, the consultant has observed more communication across departmental boundaries in SDDOT than is evident in many other State DOTs.

4.5.2 Other Criteria

With the completion of this research project SDDOT will have a pavement management system that is technically complete. This system is capable of providing all of the standard analysis and model development needed to provide the most efficient pavement rehabilitation program information. It meets both the AASHTO Guidelines and the new FHWA requirements for pavement management systems. To be fully implemented, however, the pavement management system will also have to meet the following somewhat nontechnical criteria:

1. The PMS must have top level executive support (policy, funding, workforce);
2. The PMS must fit well with the operational workings of the agency, and;
3. The PMS must have broad organizational support within the agency.

4.5.3 Support from Executive Level

The first criteria is absolutely critical and is often mentioned in pavement management system implementation guidelines. The top executive level in the agency must support the use of the pavement management system as a highly effective tool to help develop the agency's pavement preservation program. There must be active commitment to the pavement management processes at this level to have a well defined policy as well as adequate funding and workforce to support the pavement management system. Without full executive level support, there is truly little that can be done to fully implement a pavement management system, or any management system for that matter.

4.5.4 Fitting into Agency

For the discussion regarding the second criteria, the consultant borrows heavily from the chapter on pavement management implementation that Jim Hall prepared for the NHI Advanced Course on Pavement Management Systems[16]. In that chapter, Mr. Hall described various aspects of implementation. He specifically described two areas that cover the semi-technical issue of fitting a pavement management system to the functional operation of an agency.

The first of these areas is making the pavement management system compatible with the way the agency develops its pavement preservation program. The operation of the pavement management system must reflect and serve the true nature of the Agency; be it centralized, decentralized or a blend of both. Most pavement management systems are developed assuming a centralized programming process. SDDOT has a fairly centralized procedure for selecting projects, and a decentralized approach to preparing the plans for the individual construction projects. That is why the pavement management system developed through this research project was developed with the clear intent to provide: (a) the optimum information needed for most efficient repair strategies on individual projects for network level decisions, and (b) the timing and scope of the projects to aid the Regions' project level needs and concerns.

The second of these semi-technical operational areas is the simple realization that the products of the pavement management system must be consistent with the organizational hierarchy of the Agency. The four primary functions in most large Agencies are **Policy, Planning, Programming** and **Project Management**. These functions are often represented as layers within the organization pyramid as shown in the following from Hall[16]:

Policy

Planning

Programming

Project Management

The amount of detailed data required at each of these levels is indicated by the shape of the pyramid. At the policy level the basic need is for network summaries, trends, and statistics. The more graphical the displays, the better. Here there is a clear preference, if not need, for the information to be displayed simply and graphically using pie charts, bar graphs, and mapping displays. At the project management level, much more project specific and detailed information is desired, so that detailed analysis and work plans can be developed. A moderate amount of detail somewhere between these two extremes is desired for the levels in the middle of the pyramid.

The outputs of the PMS must reflect the organizational hierarchy, and the level of need and detail that the particular output is serving.

4.5.5 Support from Departments

Developing and maintaining active support from the many and varied departments within a Transportation Agency is by far the hardest of these criteria to manage. It can be accomplished but it takes a large and continuous effort.

Pavement management systems reside in various organizations within a Transportation Agency. In SDDOT the pavement management group resides in the Planning Office. No matter where it resides, it's a well known fact that those responsible for the pavement management system must collect data from other departments. As well, they should provide information, analyses, and/or models to not only their own Planning Office, but, to many other departments within the Agency. Departments such as Design, Materials, Regions, and Administration all need pavement management system information. It is very difficult to cross these organizational boundaries without dealing with the people in those departments. Along with those dealings come their feelings of data ownership along and their concern for losing authority for their processes or products.

Thus, for a pavement management system to be fully utilized those responsible for it **must**:

- provide full service to other departments within the Agency,

- minimize perceived threat to other departments within the Agency, and,
- encourage communication between departments, preferably by forming and using a Pavement Management System Steering Committee.

4.5.6 Quality of Service

Most departments within a Transportation Agency have missions and goals. However, these are usually described and produced in terms of an engineering product. For instance, the Planning Department may conduct advanced planning studies, or traffic studies, while the Construction Departments' goals may be to minimize cost overruns or reduce the number of post construction claims. It is not normal for an engineering department or an office within an engineering department to measure its success, or the quality of its product, in terms of how it is used and accepted by other departments within the Agency.

To be successful, the Pavement Management Office must constantly strive to improve the quality of its service and products. As a minimum the Pavement Management Office must insure that the pavement condition survey, indexes and performance curves truly reflect the pavement condition and the change in condition over time as observed in the field. For instance, if the pavement management system data shows that there is 10% severe alligator cracking at MRM 34 on SR 123, then, there better be 10% severe alligator cracking at MRM 34 on SR 123. If there is not, it is very likely that the Regions will lose confidence in the pavement management system and its products.

Obviously, the detailed pavement management system models must be reasonably intuitive and understandable in both economic and engineering terms. If a special analysis is requested by another department, it needs to be produced quickly, to meet their timing needs. The product should be put out in a manner that makes it easily understood by presenting it in an intuitive and understandable way. In short, all reports, models or special studies produced by the Pavement Management Office must be accurate, timely and understandable. In addition, the Pavement Management Office should make an effort to meet with its' customers in other departments to make sure that the products are meeting their needs and to see if they have other particular needs that should be included in the pavement management system.

4.5.7 Getting Data

Pavement Management Offices are also customers of other groups in other organizations. To function properly they must get data from many other departments in the Agency. They need to have the last construction dates and where possible the full construction history of all road sections, which usually comes from the Central Construction or Region Construction Offices. They need route location reference and geometric files as well as traffic data which usually comes from the Planning Data Offices. They also need, where possible, maintenance actions and costs that come from the Maintenance Office, and the most current pavement rehabilitation procedures and costs that come from the Design and Materials Office. Again, the Pavement Management Office must cross many organizational boundaries to get the data necessary to produce a fully functioning pavement management system. In fact, the quality of its product is totally dependent upon the quality of the data it receives from the other departments.

Most of this data comes to the Pavement Management Office after a series of meetings (negotiations) with the other departments who are responsible for it. Since most Transportation Agency personnel gain their negotiating experience through contract negotiating which is a win - lose type of negotiating, they need to be careful when negotiating with a department within the Agency where there should be common Agency goals. It is possible to conduct win - win negotiations for the data from other departments within an Agency. The simple fact that having a defined and recognized customer base beyond the individual department often provides added support for the funding and workforce necessary to collect and maintain the required data.

4.5.8 Steer the PMS

Undoubtedly the single most effective step an Agency can make in developing, implementing and utilizing a pavement management system is the formation of a PMS Steering Committee. Most of the issues mentioned above deal with communications between different departments within the Agency. There is probably no better option for improving communication than the formation of a PMS Steering Committee composed of organizations supplying data to the pavement management system and those organizations using its products. The PMS Steering Committee should be an active committee, meeting: (a) before each program building cycle to be sure that there are no misunderstandings about the data and information needed for the pavement management system, and (b) before the products are put out to the users to make sure they meet their needs.

Pavement management systems are <u>tools</u> that provide technical information, analysis, and models to aid engineers in making more systematic and informed decisions in developing their Agency's pavement preservation program. The point to stress here is that the system's purpose is to provide data reports, analysis, and models to help engineers in both the Region and Central Headquarters in the development of the Agency's pavement preservation program. The Pavement Management Office must view its role as that of an engineering support group responsible for providing the highest quality products possible for the Agency's pavement preservation program.

5. Develop Pavement Models

In consultation with SDDOT pavement management and design personnel, develop performance (life-cycle) curves for asphalt and Portland cement concrete pavements and assess the curves' quality. The curves should be expressed in terms of individual and composite condition indexes, and should be based on historical data available within the Department and on expert opinion of Department engineers.

5.1 The Models

A significant portion of the consultant's time spent on this project went towards the development of pavement models. The products of this task are the pavement models developed by expert opinion. This task resulted in the following products:

1. A set of Pavement types which isolate the various performance characteristics for SDDOT pavements,
2. A set of treatment alternatives which are used to repair pavements in South Dakota.
3. A set of failure mechanisms for each of the pavement types which are the primary deficiencies causing these pavements to fail and be repaired,
4. An condition index scale and threshold value which tell how the above deficiencies are to be represented, and what values indicate failure,

5. A set of individual condition indexes, their extent and severity levels, and the associated deduct values, to be used to indicate the need and timing of repair treatments,
6. A composite index to be used to evaluate the overall health of the network, and,
7. A set of deterioration curves for new pavements.

To complete this task, the consultant had to develop some pavement condition indexes. These indexes where constructed specifically to fit the pavement types and related performance concerns which are unique to South Dakota. The condition indexes and resulting pavement performance curves for the basic pavement types used in South Dakota were developed from a large amount of information obtained through expert opinion supplied by the PMS Advisory Team. The information was obtained from several meetings with the team and from their responses to a very detailed questionnaire which covered their collective pavement performance experience and observations. The following sections explain the detail behind these steps.

5.2 The PMS Advisory Team

The PMS Advisory Team supplied the expert opinion required to complete this and the next task in the project. The members of this team are given on the back of the front cover. The team consisted of engineers from departments such as: Research, Materials, Planning, Maintenance, Regions and Areas.

5.3 The Meeting

The consultant met with the PMS Advisory Team. The purpose of this meeting was to lay the ground work for the engineering part of this entire project. The consultant expected to leave this meeting with a good enough understanding of pavements in South Dakota to allow him to begin work on the pavement models. The meeting took the form of an interview with plenty of discussion. The consultant directed the flow of the meeting so as to cover all the required topics. The following sections describe the decisions made at the meeting.

5.3.1 Pavement Types

One of the first major issues discussed at the meeting was what characteristics affected pavement performance the most in South Dakota. After much discussion regarding topics such as design standards, environmental factors and soil support, the PMS Advisory Team decided that the single biggest influence on pavement performance was pavement type. In fact, the PMS Advisory Team decided that pavement type was so much of an influence that it alone could account for much of the significant differences in pavement performance. This conclusion seems reasonable because of the very narrow distribution of traffic loadings in South Dakota, the relatively constant soil support, and the consultant's experience in many other state DOT's.

The PMS Advisory Team decided on five basic forms of flexible pavement types and five basic forms of rigid pavement types. These are listed in Table 7 and Table 8, respectively. Although at the time it did not seem to be a problem, later the consultant would discover that identifying the pavement type of particular road sections would be a slight problem.

Code	Type	Description
FD	Full Depth	> 10 in. ACP w/no granular base
THK	Thick	5 to 10 in. ACP w/ granular base
TonS	Thin on Strong	2 to 5 in. ACP on > 8 in. granular base
TonW	Thin on Weak	2 to 5 in. ACP on < 8 in. granular base
AonC	ACP on PCCP	Asphalt overlay on top of PCCP

Table 7: Flexible pavement types in South Dakota.

Code	Description
CRCP	Continuous reinforced PCCP
TKSJ	Thick (>8 in.) Short Jointed (<20 ft.) w/o dowels
TKSJD	Thick (>8 in.) Short Jointed (<20 ft.) w/ dowels
TNSJ	Thin (<8 in.) Short Jointed (<20 ft.) w/o dowels
MESH	Mesh reinforced long jointed (>20 ft.) w/ dowels

Table 8: Rigid pavement types in South Dakota.

5.3.2 Treatment Types

Another issue covered during the meeting with the PMS Advisory Team was identifying a list of treatment alternatives used to repair pavements in South Dakota. The reason these treatments had to be identified during this task was that they are required to build performance curves. There are two major types of performance curves: (1) those for new pavements, and (2) those for repaired pavements. In order to extract the expert's opinions regarding the second type, it was necessary to know what the repairs were. A list of treatments was developed for flexible pavements, shown in Table 9, and for rigid pavements, shown in Table 10. It was agreed that the South Dakota PMS would be set up to handle these treatments. Although these treatments will be discussed in more detail in the next chapter, it is necessary to introduce them here so that the performance curve development work can proceed in the proper context.

Treatment Description	Code
Reconstruction	**RECF**
2" AC Overlay	**2ACO**
Mill 1" w/ 2" AC Overlay	**M120**
Mill 1" w/ 3.5" AC Overlay	**M135**
2" Mill and Replace	**2MAR**
Cold In-place Rec w/ 3" Ovl	**CPR3**
Rout and Seal	**RAS**
Chip Seal	**CS**

Table 9: Flexible pavement treatments used in South Dakota.

Treatment Description	CODE
Reconstruction	**RECR**
Crack & Seat w/ 4.5" AC Ovl	**CS45**
4.5" AC Ovl (no Crk & Seat)	**45AO**
Pavement Restoration 1	**PR1**
Pavement Restoration 2	**PR2**
Pavement Restoration 3	**PR3**
Saw and Seal Joints	**SASJ**
Unbonded Concrete Overlay	**UBCO**
Bonded Overlay	**BO**

Table 10: Rigid pavement treatments used in South Dakota.

5.3.3 Failure Mechanisms

Before this section is presented, it is worth while to define some terms which may appear to be used arbitrarily, but, actually are not. These terms all refer to describing a pavement's condition and are used throughout this report.

Pavement Deficiency:

Something that causes a pavement to be less than perfect.

Failure Mechanism:

A failure mechanism is a pavement deficiency which has caused, or will likely cause, SDDOT to take action to repair or protect the pavement.

Pavement Condition Index:

The set of all pavement deficiencies defined by pavement management engineers including measures for deflection, cracking, deformations, roughness, rutting and friction which have clear definitions and a scale defining the relative amount of the deficiency.

Pavement Distress Index:

The subset of pavement condition indexes dealing with cracking and other surface deformations, but, not with deflection, rutting, roughness or friction.

The next issue the PMS Advisory Team had to examine was identifying the failure mechanisms for pavements in South Dakota. These deficiencies, then, are the key to making repair decisions in SDDOT. The PMS Advisory Team identified the deficiencies listed in Table 11 as the primary failure mechanisms for flexible and rigid pavements in South Dakota. There was considerable discussion regarding these deficiencies and the levels of each which would be repaired.

Flexible Pavements	Rigid Pavements
Transverse Cracking	D Cracking and ASR
Fatigue Cracking	Joint Spalling
Patching/Patch deterioration	Corner Cracking
Block Cracking	Faulting
Rutting	Joint Seal Damage
Roughness	Roughness
	Punchouts

Table 11: Failure mechanism deficiencies for flexible and rigid pavements in South Dakota.

These failure mechanisms would eventually form the foundation of most of the modeling in the pavement management system developed on this project. Therefore, throughout the remainder of this report these deficiencies, and their resulting condition indexes, are consistently referenced as the primary mechanisms of identifying the need for pavement repair. For this reason, the PMS Advisory Team needed an unambiguous method to identify the endless number of ways any one of these deficiencies could actually manifest itself in the field. The industry standard for unambiguously identifying them in the field is through a set of well defined extents and severity's. Therefore, the next step in the project was to do this.

5.3.4 Extent and Severity

Following the identification of the pavement failure mechanisms, the consultant and the PMS Advisory Team had to decide on the categories for describing the severity and extent of each condition. The severity of a condition describes how bad it is. The extent of a condition tells how much of it there is. It is important to select the categories for both the severity and the extent carefully. Precise categories are necessary to describe each deficiency in enough detail to be used in a fully predictive type pavement management system. For this project, the consultant based the severity and extent categories on those given in the SHRP Distress Identification Manual[17].

A complete description of the severity and extent categories for each condition are shown in matrix form in Appendix B, where each deficiency has its own matrix. Briefly, the consultant used the descriptions for three basic categories (or levels) of severity found in the SHRP Manual with a few minor changes. The severity usually expresses how bad the deficiency is. The severity levels defined for this project are shown in Table 12 for all but rutting and roughness. The rutting and roughness severity levels are shown in Table 13.

DEFICIENCY	LOW	MEDIUM	HIGH
Transverse Cracking	<1/4 inch width	> 1/4 inch width & <1/4 inch depressions	> 1/4 inch width & >1/4 inch depressions
Fatigue Cracking	Fine parallel hairline cracks.	Alligator pattern clearly developed	Alligator pattern clearly developed with spalling and distortion
Patching and Patch Deterioration	Little or no defects with smooth ride	Clear signs of cracking on notable roughness.	Heavy cracking or other distress with distinct roughness
Block Cracking	<1/4 inch or sealed cracks with sealant still good.	> 1/4 inch and <3/4 inch.	> 3/4 inch.
D Cracking & ASR	Cracks are light, with no loose or missing pieces.	Cracks are well defined and some small pieces are loose or missing.	Cracks are well developed pattern with a significant amount of loose or missing material.
Joint Spalling	Spalls < 3 inches wide with no significant loss of material.	Spalls 3 to 6 inches with loss of material.	Spalls > 6 inches with significant loss of material.
Corner Cracking	Crack not spalled with no faulting & piece not broken.	Crack spalled slightly, or faulting < 1/2 inch, or piece broken.	Crack spalled, or faulting > 1/2 inch, or piece broken.
Faulting	< 1/8 inch.	1/8 to 1/4 inch.	> 1/4 inch.
Joint Seal Damage	damage to < 10% of joint.	Damage to 10% - 50% of joint.	Damage to > 50% of joint.

Table 12: Severity levels used to describe the cracking failure mechanism deficiencies.

DEFICIENCY	LOW	MODERATE	HIGH	EXTREME
Rutting	< 1/8 inch	1/8 - 1/4 inch	1/4 -1/2 inch	1/2 - 3/4 inch
Roughness	> 3	2.5 - 3	2 - 2.5	0 - 2

Table 13: Severity levels used to describe the rutting and roughness failure mechanisms.

The extent levels used in this project were also based on the SHRP manual with a few modifications. For distresses where extent is defined in terms of spacing, it was described in three categories of low, medium, and high. For distresses where the categories of extent described percent of total area, four basic categories of low, moderate, high, and extreme were used. The extent levels defined for this project are shown in Table 14.

DEFICIENCY	LOW	MODERATE	HIGH	EXTREME
Transverse Cracking	> 50 ft. spacing.	>25 ft. & < 50 ft. spacing	< 25 ft. spacing.	N/A
Fatigue Cracking	1% to 9% of wheel path	10% to 24% of wheel path	25% to 49% of wheel path	> 50 % of wheel path
Patching and Patch Deterioration	1% to 9% of wheel path	10% to 24% of wheel path	25% to 49% of wheel path	> 50 % of wheel path
Block Cracking	6 ft to 10ft. block sizes	3 ft. to 6 ft. block sizes	< 3ft. block sizes	N/A
D Cracking & ASR	1% to 9% of slabs	10% to 24% of slabs	25% to 49% of slabs	> 50 % of slabs
Joint Spalling	1% to 9% of joints	10% to 24% of joints	25% to 49% of joints	> 50 % of joints
Corner Cracking	1% to 9% of slabs	10% to 24% of slabs	25% to 49% of slabs	> 50 % of slabs
Faulting	1% to 9% of slabs	10% to 24% of slabs	25% to 49% of slabs	> 50 % of slabs
Joint Seal Damage	1% to 9% of joints	10% to 24% of joints	25% to 49% of joints	> 50 % of joints

Table 14: Extent levels used to describe the cracking failure mechanism deficiencies.

5.4 The Questionnaire

After the initial meeting the consultant had a set of pavement types, a set of treatment alternatives, a set of failure mechanisms, an understanding of the levels of deficiency which triggered treatments, and a set of severity and extents. This was enough background for the consultant to develop a questionnaire which would be used to quantify the expert opinion of the PMS Advisory Team. From this point in the report onward, the consultant will make repeated references back to this questionnaire since it formed the basis of most model development work.

Appendix B contains a copy of this questionnaire. Basically, the questionnaire consisted of the following four parts:

1. **Flexible Pavement Performance for New Pavements**

   Designed to quantify the number of years new flexible pavements take to get to a certain level of extent and severity.

2. **Rigid Pavement Performance for New Pavements**

   Designed to quantify the number of years new rigid pavements take to get to a certain level of extent and severity.

3. **Pavement Treatment Triggers**

   Designed to get the experts opinions on which treatments are used on which pavement types and what levels of extent and severity the treatment can be used to repair.

4. **Performance of Treatments**

   Designed to quantify the number of years a treatment will last until the pavement returns to an average level of deficiency.

The first thing to realize about getting this kind of information from the experts is the extreme amount of data involved. For example, for new pavements each combination of pavement type and deficiency has its own performance curve. The total number of new pavement performance curves, therefore, is 30 for flexible and 35 for rigid. For each individual curve, the consultant required expert opinion as to how many years it would take to reach each level of severity and extent. Therefore, theoretically, the experts had to fill in a three by four matrix for each of the sixty five curves. This would mean they had to fill in a total of 780 cells (65*3*4). Since each cell required a great deal of thought, the consultant reduced this number by asking the experts to supply a subset of the cells in a typical extent versus severity matrix. Table 15 shows this typical matrix with the cells the experts did not provide ages for blacked out. There was approximately 390 (65 * 6) cells in which the experts provided ages. Other short-cuts were used to reduce the amount of data the experts had to supply. These short-cuts will be explained in the respective sections of the report.

	Extent			
severity	LOW	MODERATE	HIGH	EXTREME
LOW				
MEDIUM				
HIGH				

Table 15: **Cells of a typical extent versus severity matrix which the experts gave expected lives for.**

The consultant designed a questionnaire and sent it to each member of the PMS Advisory Team. Then, the members spent some two weeks filling in values representing their experience of pavement life and treatment triggering in South Dakota. After the responses came back, the consultant noticed that the results looked odd. It was then decided that the instructions were not entirely clear to all members of the PMS Advisory Team. Therefore, the consultant rewrote the instructions and had a meeting with the Team to explain them and answer any questions. Then, the Team members went away a second time and completed their responses. The second round results were excellent.

5.5 The Condition Indexes

The next step in this task was to develop pavement condition indexes for each deficiency. This step was carried out by the consultant using the information gathered from the discussions at the initial meeting with the PMS Advisory Team and experience from work done by the consultant and others.[18, 19, 20, 21, 22]

In general, a pavement management system requires pavement condition indexes for three reasons.

1. **Pavement condition indexes help determine when to apply a treatment.**

   For example, some indexes like transverse cracking are sometimes used initially to help determine when to seal cracks, a maintenance type action. Others, like fatigue cracking and patch deterioration, are used to help determine when to resurface the pavement, a programmed construction type action. When used individually pavement condition indexes are an indicator for the timing of actions. They are not necessarily a measure of the structural quality of a pavement, nor should they represent the relative value of that specific condition to the structural quality of the pavement.

2. **Pavement condition indexes help calculate the cost of a treatment.**

   For example, some cracking indexes are sometimes used to calculate the amount of cracks that need filling. This helps calculate the cost of crack filling on a sections of road. Other indexes such as rutting are used to help determine whether a resurface treatment needs a leveling course.

3. **Pavement condition indexes help monitor the overall health of the network.**

   Whereas the other two reasons necessitated pavement condition indexes which described individual deficiencies, this need requires an overall or composite index. A composite index combines all condition indexes into one overall number which when comparing one road section against another gives an overall idea of which one is in better condition. Composite indexes are seldom used to trigger treatments or calculate costs. The composite index used in South Dakota's pavement management system is described later in this report.

Pavement condition indexes are commonly given on scales which go from 0 to 100, or 0 to 5. Typically, although not universally, the 100, or 5, indicates the best condition and the 0 represents the worst condition. For the purpose of this work, the PMS Advisory Team decided to use a scale of 0 to 5. This, they reasoned, would allow them to stay consistent with past practices.

5.5.1 Deduct Values

The individual value for a pavement condition index are commonly calculated using deduct values. In this approach each cell in a matrix whose rows are severity and whose columns are extent receives a deduct value. The greater the severity and extent, the greater the deduct value. To obtain a value for a condition index whose severity and extent is known, the corresponding deduct value is simply subtracted from the maximum value (either 100 or 5). As the deficiency gains greater severity and extent with time the index value approaches zero.

Through the deduct values, the engineer developing the condition index has complete control over the range of values in the scale that end up being used.

Sometimes, for example, engineers develop condition index scales in which only about 40% or so of it is ever used. The argument goes, "we can't build them that good" on the top part of the scale which is never used, and "we don't let them get that bad" on the bottom part which is also never used. With this in mind, there are two basic criteria which are important for developing the deduct values for an index.

The first and most critical criteria is that the deduct values should be scaled so that the threshold value (or action point) occurs at about the middle of the scale. Preferably, engineers like to keep the "should consider action" level at about 60% of the scale. Furthermore, the "must consider action" is typically kept at about 30% of the scale. This concept is similar to the common Pavement Serviceability Index (PSI) developed by AASHTO after the Road Test. The PSI is a 0 to 5 scale, where a value of 3 is usually considered the proper timing to take action on a high quality roadway, and a value of 2 is considered fairly poor quality for even a secondary road.

The second criteria is that the index should transition as smoothly as possible with time. Remember, the deterioration rate represents the basic nature or trends of that distress as observed in the field. Most deficiencies, once they become apparent, tend to increase in both severity and extent at a constantly increasing rate with time. Thus, the index representing that deficiency should decrease at a constantly increasing rate, at the proper time period. Also, the rate of deterioration should be consistent with the type of deterioration. For example, consider transverse cracking again. Transverse cracks reflect from the underlying pavement quite soon after the construction of a new overlay. How they perform with time depends largely on the maintenance of those cracks. If they are sealed soon after they occur their deterioration rate is fairly slow, and linear. Where they are not maintained early or consistently they tend to deteriorate at a much higher rate, which is more exponential than linear. These trends, as experienced in the field must be reflected in the numeric trends of the indexes used in a successful pavement management system. And, once again, it is the deduct values that give the engineer this control.

There are two methods of obtaining deduct values: by expert opinion, or by scaling[23]. While, the expert opinion process seems to be the most common practice used by agencies in the past, through experience, it is the consultant's impression that this process tends to hide the problem at hand. In this approach, the agency gets its PMS Advisory Team together and asks them to assign deduct values for each severity and extent cell in the typical condition matrix. Through this process, the PMS Advisory Team tends to produce indexes that do not transition well (smoothly and consistently) with time. The reason for this is that the Team seldom takes the time to examine the mathematics behind the process and tends, instead, to rely on judgment to assign relative weights to each cell. Although this judgment is required, if it is acquired out of context, it tends to produce indexes which are not smooth over time. In fact, many members of the PMS Advisory Team indicated both during the meeting and after answering the questionnaire, that they had not thought before about the individual pavement conditions and their responses with time. Thereby indicating the difficulty it would have been developing deduct values from expert opinion.

Taking advantage of lessons learned over many years from various agencies, and using work by others[22,23], the consultant developed a new, but fairly simple procedure to produce the deduct values for South Dakota. This new procedure was base on scaling, and it did take the mathematics of the problem into account. The procedure involved the consultant developing the basic deduct values for each condition index by scaling them from straight line relationships on a log log graph; one graph for each condition. The x axis on these graphs was the log of the extent. The y axis on these graphs was the log of the deduct value. Each graph has three lines, one line for each level of severity.

The advantage of this approach is that it helps provide deduct values that have a fairly smooth transition over time. This process also tends to approximate an exponential form when the values are transformed. Through this process the resulting condition indexes should come fairly close to representing the specific deficiency trends as observed in the field in South Dakota. This will provide a good set of indexes to start the new South Dakota pavement management system. The consultant expects, however, that some of these values may need to be revised with more experience and time. Such experience will come after SDDOT follows the individual pavement condition trends and performance lives in South Dakota.

Examples of the typical deduct values established for a condition index which needs an action identified early in the severity and extent of the condition, are given in Table 16. The consultant used these deduct values for the following condition indexes: (a) Fatigue Cracking, (b) Patching and Patch Deterioration, (c) Corner Cracking, (d) D Cracking and ASR, and (e) Faulting. The deduct values for the other condition indexes are listed in the next section.

Notice how the matrix in Table 16 has actual extent values and not the ranges in extent which were given in previous extent discussions. This is because the table can be used as a starting place when adjusting the slope for each severity line on the log(EXTENT) vs log(DEDUCT) graph shown in Figure 2. SDDOT can adjust the slope of each severity line to determine the deduct values for each cell in the matrix for each individual condition index.

CONDITION	EXTENT				
SEVERITY	0%	5%	15%	35%	70%
Low	1	8	16	28	40
Medium	1	16	34	62	100
High	1	22	54	100	100

Table 16: Example deduct values for a condition requiring early action.

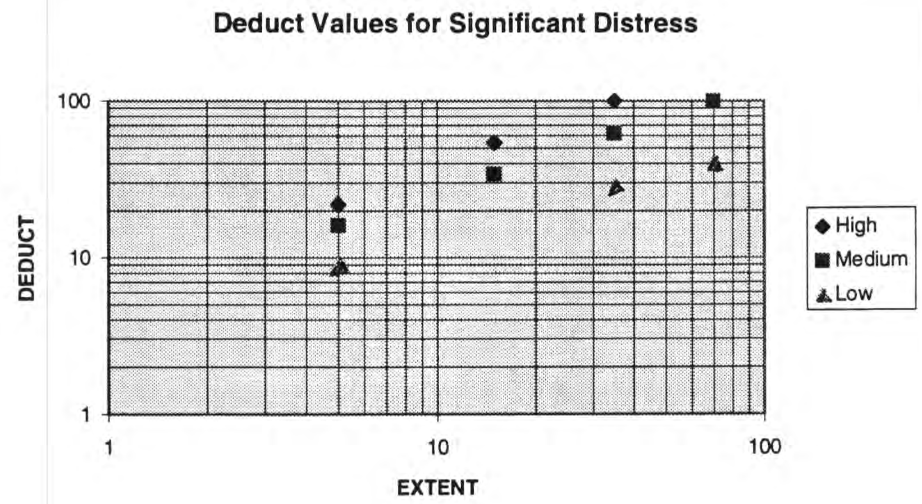

Figure 2: Plot of example deduct values for a condition requiring early action.

The deduct values given above are consistent with the general timing desires identified by the PMS Advisory Team during the initial meeting, as well as those developed by the consultant in other agencies.

As long as the pavement condition surveys in SDDOT collect the distresses based on the four levels of extent described earlier, this single deduct value matrix is clearly the simplest means to establish a condition index for conditions needing action identified early. Currently, automated pavement condition collection equipment cannot identify accurately some of the low severity levels of distress.[24, 25] In the future, however, automated pavement condition collection equipment should improve to a point where they can more accurately identify the distresses, from low to high severity, and can measure extent in a reasonably cost effective manner. When this happens, and fully automated equipment is used to collect the pavement condition data, SDDOT should change from using the individual deduct values in the matrix of Table 16 to the actual equations of the lines in Figure 2. This will allow SDDOT to make use of the continuous range of measured extent.

5.5.2 Individual Indexes

The following tables display the deduct values developed by the consultant for all individual condition indexes. In all, there are two sets of deducts. One for an index scale of 0 to 100, and, another for an index scale of 0 to 5. The consultant included the 0 to 100 scale to allow for general comparisons with other research studies and agencies using that scale. The deducts for flexible pavement condition indexes on a 0 to 5 scale are shown in Table 17, and for a 0 to 100 scale in Table 18. The deducts for rigid pavement condition indexes on a 0 to 5 scale are shown in Table 19, and for a 0 to 100 scale in Table 20.

FATIGUE CRACKING and PATCHING				
	EXTENT			
SEVERITY	Low	Moderate	High	Extreme
Low	0.4	0.8	1.4	2.0
Medium	0.8	1.7	3.1	5.0
High	1.1	2.7	5.0	
TRANSVERSE CRACKING				
SEVERITY	Low	Medium	High	
Low	0.1	0.2	0.5	
Medium	0.2	0.6	1.5	
High	1.0	2.2	5.0	
BLOCK CRACKING				
SEVERITY	Low	Medium	High	
Low	0.7	1.2	2.0	
Medium	0.8	1.6	3.0	
High	0.9	2.2	5.0	
RUT DEPTH				
SEVERITY	All extent			
Low	0.7			
Medium	1.5			
High	3.2			
Extreme	5.0			
ROUGHNESS				
Roughness value	All extent			
5	0			
4	0.2			
3	1.0			
2.5	2.2			
2	5.0			

Table 17: Deduct values for the failure mechanism conditions on flexible pavements using an index scale from 0 (bad) to 5 (good).

FATIGUE CRACKING and PATCHING				
	EXTENT			
SEVERITY	Low	Moderate	High	Extreme
Low	8	16	28	40
Medium	16	34	62	100
High	22	54	100	100
TRANSVERSE CRACKING				
SEVERITY	Low	Medium	High	
Low	2	4.5	10	
Medium	5	13	30	
High	20	45	100	
BLOCK CRACKING				
SEVERITY	Low	Medium	High	
Low	14	24	40	
Medium	16	31	60	
High	18	43	100	
RUT DEPTH				
SEVERITY	All extent			
Low	14			
Medium	30			
High	65			
Extreme	100			
ROUGHNESS				
Roughness value	All extent			
5	0			
4	5			
3	20			
2.5	45			
2	100			

Table 18: **Deduct values for the failure mechanism conditions on flexible pavements using an index scale from 0 (bad) to 100 (good).**

CORNER CRACKING				
	EXTENT			
SEVERITY	Low	Moderate	High	Extreme
Low	0.4	0.8	1.4	2.0
Medium	0.8	1.7	3.1	5.0
High	1.1	2.7	5.0	5.0
D & ASR CRACKING				
SEVERITY	Low	Moderate	High	Extreme
Low	0.4	0.8	1.4	2.0
Medium	0.8	1.7	3.1	5.0
High	1.1	2.7	5.0	5.0
FAULTING				
SEVERITY	Low	Moderate	High	Extreme
Low	0.4	0.8	1.4	2.0
Medium	0.8	1.7	3.1	5.0
High	1.1	2.7	5.0	5.0
JOINT SEAL				
SEVERITY	Low	Moderate	High	Extreme
Low	0.4	0.7	1.0	1.5
Medium	0.6	1.2	2.0	3.0
High	0.8	1.7	3.2	5.0
JOINT SPALLING				
SEVERITY	Low	Moderate	High	Extreme
Low	0.4	0.7	1.0	1.5
Medium	0.6	1.2	2.0	3.0
High	0.8	1.7	3.2	5.0
ROUGHNESS				
ROUGHNESS	All extents			
5	0			
4	0.2			
3	1.0			
2.5	2.2			
2	5.0			

Table 19: Deduct values for the failure mechanism conditions on rigid pavements using an index scale from 0 (bad) to 5 (good).

CORNER CRACKING				
	EXTENT			
SEVERITY	Low	Moderate	High	Extreme
Low	8	16	28	40
Medium	16	34	62	100
High	22	54	100	100
D CRACKING & ASR				
SEVERITY	Low	Moderate	High	Extreme
Low	8	16	28	40
Medium	16	34	62	100
High	22	54	100	100
FAULTING				
SEVERITY	Low	Moderate	High	Extreme
Low	9	17	28	40
Medium	16	34	62	100
High	22	54	100	100
JOINT SEAL				
SEVERITY	Low	Moderate	High	Extreme
Low	8	14	20	30
Medium	12	22	40	60
High	16	34	64	100
JOINT SPALLING				
SEVERITY	Low	Moderate	High	Extreme
Low	8	14	20	30
Medium	12	22	40	60
High	16	34	64	100
ROUGHNESS				
ROUGHNESS	All extents			
5	0			
4	4			
3	20			
2.5	44			
2	100			

Table 20: Deduct values for the failure mechanism conditions on rigid pavements using an index scale from 0 (bad) to 100 (good).

5.5.3 Composite Index

The South Dakota pavement management system will use a composite index for calculating the benefits of a strategy, and for monitoring the overall health of the network, but, not for triggering treatments. During the process of developing the performance curves, the consultant did some investigating to find a method for calculating a composite index [26,27,28]. The problem with traditional composite index calculation methods is that if a pavement only had one bad deficiency, its impact on the composite index would be washed out by the good values of all the other deficiencies. Therefore, the consultant developed a mechanism to calculate a composite index without this traditional problem. As a result of this work, the equation for the composite index is shown below as Equation 9.

$$\text{COMP} = \text{mean} - 1.25 \times \text{sd}$$

Equation 9: Composite index calculation equation.

where:

COMP	= the composite condition index
mean	= the mean of all contributing individual condition indexes
sd	= the standard deviation for the above mean

There are two issues involved in this composite index which deserve some attention. The first regards which individual indexes are included when the mean is calculated, and the second regards the '1.25' standard deviation multiplier.

After a few trials with the above equation in the software, the consultant noted that if all the individual condition index values were included for rigid pavements, the composite index tended to be skewed. The two individual indexes which raised this issue are: the D Cracking & ASR index and the Joint Sealant index.

The problem with the D Cracking & ASR index was that this deficiency was not present in many pavement sections. And, when the deficiency is not present, the value for the index was always 5. Hence, no matter how bad the other deficiencies got on these sections, the D Cracking & ASR Index would always remain at 5 and would cause both the mean and the standard deviation to be higher than they would otherwise be. The overall effect this had on the analysis was to give pavements which did have D Cracking & ASR a bigger benefit when they were repaired. The benefit was so much bigger that the system tended to pick all the road sections with this deficiency before many of the others. Since this is not a policy at SDDOT, the consultant made the assumption that the D Cracking and ASR index would only be included in the composite index if the deficiency was present on the road section.

The Joint Sealant index was another index which caused funny things to happen with the composite index. In the end, the consultant reasoned that this index was only required in the pavement management system to indicate the need to take action such as reseal the joints, and not to asses the overall condition of the pavement section. Damage resulting from loss of joint sealant material would manifest itself through other indexes such as spalling. Therefore, the consultant removed this index from the calculation of the composite index.

The end result of which indexes are included in the composite index calculation for each rigid pavement type is shown in Table 21. Flexible condition indexes are not shown in this table because all are included in calculating the composite.

Pavement Type	D & ASR Cracking	Punchouts	Corner Cracking	Faulting	Joint Seal	Joint Spallng	Roughness
CRCP	no if = 5	yes	no	no	no	no	yes
TKSJ	no if = 5	no	yes	yes	no	yes	yes
TKSJD	no if = 5	no	yes	yes	no	yes	yes
TNSJ	no if = 5	no	yes	yes	no	yes	yes
MESH	no if = 5	no	yes	yes	no	yes	yes

Table 21: Individual condition indexes involved in the calculation of the composite index.

The consultant selected the 1.25 multiplier in the composite index equation for a number of reasons. On the one hand, one bad value is not washed out by several good values. On the other hand, several bad values would draw the composite down far enough to be recognized as a bad pavement. The consultant went through a number of iterations before deciding on 1.25. Once again as well, the consultant's experience was heavily relied on. From a statistical point of view, Equation 9 represents an index value where 90% of the other contributing index values are higher than it and only 10% are lower. Form the consultant's experience, this seemed like a reasonable area for a composite index.

In the South Dakota pavement management system, the composite index is calculated each year in the future rather than predicted. This is done because the composite is not independent from the other condition index values. Therefore, it can not be independently predicted. Rather, the system first predicts the individual composite indexes into the future, then, the system uses these values to calculate the composite index. In spite of this, the consultant still used the same regression procedures to develop a performance curve for the composite index, as will be discussed later. This was done for general interest and not for use in the pavement management system.

5.6 The Performance Curves

After the consultant developed the deduct values for each condition index, the next step was to develop the performance curves. Each combination of pavement type and condition index has its own performance curve which needed developing. To do this development, the consultant used the results of the questionnaire which was explained in an earlier section. See Appendix B for a copy of this questionnaire. Basically, the experts gave ages for selected pairs of extent and severity.

To develop the curves, the consultant used the average of all the ages given by the PMS Advisory Team on their questionnaire responses. Recall Table 15 showed the cells of the extent versus severity matrix in which the experts gave estimated ages. Also recall that the consultant developed deduct values for each of the cells in this matrix which allowed for the calculation of the condition index for each cell. By combining these together and performing a regression analysis, the consultant developed the performance curves.

A summary of the PMS Advisory Team's age responses is given in Appendix C for flexible pavements and Appendix D for rigid pavements. All of the tables in

Appendix C and D follow the same basic form. The first column in each table indicates the condition while the next two columns indicate the levels of severity and extent, respectively. The next eleven columns indicate the response from each expert, and the last two columns represents the average age and the standard deviation of the responses. The average age was used in the regression analysis for developing the performance curves.

There are several general rules which can help interpret the responses. First, when the standard deviation value is below 25% of the average value, there is little diversity among the experts. If the standard deviation value ranges from 25% to 50% of the average value, there is a fair diversity of opinion among the experts. In this case the average value for that condition should be regarded with some suspect. If the standard deviation exceeds 50% of the average value, there is a large diversity of opinion among the experts. In such a case, the resulting average value should be regarded as highly suspect.

Given these rules of thumb, the consultant regards the overall response as excellent with most of the standard deviations being around the 25% mark. Although there is some degree of spread among the answers, in general, there is a significant amount of clustering. This spread could be reduced if the experts were asked to change the way they look at pavement condition from now on. Many experts said they had never looked at it like this before and, hence, had difficulty completing the questionnaire. In any case, the consultant considers the results as being excellent.

5.6.1 Curve Parameters

To express the performance curves mathematically, the consultant used the standard form of an exponential pavement performance equation as shown in Equation 10. This form of performance equation was introduced in Washington[29] and has been used extensively since then. It provides excellent diversity and control over the shape of the curve.

$$\text{Index} = C + M \text{ age}^{B}$$

Equation 10: Performance curve general equation.

where:

Index	= the individual condition index or the composite index
C	= the maximum value of the index
M	= the slope coefficient of the curve
age	= pavement age
B	= the exponent coefficient of the curve

5.6.2 Individual Curves

Using the questionnaire data, the consultant developed a total of 70 performance curves for the five basic flexible pavement types (35 for each index scale), and, 66 performance curves for the rigid pavement types (33 for each index scale). Note that the consultant developed two sets of performance curves; one set for a scale of 0 to 5 for use in the South Dakota pavement management system, and one set for a scale of 0 to 100 for comparison purposes. In general, for each pavement type there is one equation for each of the six individual condition indexes and one for the composite index. The one exception to this pattern is that CRCP pavement type only has four condition types rather than the six used for the other rigid pavements.

The consultant used a regression software package to develop the equation coefficients. The resulting C, M, and B values for each performance curve and for each pavement type are summarized in Appendix E. The ten appendices that follow Appendix E give the details of the deduct values, the smoothness of the transition, and the performance curve. These numbers for these Appendices are given in Table 22.

Appendix	pavement Type
F	Full Depth
G	Thick
H	Thin on Strong
I	Thin on Weak
J	ACP on PCCP
K	Continuous reinforced PCCP
L	Thick Short Jointed w/o dowel
M	Thick Short Jointed w/ dowels
N	Thin Short Jointed w/o dowels
O	Mesh reinforced long jointed w/ dowels

Table 22: List of Appendices which give the details for the performance curves for each pavement type.

There is a great deal of information presented in each of these Appendices. The following paragraphs explain what this information is. In a sense, these paragraphs also present the manner in which the consultant progressed while developing the curves. However, there were more iterations than the discussion presents.

Each Appendix contains three pages for each condition index followed by four pages for the composite index. The first of the three condition index pages has two matrices and two graphs. The matrix at the top of the page shows the deduct values for that condition on a scale of 0 to 100. The corresponding graph is a log log plot of these deduct values versus the extent. The graph shows one line for each level of severity. The matrix at the bottom of the page shows the deduct values, the corresponding average age to reach that level of severity and extent (from the questionnaire), and the resulting condition index value (shown as PSR) on a scale of 0 to 100. The corresponding graph is a plot of this matrix. This graph shows the transition of the condition index over time. In other words, this bottom graph shows how the index would change over time for a typical pavement section.

It is important to remember that the shape of this bottom graph is affected by two things: (1) the deduct value curve selected by the consultant's judgment, and (2) the opinion of the PMS Advisory Team as given in their answers to the questionnaire. This is precisely where all the iteration took place in the development of the indexes. If, after plotting this graph, the consultant did not feel the transition was smooth enough, he would go back and adjust the deduct values until it was.

The next two primary condition pages in Appendices differ only in the scale of the performance curve; one for a 0 to 100 scale and one for a 0 to 5 scale. The top part of these pages demonstrates the results of performing a regression analysis on the index,age points at the bottom of the previous page. The information presented at the top consist of: (a) the equation coefficients, (b) the coefficient of correlation, and (c) the standard error of estimate. The numbers at the bottom of the page show how the index varies with time according to the developed equation.

The last four pages of each Appendix deal with the composite index.

5.6.3 Composite Curves

Basically, the composite index performance curves are shown on three pages each. The first page shows a matrix at the top and a graph at the bottom. The matrix shows the index,age points for each of the individual condition indexes. The last three rows of this matrix show the mean of these condition index values for each age, the standard deviation, and the resulting composite index. The graph is a plot of the age versus all the indexes including the composite. The second and third pages show the result of performing a regression analysis on the composite,age points for each of the two index scales.

5.7 The Curves' Quality

In the science of pavement prediction where there is a great deal of learning to do with respect to characterizing the rate of change in condition. [30, 31, 32] That is why in SDDOT, these results are appealing. Since the process produced curves which would pass the test of reasonableness to most pavement engineers, they are at least as good as curves developed by other DOT's. This statement, unfortunately, does nothing to attest to the curves' actual quality. However, to measure whether or not something has quality, one must define what quality is. In the absence of a clear definition of what performance curve quality is, the consultant has assumed that quality means that the best curves were developed with the available data, as is certainly the case in this project.

To quantify the actual quality of the performance curves developed in this project, one would have to rely heavily on subjective opinion. There are several reasons for this. First, there was no historical data which would give hard evidence as to whether the experts opinion matched what actually happens in the field. Second, since the curves were based only on pavement type indicates that there is a built in inherent variability caused by such things as geography, maintenance, and construction which has not been accounted for. And, finally, this is the first time performance curves of this detail have been developed in

SDDOT, therefore, no one knows how they ought to look. This suggests that if the PMS Advisory Team was to do the questionnaire again, the curves would likely change because the members would have had a chance to update their opinions.

In any case, regardless of the actual quality, the results of this study must still be regarded as preliminary. The ultimate pavement management system has a performance curve for each condition and each road section which is based on actual historical data. And, although SDDOT's pavement management system software has the capability to do this, SDDOT lacks the historical data which it requires. Therefore, SDDOT must revisit these curves after a few years of observation have passed, and must ultimately strive for individual curves for each road section.

6. Develop Treatment Models

Construct, by decision trees or other appropriate methods, comprehensive maintenance, rehabilitation and reconstruction strategies based upon history of past performance in South Dakota, proven engineering principles, and expert opinion. Identify costs, selection criteria, and expected improvements for each treatment considered.

6.1 The Models

Once the consultant developed all the condition indexes and their associated performance curves, attention could be turned toward the treatment alternatives. This task in the project resulted in the consultant developing the following products:

1. A treatment cost matrix.
2. A set of treatment triggers.
3. A set of treatment impacts.

In the context of the South Dakota pavement management system, it is important to distinguish between the term *treatment* and *strategy.* The term *treatment* is used to describe an action taken on a road section at a specific point in time. In fact,

Table 9 and Table 10 already listed the treatments used in SDDOT to repair the pavements. A *strategy*, on the other hand, is a series of one or more treatments performed over a period of time. The period of time where treatments are applied is called the *treatment application period*. The period of time where the benefits of strategies are calculated is called the *analysis period*. In the SDDOT initial implementation of the software the treatment application period is twenty years and the *analysis period* is thirty five years.

The South Dakota pavement management system does not evaluate *treatments*, it evaluates *strategies*. The software uses the triggering rules to develop these strategies. Since the *treatment application period* is twenty years, many strategies will have more than one treatment. In fact, most will have several overlays and several of the lighter periodic treatments such as rout and seal, chip seal, and saw and seal joints.

6.2 The Costs

The consultant developed treatment costs equations to calculate the cost of applying a treatment to a section. SDDOT provided a table entitled Summary of Costs for Planning Estimates. This table is presented in Appendix PP. The table shows the cost for each treatment as a function of the following items: (a)

Surfacing cost, (b) Mobilization cost, (c) Traffic Control cost, (d) Slope flattening cost, (e) Guard Rail cost, (f) Lighting cost, (g) Project Engineering cost, (h) Construction Engineering cost, (i) Right of Way costs, and (j) Utility costs.

The surfacing costs for reconstruction of flexible and rigid pavements was broken down into further categories based on the surface width, the divided status, the ADT, and the Truck Volume. For interstate sections the costs were based on old PCCP removal and new surfacing. Other divided highway costs were based on old PCCP removal, grading, and new surfacing. The remaining non-divided NHS and STP costs were based on the salvage of the old AC surface, grading, and new surfacing.

6.3 The Triggers

6.3.1 Questionnaire Results

In order to get the PMS Advisory Team's expert opinion with regard to when the treatments apply, the consultant included a section in the questionnaire covering this topic. The purpose of that study was to determine the PMS Advisory Team's opinion as to the minimum and maximum levels of condition which would trigger these treatments. The term trigger is used throughout this report to refer to the set of criteria dictating when a treatment alternative is feasible.

The questionnaire required the experts to fill in Yes/No values on the pavement treatment trigger pages based on their experience. The questionnaire had one matrix for each treatment type. The rows in this matrix represented the respective pavement types. The columns in this matrix represented the severity and extent levels for each of the respective pavement conditions.

The experts placed a "Y" in a matrix cell if the answer to the following question was Yes: "If I had this type of pavement in this condition, would I typically perform this treatment to correct it, Yes or No?" The PMS Advisory Team was instructed to answer the question independent of budget constraints, but, not independent of practical constraints. A "N" in any cell would signify a No answer to the question. An "X" indicated the expert had no experience with the treatment on that pavement type, and an "N/A" indicated that the expert did not think that treatment applied to that pavement type.

The consultant examined the responses from each expert and designed a database to store the responses for later analysis. The database consisted of one record for each treatment type and each pavement type. Each record had one field for each cell in the typical extent versus severity matrix. The database for

FLEXIBLE pavements consisted of 40 records for each questionnaire (8 treatments and 5 pavement types). RIGID pavements required 45 records for each questionnaire (9 treatments and 5 pavement types). The fields in the database represented the condition levels at which each treatment would or would not be practical. There were a total of some 900 records in this database and a total of some 30,000 fields of data.

Each field in the database could receive one of two values. A value of "1" represents that the respective treatment would be practical for a given pavement type. A value of "0" represents that the treatment was not practical, or, that the expert had no experience with that particular treatment or that particular pavement type.

The consultant then entered the responses from each expert into the FLEXIBLE and RIGID databases for tabulation. Following this, the consultant wrote a computer program to summarize the data and tabulate a total score in the form of a matrix. Table 25 illustrates what one of these matrices looked like. There is one matrix for each treatment type, and pavement type and a total of nine (or twelve) cells representing the different levels of condition. The maximum number any cell could receive would be eleven because that is the total number of experts on the PMS Advisory Team. Appendix CC and DD display this summary report for flexible and rigid pavement respectively.

To analyze this data properly, however, the consultant had to first determine how many experts thought the treatment was not applicable on the particular pavement type. This would help indicate the maximum number of responses any of the cells mentioned above could receive. Table 23 and Table 24 summarize this information for flexible and rigid pavement treatments respectively.

The result of this analysis allowed the consultant to eliminate certain treatments from further consideration. For example, cells in these tables with light shading were eliminated by the consultant because of the number of 'not applicable' responses. Additionally, the SDDOT PMS engineer decided that other treatments were also not applicable and eliminated them. These are shown by cells with dark shading.

pavement Type	RECF n/a,n/e	2ACO n/a,n/e	M12O n/a,n/e	M135 n/a,n/e	2MAR n/a,n/e	CPR3 n/a,n/e	RAS n/a,n/e	CS n/a,n/e
FD	0,3	3,1	1,3	6,1	1,2	4,4	0,1	0,1
THK	0,3	4,0	1,2	4,2	0,2	1,3	0,0	0,0
TonS	0,2	0,0	1,2	2,1	5,2	0,3	0,0	0,0
TonW	0,2	0,1	2,2	2,1	6,2	0,3	0,0	0,0
AonC	0,5	5,3	2,4	4,4	0,4	6,5	1,1	0,2

Table 23: Number of responses indicating the flexible pavement treatment is not applicable (n/a) or the rater had no experience (n/e) for each pavement type.

pavement Type	RECR n/a,n/e	CS45 n/a,n/e	45AO n/a,n/e	PR1 n/a,n/e	PR2 n/a,n/e	PR3 n/a,n/e	SASJ n/a,n/e	UBCO n/a,n/e	BO n/a,n/e
CRCP	0,3	9,2	1,4	10,1	9,2	7,3	9,2	0,7	1,9
TKSJ	0,2	0,3	5,3	0,2	0,3	0,3	0,2	0,6	0,8
TKSLD	0,2	0,3	5,3	0,2	0,3	0,3	0,2	0,6	0,8
TNSJ	0,2	0,3	5,3	0,2	0,3	0,3	0,2	0,6	0,8
MESH	0,3	5,2	2,3	0,2	0,3	0,3	0,2	0,6	0,8

Table 24: Number of responses indicating the rigid pavement treatment is not applicable (n/a) or the rater had no experience (n/e) for each pavement type.

The consultant used experience, the above summary report, and discussions with various SDDOT personnel to judge the relative values for each condition where a treatment was considered feasible. Since it was difficult to make a set of hard and fast rules regarding what constituted a trigger and what didn't, the consultant had to use significant professional judgment to process this data. In the end, a set of triggers were developed.

The consultant used the following process to decide. The questionnaire indicated by treatment, pavement type and condition index the number of SDDOT experts that thought a certain level of extent and severity of that condition should trigger a treatment. As mentioned earlier, the questionnaire was summarized using the format shown in Table 25. From these tables, the consultant identified which cells represented a reasonable majority of the experts. The shaded cells in this example indicate this opinion. The example shows the response to fatigue cracking triggers for a two inch overlay on a thin on strong pavement type.

	Severity		
Extent	Low	Medium	High
Low	0	1	0
Moderate	2	8	4
High	0	7	0
Extreme	0	4	0

Table 25: Expert opinion as to what level of fatigue cracking could be fixed by a 2 inch AC overlay on a "Thin on Strong" pavement type.

From this, the deduct values were obtained for each severity/extent combination where the majority of experts were grouped. Theses are shown in Table 26. Finally, from the deduct values a condition index was calculated using a maximum condition index of 5.0. These are shown in Table 27.

	Severity		
Extent	Low	Medium	High
Low			
Moderate		1.7	2.7
High		3.1	
Extreme		5.0	

Table 26: Deduct values representing the fatigue cracking trigger limits for a 2 inch AC overlay on a "Thin on Strong" pavement type.

	Severity		
Extent	Low	Mediun	High
Low			
Moderate		3.3	2.3
High		1.9	
Extreme		0.0	

Table 27: Condition index values representing the fatigue cracking trigger limits for a 2 inch AC overlay on a "Thin on Strong" pavement type.

From this final table, it can be seen that at a fatigue cracking level of 3.3, one would begin to consider a 2 inch AC overlay on TonS pavements. It can also be seen that this treatment would be considered until the fatigue cracking level reached 0.0. Therefore, the fatigue cracking trigger zone for a 2 inch AC overlay on TonS pavements is 0.0 to 3.3 according to the panel of experts. This same process was carried out for every treatment, pavement type, condition index combination. The results of this analysis are shown in Appendix QQ.

Following the development of the trigger limits from the study, the consultant reviewed them with the SDDOT pavement management engineer. This review had the effect of 'smoothing' out the triggers to represent a more balanced set. The result of this review is the spreadsheet of trigger limits shown in Table 28 and Table 29.

6.3.2 Rigid Pavement Triggers

Table 28 summarizes the treatment triggers for each rigid pavement treatment. It is important to apply Boolean logic rules when reading the logical connectors joining the various condition indexes. These logical connectors are shown directly above the set of triggers to which they apply. In most cases, they apply to more than just one row. The words OR and AND, and the parenthesis () have significant meaning which is imposed by the Boolean logic rules of precedence.

6.3.3 Flexible Pavement Triggers

Table 29 summarizes the treatment triggers for each flexible pavement treatment. And, as with the table for rigid treatments, it is important to apply Boolean logic rules when reading the logical connectors joining the various condition indexes in this table. The words OR and AND, and the parenthesis () have significant meaning which is imposed by the Boolean logic rules of precedence.

Trtmnt	Pvmnt Type	D Crack	Joint Spall	Crnr Crck	Faulting	Joint Seal	Rghnss	Punchouts
Logical Connectors					OR			
REC	CRCP	0.0 - 3.3	N/A	N/A	N/A	N/A	N/A	0 - 2.3
Logical Connectors		OR (	AND (	OR	))			
	TKSJ	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
	TKSJD	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
	TNSJ	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
	MESH	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
CSO4	CRCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		OR (	AND	AND		AND	)	
	TKSJ	0.0 - 3.3	2.0 - 3.3	0 - 3.3	0 - 2.3	N/A	0 - 4.0	N/A
	TKSJD	0.0 - 3.3	2.0 - 3.3	0 - 3.3	0 - 2.3	N/A	0 - 4.0	N/A
	TNSJ	0.0 - 3.3	2.0 - 3.3	0 - 3.3	0 - 2.3	N/A	0 - 4.0	N/A
	MESH	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		OR					OR	
4ACO	CRCP	0.0 - 3.3	N/A	N/A	N/A	N/A	0 - 4.0	0.0 - 3.3
	TKSJ	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	TKSJD	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	TNSJ	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		OR (	AND	AND	AND		)	
	MESH	0.0 - 3.3	2.0 - 3.3	0 - 3.3	0 - 2.3	N/A	0 - 4.0	N/A
PR1	CRCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		AND	AND					
	TKSJ	3.0 - 5.0	2.0 - 3.8	4.0 - 5.0	N/A	N/A	N/A	N/A
	TKSJD	.0 - 5.0	2.0 - 3.8	4.0 - 5.0	N/A	N/A	N/A	N/A
	TNSJ	3.0 - 5.0	2.0 - 3.8	4.0 - 5.0	N/A	N/A	N/A	N/A
	MESH	3.0 - 5.0	2.0 - 3.8	4.0 - 5.0	N/A	N/A	N/A	N/A
PR2	CRCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		AND	AND	AND	AND			
	TKSJ	3.0 - 5.0	2.0 - 3.8	4.0 - 5.0	1.0 - 3.8	N/A	3.5 - 5.0	N/A
	TKSJD	3.0 - 5.0	2.0 - 3.8	4.0 - 5.0	1.0 - 3.8	N/A	3.5 - 5.0	N/A
	TNSJ	3.0 - 5.0	2.0 - 3.8	4.0 - 5.0	1.0 - 3.8	N/A	3.5 - 5.0	N/A
	MESH	3.0 - 5.0	2.0 - 3.8	4.0 - 5.0	1.0 - 3.8	N/A	3.5 - 5.0	N/A
PR3	CRCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		AND	AND	AND	AND			
	TKSJ	3.0 - 5.0	2.0 - 3.8	1.9 - 4.4	1.0 - 3.8	N/A	3.5 - 5.0	N/A
	TKSJD	3.0 - 5.0	2.0 - 3.8	1.9 - 4.4	1.0 - 3.8	N/A	3.5 - 5.0	N/A
	TNSJ	3.0 - 5.0	2.0 - 3.8	1.9 - 4.4	1.0 - 3.8	N/A	3.5 - 5.0	N/A
	MESH	3.0 - 5.0	2.0 - 3.8	1.9 - 4.4	1.0 - 3.8	N/A	3.5 - 5.0	N/A
SSJ	CRCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	TKSJ	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	TKSJD	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	TNSJ	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	MESH	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors					OR			
UCO	CRCP	0.0 - 3.3	N/A	N/A	N/A	N/A	N/A	0 - 2.3
Logical Connectors		OR (	AND (	OR	))			
	TKSJ	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
	TKSJD	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
	TNSJ	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
	MESH	0.0 - 3.3	0.0 - 3.3	0 - 2.3	0 - 2.3	N/A	N/A	N/A
BCO	CRCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors			AND	AND	AND			
	TKSJ	N/A	4.0 - 5.0	4.5 - 5.0	4.5 - 5.0	N/A	0.0 - 4.0	N/A
	TKSJD	N/A	4.0 - 5.0	4.5 - 5.0	4.5 - 5.0	N/A	0.0 - 4.0	N/A
	TNSJ	N/A	4.0 - 5.0	4.5 - 5.0	4.5 - 5.0	N/A	0.0 - 4.0	N/A
	MESH	N/A	4.0 - 5.0	4.5 - 5.0	4.5 - 5.0	N/A	0.0 - 4.0	N/A

Table 28: Trigger limits for rigid pavement treatments.

Treatment	Pavement Type	Transverse Crack	Fatigue Crack	Rutting	Patching	Block Crack	Roughness
Logical Connectors		OR		OR	OR		
REC	FD	0 - 4.0	0 - 2.3	N/A	0 - 2.3	0 - 2.0	N/A
	THK	0 - 3.0	0 - 2.3	N/A	0 - 2.3	0 - 2.0	N/A
	TONS	N/A	0 - 2.3	N/A	0 - 2.3	0 - 2.0	N/A
	TONW	N/A	0 - 2.3	N/A	0 - 2.3	0 - 2.0	N/A
	AONC	N/A	0 - 2.3	N/A	0 - 2.3	0 - 2.0	N/A
Logical Connectors		(OR	) AND	AND (	OR	OR	)
2ACO	FD	N/A	N/A	N/A	N/A	N/A	N/A
	THK	N/A	N/A	N/A	N/A	N/A	N/A
	TONS	0 - 2.5	2 - 3.5	1 - 5.0	2 - 3.5	2 - 3.4	0 - 2.8
	TONW	0 - 2.5	2 - 3.5	1 - 5.0	2 - 3.5	2 - 3.4	0 - 2.8
	AONC	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		AND (	OR	OR	OR	OR	)
M102	FD	0 - 4.0	2 - 3.5	0 - 3.0	2 - 3.5	2 - 3.4	0 - 2.8
	THK	3.5 - 5.0	2 - 3.5	0 - 3.0	2 - 3.5	2 - 3.4	0 - 2.8
Logical Connectors		OR	OR	OR	OR	OR	
	TONS	0 - 2.5	2 - 3.5	0 - 3.0	2 - 3.5	2 - 3.4	0 - 2.8
	TONW	0 - 2.5	2 - 3.5	0 - 3.0	2 - 3.5	2 - 3.4	0 - 2.8
	AONC	0 - 2.5	2 - 3.5	0 - 3.0	2 - 3.5	2 - 3.4	0 - 2.8
Logical Connectors		OR	OR	OR	OR	OR	
M103	FD	N/A	N/A	N/A	N/A	N/A	N/A
	THK	N/A	N/A	N/A	N/A	N/A	N/A
	TONS	0 - 2.5	1 - 2.5	0 - 3.0	1 - 2.5	2 - 3.4	0 - 2.8
	TONW	0 - 2.5	1 - 2.5	0 - 3.0	1 - 2.5	2 - 3.4	0 - 2.8
	AONC	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		AND (	OR	OR	OR	OR	)
M2R	FD	0.0 - 4.0	2 - 3.5	0 - 2.0	2 - 3.5	2 - 3.4	0 - 2.8
	THK	3.5 - 5.0	2 - 3.5	0 - 2.0	2 - 3.5	2 - 3.4	0 - 2.8
Logical Connectors		OR	OR	OR	OR	OR	
	TONS	N/A	N/A	N/A	N/A	N/A	N/A
	TONW	N/A	N/A	N/A	N/A	N/A	N/A
	AONC	0 - 2.5	2 - 3.5	0 - 2.0	2 - 3.5	2 - 3.4	0 - 2.8
Logical Connectors			OR	OR	OR	OR	
CR03	FD	N/A	N/A	N/A	N/A	N/A	N/A
	THK	N/A	0.0 - 2.5	0.0 - 1.8	0.0 - 2.5	0.0 - 2.5	0.0 - 2.8
	TONS	N/A	0.0 - 2.5	0.0 - 1.8	0.0 - 2.5	0.0 - 2.5	0.0 - 2.8
	TONW	N/A	0.0 - 2.5	0.0 - 1.8	0.0 - 2.5	0.0 - 2.5	0.0 - 2.8
	AONC	N/A	N/A	N/A	N/A	N/A	N/A
R&S	FD	N/A	N/A	N/A	N/A	N/A	N/A
	THK	N/A	N/A	N/A	N/A	N/A	N/A
	TONS	N/A	N/A	N/A	N/A	N/A	N/A
	TONW	N/A	N/A	N/A	N/A	N/A	N/A
	AONC	N/A	N/A	N/A	N/A	N/A	N/A
Logical Connectors		AND	AND	AND	AND	AND	
CS	FD	4.0 - 5.0	3.3 - 5.0	4.0 - 5.0	2.3 - 5.0	3.4 - 5.0	4.0 - 5.0
	THK	4.0 - 5.0	3.3 - 5.0	4.0 - 5.0	2.3 - 5.0	3.4 - 5.0	4.0 - 5.0
	TONS	4.0 - 5.0	3.3 - 5.0	4.0 - 5.0	2.3 - 5.0	3.4 - 5.0	4.0 - 5.0
	TONW	4.0 - 5.0	3.3 - 5.0	4.0 - 5.0	2.3 - 5.0	3.4 - 5.0	4.0 - 5.0
	AONC	4.0 - 5.0	3.3 - 5.0	4.0 - 5.0	2.3 - 5.0	3.4 - 5.0	4.0 - 5.0

Table 29: Trigger limits for flexible pavement treatments

6.3.4 Road Width

One consideration the consultant included in developing the trigger limits was not to perform a rehabilitation treatment on a road whose width was less than the minimum tolerable. The minimum tolerable widths were supplied by SDDOT and are to be used as guidelines for the pavement management system. They are not intended to be used as 3-R design standards in any way. The list of minimum tolerable widths for resurfacing are given in Table 30.

Class of highway	Characteristic	Min. width (ft)
INTERSTATE	all segments	38
DIVIDED HIGHWAYS	non-interstate	30
NHS (non-divided)	< 500 ADT	28
	500 - 1000 ADT	30
	1000 - 1500 ADT	30
	> 1500 ADT	32
STP (non-divided)	< 400 ADT	24
	400 - 750 ADT	26
	750 - 1500 ADT	28
	> 1500 ADT	30

Table 30: Minimum tolerable widths before a road section would receive a rehabilitation treatment. PMS USE ONLY, NOT 3-R DESIGN STANDARDS.

In addition, the width of a road after it had received reconstruction was supplied by SDDOT. These too are not intended to be used as 3-R design standards in any way. The list of resulting widths after reconstruction is given in Table 31.

Class of highway	Characteristic	Total width (ft)	Individual widths (ft) [shldr-ln-ln-shldr]
INTERSTATE	all segments	38	4-12-12-10
DIVIDED HIGHWAYS	non-interstate	36	4-12-12-8
NHS & STP (non-divided)	>1500 ADT	40	8-12-12-8
	1500 -400 ADT	36	6-12-12-6
	<400 ADT	32	4-12-12-4

Table 31: Resulting width of road after reconstruction. PMS USE ONLY, NOT 3-R DESIGN STANDARDS.

6.4 The Impacts

When a treatment is applied to a road section it causes a number of changes to occur. These changes, collectively called treatment impacts, could affect: (a) the immediate condition of the road, (b) the width of the road, (c) the pavement type of the road, (d) the future performance of the road, and (c) the future treatment alternatives available for the road. A well designed pavement management system must have a mechanism to account for these changes.

The following sections discuss the treatment impact models the consultant developed for SDDOT's pavement management system.

6.4.1 Condition Resets

One of the first impacts a treatment has when applied to a road is how the condition of the road is changed. This changed is referred to as the condition index reset. It is required in the pavement management system so that the system can predict what the future condition index values will be in the years following the treatment. These future values, in turn, are used to trigger any subsequent treatments. Table 33 and Table 34 define the condition index resets used in South Dakota. These impacts are given in these tables as "C-X", where "C" is the code representing the type of improvement, and "X" is the amount of the improvement. The possible type of improvement codes for "C" are listed in Table 32.

Code	Meaning
A	Absolute reset means when the treatment is applied, the index gets reset to the value supplied;
R	Relative reset means when the treatment is applied, the index gets reset by adding the amount of improvement to the current value of the index.
P	Percent reset means when the treatment is applied, the index gets reset by adding a percent of the current value of the index to the current value of the index.
N	No reset means that the treatment has no effect on the index.

Table 32: Types of improvement a treatment can have on any condition index.

Treatment	TRCR	FTCR	PTCH	BLCR	RUT	RUFF
RECF	A-5	A-5	A-5	A-5	A-5	A-5
2ACO	A-5	A-5	A-5	A-5	A-5	A-4.8
M120	A-5	A-5	A-5	A-5	A-5	A-4.8
M135	A-5	A-5	A-5	A-5	A-5	A-5
2MAR	A-5	A-5	A-5	A-5	A-5	A-5
CPR3	A-5	A-5	A-5	A-5	A-5	A-5
RAS	N-0	N-0	N-0	N-0	N-0	N-0
CS	R-1	R-1	R-1	R-1	N-0	N-0

Table 33: Flexible pavement treatment condition index reset values.

Treatment	DASR	JTSP	CRCR	FLTG	JTSL	POUT	RUFF
RECR	A-5	A-5	A-5	A-5	A-5	A-5	A-5
CS45	see note 1						
45AO	see note 1						
PR1	R-1	A-5	N-0	N-0	A-5	N-0	N-0
PR2	R-1	A-5	N-0	A-4.5	A-5	N-0	A-4.5
PR3	R-1	A-5	R-1.5	A-4.5	A-5	N-0	A-4.5
SASJ	N-0	N-0	N-0	N-0	A-5	N-0	N-0
UBCO	A-5	A-5	A-5	A-5	A-5	A-5	A-5
BO	A-5	A-5	A-5	A-5	A-5	A-5	A-5

Table 34: Rigid pavement treatment condition index reset values.

NOTE 1:

The treatments **CS45** (crack and seat with a 4.5" overlay) and **45AO** (4.5" overlay) are different from the other rigid pavement treatments. The reason for this is they change the pavement type to **AonC** (Asphalt on Concrete). And, the condition of AonC pavement sections is evaluated using the flexible condition indexes, not the rigid indexes. This means that although the treatment fixes the rigid condition, the resets are actually applied to the flexible indexes because from the time the treatment is applied until the end of the analysis period, the section is evaluated as if it were an AonC and not a rigid pavement.

6.4.2 Other Resets

Besides resetting the condition index values, pavement treatments have a number of other impacts on the road section. These are things like roadway widths as presented earlier in section 6.3.4 Road Wid. A treatment can also change the type of pavement such as when an asphalt overlay is placed on a rigid pavement thereby making the pavement type an AonC.

Another type of treatment impact has to do with the slope of the resulting performance curve. When predicting the future condition index values, the South Dakota pavement management system follows the slope of the performance curve at the current age of the pavement. This means that if current age,condition point for the condition index does not fall on the performance curve the software shifts the performance curves horizontally so that it goes through the current age,condition point.

This "shifting" happens: (a) at the beginning of the analysis for a particular pavement section, and (b) after a treatment has been applied and the condition indexes have been reset. Recalling that the slope of the performance curves increases as the age increases will help understand that, a second mechanism to show a treatment's impacts is to reset the age. For example, if a treatment resets the age of the pavement back to zero, the resulting performance curve will have a smaller slope than it would have if the age were not set back to zero.

To deal with this issue properly, the consultant had to set up and track a number of different ages for each pavement section. For instance, the age of joint sealant is set to zero when the sealant is replaced, or the joint is covered. Therefore, the age used for the joint sealant condition index would use a joint seal age rather than a pavement age. This elaborate set of ages is explained in a later chapter which presents how the software was set up. It is mentioned here for completeness.

6.4.3 Performance Resets

The manner in which the South Dakota pavement management system calculates the benefits of a strategy is to use the area-under-the-curve[3]. In short, this approach calculates the benefit by subtracting the composite index for the do-nothing strategy from the composite index which results after applying the treatments for a repair strategy. The composite index for the do-nothing strategy is calculated using Equation 9 which combines the individual indexes. The composite index for the repair strategy is calculated from the respective composite index performance equation which is used after a treatment is applied. This subsequent performance equation is also called a treatment impact.

To provide an estimate of the performance life of the various rehabilitation treatments used in South Dakota, the consultant included this issue in the questionnaire. The questionnaire asked the PMS Advisory Team to estimate, from their experience, the time it took for each rehabilitation treatment to deteriorate to conditions which existed prior to the rehabilitation treatment being applied.

Since the PMS Advisory Team was asked to estimate the average life based on a set of combined pavement condition, the consultant could only develop treatment pavement performance curves for the composite index. To develop performance curves for each individual condition index would have required the PMS Advisory Team to provide life estimates for more than 400 matrices representing the combinations and permutations of rehabilitation treatments, pavement types and pavement conditions. This would have been an almost impossible task.

Therefore, for the purposes of this project, the performance curves resulting from this step serve only to calculate the benefits of applying treatments. In the actual South Dakota PMS the assumption is made that the performance for each individual and composite index after a treatment is the performance for the resulting pavement type at an age of zero. Recall that the pavement type is reset before the new performance curve is used. For instance, when an asphalt overlay is performed on a rigid pavement, the system first changes the pavement type to AonC, then it follows the performance curve for that pavement type.

The conditions described on the questionnaire as existing prior to the rehabilitation of flexible pavements were as follows:

- transverse cracking with medium severity and medium extent,
- fatigue cracking with medium severity and moderate extent,
- patching / patch deterioration with medium severity and moderate extent,
- block cracking with low severity and low extent,
- rutting with moderate severity,
- roughness with moderate severity.

The conditions described on the questionnaire as existing prior to the rehabilitation of rigid pavements were generally as follows:

- joint spalling with medium severity and high extent,
- corner cracking with low severity and low extent,
- faulting with medium severity and high extent,
- joint damage with medium severity and high extent,
- roughness with moderate severity.

The results of the questionnaire are presented in Appendix P for flexible pavements and Appendix Q for rigid pavements. One of the first observations to make when examining these appendices, is the fact that not all experts provided estimates. This is so because those experts felt that they did not have sufficient experience with either the treatment or the pavement type to provide reliable answers.

The consultant developed performance equations from this information in much the same manner as before. In general, this means that the consultant used the standard equation previously introduced as Equation 10, and, the deduct value matrix for the respective condition and pavement type. After these two similarities, however, there were two significant differences in the approach.

First, the consultant only had two points to regress a curve through. One point was the composite index represented by the assumed pavement conditions. For flexible pavements this value was 46.8 based on a scale of 0 to 100, and 2.34 based on a 0 to 5 scale. For rigid pavements the value was 41 for a scale of 0 to 100, and 2.1 for a scale of 0 to 5. The second point used in the regression was a perfect rating of 100 or 5 at 0 age.

The second difference was the manner in which the consultant forced the regression to return an exponential form rather than a straight line. To produce an exponential form, the consultant assumed an exponent value of 2.00. The consultant selected the value of 2.00 because it was a nice round figure, and, it represented a typical exponent value found in the consultant's experience with various other states. An exponent of 2.00 is much more typical than an exponent of 1.00, which would represent a straight line.

Given these two assumptions, the consultant proceeded to perform the regression analysis. Appendix R shows the equation coefficients which ultimately resulted from this analysis. In addition, Table 35 shows the appendix number which has the details of the regression for each treatment type.

Appendix	pavement Type
S	Full Depth
T	Thick
U	Thin on Strong
V	Thin on Weak
W	ACP on PCCP
X	Continuous reinforced PCCP
Y	Thick Short Jointed w/o dowel
Z	Thick Short Jointed w/ dowels
AA	Thin Short Jointed w/o dowels
BB	Mesh reinforced long jointed w/ dowels

Table 35: List of Appendices which give the details for the composite index performance curves which result after a treatment is applied for each pavement type.

7. Prepare Interim Report

Provide an interim report and presentation to the project's technical panel describing findings of Tasks 1-6.

Two significant issues appeared in the project which had an impact on the nature of the work being done. The first was the discovery of the fact that there was no historical data to develop performance curves from. The second was that there was no appreciable distress data to test the system with. The urgent need for a resolution of these two issues caused the nature of this particular task to change somewhat. Under mutual agreement, the project manager agreed to exchange this task for: (a) the design, execution and re-execution of the very detailed expert opinion questionnaire, (b) the preparation of the report explaining the type of distress survey required in SDDOT to support a life cycle cost optimization analysis (see Appendix RR for this report), and (c) a presentation to the Executive Team explaining why the distress survey was required. The success of (b) and (c) above was manifested in the addition of the following task to implement a pilot distress survey.

8. Implement Distress Survey

Design pavement distress survey and check procedures, calibrate raters, create data entry software, train SDDOT staff, collect data on all of I29, I90, I229 and US 281, and enter the data into the enhanced pavement management system.

8.1 The Pilot Project

This chapter of the report covers a basic description of the additional work done to conduct a pilot pavement distress survey of the Interstate Highway System and US281 and enter it in the database for South Dakota as part of this project. The pavement distress survey was based on the SHRP manual[17] and work done by others.[10, 20, 33]

The pavement distresses surveyed covered the distresses developed specifically for South Dakota under a previous task. A list of these distresses and their associated severities has already been given in Table 12 on page 82. Similarly, the extents for these distresses were given in Table 14 on page 83. To conduct the pavement condition survey a computer program was developed to provide an easy form to input and save the condition data. A copy of that computer program has been supplied to SDDOT. For this reason the following explanation of the survey procedures mentions how to use this program.

In addition, a pavement distress survey procedure was developed in line with the original recommendations for a pavement distress survey procedure made by the consultant to SDDOT prior to the contract modification. A copy of those recommendations are included in this report as Appendix RR.

8.2 The Distress Survey

The pilot pavement distress survey was conducted using the following instructions to the raters and descriptions for the use of the computer input.

8.2.1 Location

The route and mile reference marker information has been precoded into the computer program for all rating segments, along with a description of the starting MRM. Basically, a new rating segment is started every 1/4 mile, or every MRM, or every pavement type change. The intent is to rate the roads in 1/4 mile increments, however, it was important to keep the segments lined up with the MRMs. This location information generally should not have to be changed. Any necessary changes should be noted in the comment field at the bottom of the screen.

8.2.2 Exempt Code

Enter an exempt code when: (a) you cannot enter pavement condition information on the screen for all or a portion of the segment, or, (b) the condition has not changed from the previous segment. The exempt codes are given in Table 36.

Exempt Code	Description
1	Bridge
2	Unpaved Road
3	Under Construction,
4	Other
5	Same condition as previous segment.

Table 36: Exempt codes for the pavement distress survey.

Where bridges extend over the full length of the segment, fill in the exempt code and pavement condition information. Where the bridge does not extend over the full length of the segment, fill in the exempt code and the pavement condition information for the rest of the segment. Indicate the MRM of the end of bridge/beginning of pavement in the comments field at the bottom of the screen.

Do not enter pavement condition data for unpaved roads or for pavements that are obviously under construction. If this circumstance extends only partially through the segment, then enter the pavement condition data for the remainder of the segment and enter the beginning (or ending) of that segment in the comments field.

Enter an exempt code of (4) if pavement condition data is not available for any other reason. Then, give the reason in the comments field.

Use exempt code (5) if the pavement conditions for the current segment are the same as the preceding segment. This exempt code is provided so repetitive data does not have to be entered.

8.2.3 Pavement Type

The pavement type code has been precoded from the Planning File along with the MRM data.

Pavement Type Codes are: (B) Bituminous Pavement and (C) Portland Cement Concrete Pavement. Knowing the pavement type code allows the software to select the input form with the proper distresses on it (recall that flexible and rigid pavements have different distresses). If the pavement type observed in the field is different from that shown on the screen for the segment being rated, change the code to the pavement type observed and input the condition data for the appropriate pavement type. If there is a pavement type change within the segment being rated use the code for the predominate type of pavement in the segment and note the MRM where the pavement type changes in the comment field.

8.2.4 Selecting from Lists

Descriptions of both the distress severity and extent as well as the exempt and pavement codes can be seen for each field having a downward pointing arrow beside it. To view the codes and descriptions for such fields press the **[Ctrl]** and **[PgDn]** keys together. Then, when the list of codes is being displayed, use the arrow keys to highlight the desired code and press **[Enter]** to select it.

8.2.5 Flexible Distress Data

The following sections explain what to observe and record for each distress type. Table 37 shows some guidelines as to how to interpret the different extent levels for each flexible pavement distress.

8.2.5.1 Transverse Cracking

For Transverse Cracking enter the code for the total extent of cracking observed in each rated section under the column for the *predominant* severity observed for each section.

Transverse Cracking Extent Code:

1) = > 50 ft. spacing,

2) = 25 ft to 50 ft spacing,

3) = < 25 ft spacing.

8.2.5.2 Fatigue Cracking

For Fatigue Cracking, enter code for the total extent of fatigue cracking in the wheelpaths of the section under the column for the *predominant* severity observed for each section.

Fatigue Cracking Extent Code

1) = 1% to 9% of the wheelpaths,

2) = 10% to 24% of the wheelpaths,

3) = 25% to 49% of the wheelpaths,

4) = 50% to 100% 0f the wheelpaths.

8.2.5.3 Patching / Patch Deterioration

For Patching/Patch Deterioration, enter the code for the total extent of cracking observed for the total area in each rated section under the column for the column for the *predominant* severity observed for each section.

Patching/Patch Deter. Extent Code

1) = 1% to 9% of the total lane area,

2) = 10% to 24% of the total lane area,

3) = 25% to 49% of the total lane area,

4) = 50% to 100% of the total lane area.

Note, when a patch crosses only one wheelpath it is considered 1/2 lane patch, when the patch crosses both wheel paths it is considered a full lane patch.

8.2.5.4 Block Cracking

For block cracking enter the code for the total density of cracking observed for the total area in each rated section under the column for the *predominant* severity observed for each section.

Block Cracking Extent code:

1) = 6 ft to 10 ft block spacing,

2) = 3 ft to 6 ft block spacing,

3) = < 3 ft block spacing

Distress	Extent	Units /Segment	Segment Length 0.01 mile	0.10 mile	0.25 mile
Transverse Cracking	1)= > 50 ft.,	Number/Segment	< 1	1 - 10	1 - 26
	2)= 25 ft - 50 ft,		1 - 2	11 - 21	27 - 52
	3)= < 25 ft.		>2	>21	> 52
Fatigue Cracking	1)= 1 - 9% of wp,	Total ft./Segment	1' - 9'	10' - 95'	26' - 238'
	2)= 10 - 24% of wp,		10' - 25'	96 - 253'	239' - 634
	3)= 25 - 49% of wp,		26' - 52'	254' - 517'	635' - 1294
	4)= 50 - 100% of wp.		>52'	>517'	> 1294
Patching/ Patch Deterioration	1)= 1 - 9% area,	Total ft./Segment	1' - 5'	5' - 48'	13' - 119'
	2)= 10 - 24% area,		6' - 13'	49' - 127'	120' - 317'
	3)= 25 - 49% area,		14' - 56'	128' - 259'	317' - 647'
	4)= 50 - 100% area.		> 56'	> 259'	> 647"
Block Cracking:	1)= 6 - 10 ft spacing,	No./Segment	4 - 8	45 - 88	110 - 220
	2)= 3 - 6 ft spacing,		9 - 17	89 - 176	221 - 440
	3)= < 3 ft block spacing.	"	> 17	> 176	> 440

Table 37: Flexible pavement distress extent guides.

8.2.6 Rigid Distress Data

The following sections explain what to observe and record for each distress type. Table 38 shows some guidelines as to how to interpret the different extent levels for each rigid pavement distress.

8.2.6.1 D Cracking & ASR, and Corner Cracking

For both D Cracking & ASR as well as for Corner Cracking, enter code for the total extent of the slabs crack in the section under the column for the most *predominant* severity observed for each section.

D Cracking & ASR and, Corner Cracking Extent Code:

1) = 1% to 9% of the slabs,

2) = 10% to 24% of the slabs,

3) = 25% to 49% of the slabs,

4) = 50% to 100% 0f the slabs.

8.2.6.2 Joint Spalling, Faulting, and Joint Seal Damage

For Joint Spalling, Faulting, or Joint Seal Damage, enter the code for the total extent of the distress observed for the total number of joints in each rated section under the column for the column for the most *predominant* severity of the distress observed for each section.

Joint Spalling, Faulting, and Joint Seal Damage Extent Code:

1) = 1% to 9% of the total joints,

2) = 10% to 24% of the total joints,

3) = 25% to 49% of the total joints,

4) = 50% to 100% of the total joints.

8.2.6.3 Punchouts

For Punchouts enter the code for the total number of Punchouts observed per mile in each rated section under the column for the most *predominant* severity observed for each section.

Punchouts Extent Code:

1) = < 10 per mile,

2) = 10 to 25 per mile,

3) = > 25 per mile.

Distress	Extent	Units/Segment	Segment Lengths		
			0.01 mile	0.10 mile	0.25 mile
D Cracking & ASR, and Corner: Cracking	1)= 1 - 9% slabs,	# Slabs/Segment	-	1 - 2	1 - 6
	2)= 10 to 24% slabs,		-	3 - 6	7 - 15
	3)= 25 to 49% slabs,		1	7 - 12	16 - 32
	4)= 50 to 100% slabs.		2 - 3	13 - 26	33 - 66
Joint Spalling, Faulting, and Joint Seal Damage:,	1)= 1 to 9% joints	# Joints/Segment	-	1 - 2	1 - 6
	2)= 10 to 24% joints		-	3 - 6	7 - 15
	3)= 25 to 49% joints,		1	7 - 12	16 - 32
	4)= 50 to 100% joints.		2 - 3	13 - 26	33 - 66
Punchouts:	1) = < 10 per mile,	Number/Segment	-	-	1 - 2
	2) = 10 to 25 per mile,		-	1 - 3	3 - 6
	3) = > 25 per mile.		-	>3	>6
Note: The values listed assumes short jointed PCCP with average 20 ft. Joints which are typical for South Dakota, for 60 ft reinforced PCCP divide values shown by 3.					

Table 38: Rigid pavement distress extent guides.

8.3 The Field Work

The pilot pavement distress survey was conducted by personnel from Nichols Consulting Engineers working out of Reno, Nevada. The survey was conducted over a period of 3 weeks from Sept. 12 through to the end of the month.

The survey was conducted by Mr. Mark Potter from Nichols Consulting Engineers, with van and driver supplied by South Dakota DOT.

The consultant estimated that the duration of the survey would take about 200 hours. The actual time required to conduct the survey was very close to this time limit.

There were no major problems encountered during the survey processes. However, there was a minor problem with the time required to enter the distress data into the computer program in the field survey. The problem seemed to relate mostly to very short distance between MRM's listed in the segment file. The survey was designed to enter data for 1/4 mile segments. To accomplish this the survey database was preloaded with segments which began at every MRM, or every 1/4 mile, or every pavement type change. This segmenting process resulted in a large number of segments with very short lengths, some as short as 30 ft, occurring at the end of the MRM's 'mile'. The very large number of short segments in the segment database made it very time consuming to enter the data into the computer in the field.

To correct this problem, the data was recorded on hard copy at longer segment lengths, then transferred to the computer program in the office. This problem can be corrected in the future by screening the MRM locations loaded into the computer file and limiting the segment lengths to 1/4 mile *or greater*, especially at the end of an MRM section.

For future pavement condition surveys the consultant recommends that SDDOT set up a check scheme to confirm the reliability of that survey. We recommend a procedure similar to that recommended by Dr. Joe Mahoney at the University of Washington[34].

In short, this procedure would consist simply of SDDOT collecting their own pavement distress data on a randomly selected 5% sample of the rated segments. The original rating could be carried out by SDDOT personnel or by a contractor. It assumed that the SDDOT personnel would use a manual collection procedure, while the contractor would use either manual or automated collection procedures. In either case, the 5% sample data used for checking should be collect by SDDOT manually.

The pavement distress data should then be converted to the respective index values using the deduct values recommended earlier, or other such update deduct values. This would result in the contractor's data format matching 5% sample data's format. Both sets of data would then be tested using standard statistical paired t-tests. The paired two sample Student's t-test for means using a standard significance value of 5% would be the easiest to interpret.

To reduce the cost of collecting pavement distress data the SDDOT could consider the collection only a sample of the entire State highway system.

Although this should be used as a last resort in the absence of adequate funding. There has been very little research done in this area to help define what the sample size should be to fully represent the entire pavement network. Some work was done in Texas by Dr. Joe Mahoney based on a full sample from one of the 26 Districts in the State. He found that a sample size of about 10% could be used to reasonably represented the average found on the highway network[35]. Similar work was done in Virginia with somewhat the same findings[20].

Furthermore, in the NHI class on Pavement Management for Local Agencies, Dr. Roger Smith reviewed the same issue about necessary sample size. The recommendations he put in the class notes was that a 10% sample was needed to represent the average pavement's conditions. For reasonable network pavement performance projections a sample size of 20 % was needed. To estimate costs associated with pavement condition over time and various actions a sample size of 30 % was needed[36].

One possible way to verify the required sample size would be for SDDOT to look at the data collected on US281 and check the sensitivity of the pavement distress data at various sample levels to represent the average conditions found on that route. SDDOT could test a 5%, 10%, 15%, and 20% randomly selected sample from the same route and check to see how well it represents the same average. If a 10% sample reasonably represents the same average as the original sample then the sample sizes noted above may be followed. If higher or lower value provides a more reasonable estimate of the average value then the ranges noted above should be shifted to match. This test, of course, should be properly designed if SDDOT were to rely on the results.

9. Configuring the Software

Provide and install operational software which incorporates the developed performance curves and treatment strategies, which provides full pavement management functions (including database management, analysis of pavement performance, selection of maintenance, rehabilitation and reconstruction alternatives, optimized investment strategies, and graphic representation of results), and which interfaces to existing data structure. Software should support at least six users via Local Area Network, and should support pavement management on the state's entire 8000 mile highway network.

The consultant configured the three pieces of software, dROAD, dTIMS, and dMAP, to store all required data, and perform all required analysis using the engineering models described in the previous sections.

9.1 dROAD: The Database

9.1.1 Overview

This section of the chapter gives an overview of dROAD which was the first of three software packages installed and set up by the consultant for SDDOT's pavement management system. Anyone who intends to use dROAD must read and understand its documentation.[6,37]

dROAD is a microcomputer software system. It is a completely generic and flexible database management system. It was built exclusively to handle all the problems associated with storing and retrieving roadway data. dROAD enables a user to design, build and maintain a sophisticated relational database. With dROAD a user can integrate all their infrastructure data into one relational database. The user can keep data organized in an efficient logical manner. As a database management system, dROAD is capable of storing and retrieving data that describes the attributes of what is on, under, or beside every foot of roadway in a road network. dROAD is designed to allow users to define and maintain a set of independent, yet interconnected data tables.

dROAD is easy to use because it has the following basic features:

1. user-friendly interface with menus and context sensitive help;
2. comprehensive, easy-to-follow user manual;
3. modular design that can be integrated with other systems;
4. no extra hardware or software requirements.

dROAD was not only the first, but remains one of the only database systems that perform *Dynamic Segmentation*. Dynamic Segmentation automatically combines data that describe different sets of sections. dROAD can mix a variety of data types in the same database. The data can be mixed together, regardless of the number of ways the road network is divided into sections.

dROAD stores each piece of data only once. This totally eliminates data redundancy; a problem encountered with traditional relational databases approaches. In addition, dROAD is completely flexible. It is flexible about the definitions of location referencing, roadway sections, database files and, database fields. A user can build a custom database structure. It is built as quickly and easily as entering the data.

dROAD offers a wide range of reporting options. Each of the reports allow users to send the results to a printer or to a file. dROAD provides the standard database query facilities, a data dictionary and, a set of reports designed exclusively for roadway-related data. Among these, strip maps, cross sections, ad hoc query reports, and, data input forms are the most notable.

dROAD offers the perfect tools to accomplish the following tasks:

- design and create a database that meets a user's current needs;
- expand the database as the user's needs grow;
- integrate many different kinds of data into one database;

- create and maintain a single database to supply data to a pavement management system, a bridge management system, a geographic information system, and, any other analysis system;

- import data directly from existing computer files;

- establish historical files, allowing a user to keep track of such information as pavement condition, so that analysis can be performed to develop performance curves;

- use different location reference systems at the same time;

- maintain a data dictionary describing all fields in the database;

- set up a sophisticated security plan to protect important data;

- perform many different kinds of transformations on the data to calculate and replace the values in one field based on the values in other fields;

- create as many query reports, strip maps, data input forms, and transformations as needed, keep them in a library and use them at any time;

- extract any data according to any set of sections;

- sum the length of all roads that meet search conditions;

- sum the value of any database field on any road that meets search conditions;

- find the average and standard deviation for any database field on any road that meets search conditions;

9.1.2 Background

This report describes the dROAD database definition and data loading process for the South Dakota Department of Transportation (SDDOT). It briefly described the dROAD data integration capabilities and then goes on to describe the database definition and data loading procedures used to store the data supplied by SDDOT. The final sections describe the necessary changes to the structure to prepare data to drive the pavement management system and a process to track historical information over time.

Before any discussion on the database definition and data loading processes can take place, an introduction to dROAD is necessary. Although the report assumes the reader, interested in working with dROAD, is familiar with the documentation[6,37], some features of dROAD are repeated here for the convenience of readers who are not.

dROAD was designed to integrate many different types of data describing many different infrastructure elements. *Independent segmentation* refers to the process of storing and providing access to roadway data describing different data collection segments in the same database. For example, roughness data may be collected and summarized over quarter mile segments, while condition data may be summarized using one-tenth mile segments. The previously mentioned RES database in SDDOT has independent segmentation. Having the capability of independent segmentation does not guarantee, but necessitates the need for, *dynamic segmentation*. Dynamic segmentation is the ability to transfer data between different segments, and the ability to report all data according to any set of segments. dROAD performs dynamic segmentation automatically during output reports and queries. RES, on the other hand, requires custom programs to be built each time a user requires dynamic segmentation.

To provide for independent segmentation, dROAD uses the *perspective*. A perspective is defined as a specific view of the road network having a unique set of sections. dROAD allows the user to define various types of perspectives for various types of data. The perspective types, for instance, can handle point data such as structures and accidents, section data such as inventory and condition, and special historic data such as construction history, to name only a few. Perspectives allow an agency to store and analyze many different types of data in the exact manner that it was collected, hence, give dROAD independent segmentation.

Table 39 shows the list of perspectives the consultant placed into SDDOT's dROAD database when designing and loading it. The next section of this chapter describes the structure of each of these perspectives and the procedures required to load it.

Perspective	Description of contents
ROADS	Describes each road with one section which begins at the start of the road and terminates at the end of the road.
MRM	Contains the mileage reference markers used for location referencing within the SDDOT.
PLAN1993	Contains selected data fields form the State's Planning File for 1993.
PLAN1994	Contains the full 1994 Planning File describing the inventory and road condition of the network.
PCI1990/3	Describes the PCI pavement condition of the road network collected in 1990 and 1993.
DISTRESS	Contains all the raw distress data and the condition indexes for all roads considered in the pilot project.
PAVETYPE	Contains the pavement types for all roads considered in the pilot project.
PMS	Contains the section limits used for pavement management purposes.
STIP	Contains the section limits for the 5 year capital committed programme.

Table 39: Perspectives in SDDOT's dROAD database.

9.1.3 SDDOT's Database

9.1.3.1 The ROADS Perspective

The ROADS perspective contains one file which is used to describe the general characteristics about the roads themselves. Currently, the roads perspective contains one record for each of the approximately 200 roads within the SDDOT highway network. The ROADS perspective can be thought of as a place holder, it is the top level in the dROAD database structure. Currently, the perspective contains the eight character road name only. This is used for finding the road in the database and for sorting and reporting. The road identifier consists of the following:

1) one character for the data class

"1" : State road
"2" : County road
"3" : City road
"4" : Federal domain road
"5" : Frontage road

2) three character highway number

3) three character highway suffix

9.1.3.2 The MRM Perspective

The Mileage Reference Marker (MRM) perspective contains the location reference method for the state. A MRM is defined as a point in the field at a known location given in terms of the distance from the beginning of the road (mile point). The MRM perspective is a point perspective containing the mile point address of each MRM. In dROAD an address is defined as a sequence of numbers and characters used to represent the position of a point on the road. Addresses can be given in terms of any location reference method. For example, an accident occurring 0.35 miles from MRM 52.000 has at least two unique addresses. First, assuming MRM 52.000 is at mile point 52.010, the mile point address for the accident is 52.360. Second, the MRM address of the accident is "52.000 + 0.350". The mile points calculated from the MRM file were used to define the length of each road in the highway network.

9.1.3.2.1 Description

The MRM data file supplied by SDDOT contained the following fields:

update type: one character representing the following:

A	a new MRM added to the file
C	a changed MRM in the file
D	a deleted MRM in the file
E	a deleted MRM in the file
M	a MRM with a mileage adjustment

area: the DOT area having maintenance responsibility coded as follows:

A	Aberdeen area
B	Brookings / Belle Fourche area
H	Huron area
P	Pierre area
M	Mobridge / Mitchell area
W	Winner area
S	Sioux Falls area
Y	Yankton area
R	Rapid City area
C	Custer area

region: the DOT region having maintenance responsibility coded as follows:

1	Region 1 (Aberdeen)
2	Region 2 (Mitchell)
3	Region 3 (Pierre)
4	Region 4 (Rapid City)

county: the two character county code given in Table 40.

data class: The class of the road the MRM is located on coded as follows:

1	State road
2	County road
3	City road
4	Federal domain road
5	Frontage road

highway: the highway number for the highway the MRM is located on

highway suffix: the highway suffix for the highway the MRM is located on.

MRM: the mileage reference marker code.

MRM type: the MRM type coded as follows:

1 Uniform
2 Special non-uniform (structure)
3 Special non-uniform (other then structure)
4 Dummy (an MRM that can not be coded)

mileage: the mileage location of the MRM

Installation date: the date the MRM was installed.

Description: a description of the location of the MRM

Code	County	Code	County	Code	County	Code	County
02	Aurora	18"	Davison	35	Hyde	52	Pennington
03	Beadle	19"	Day	36	Jackson	53	Perkins
04	Bennett	20	Deuel	37	Jerauld	54	Potter
05	Bon Homme	21	Dewey	38	Jones	55	Roberts
06	Brookings	22	Douglas	39	Kingsbury	56	Sanborn
07	Brown	23	Edmunds	40	Lake	57	Shannon
08	Brule	24	Fall River	41	Lawrence	58	Spink
09	Buffalo	25	Faulk	42	Lincoln	59	Stanley
10	Butte	26	Grant	43	Lyman	60	Sully
11	Campbell	27	Gregory	44	McCook	61	Todd
12	Charles Mix	28	Haakon	45	McPherson	62	Tripp
13	Clark	29	Hamlin	46	Marshall	63	Turner
14	Clay	30	Hand	47	Meade	64	Union
15	Codington	31	Hanson	48	Mellette	65	Walworth
16	Corson	32	Harding	49	Miner	68	Yankton
17	Custer	33	Hughes	50	Minnehaha	69	Ziebach
		34	Hutchison	51	Moody		

Table 40: County codes used in dROAD

9.1.3.2.2 Loading Process

To load the MRM data file supplied by SDDOT, the consultant proceeded in the following manner:

1. A dBASE III+ file called MRM.DBF was created matching the data structure discussed in the previous section.

2. The ASCII (text) file supplied by SDDOT was loaded into the MRM.DBF file.

3. The mileage field was modified so the implied mileage could be the true mileage of the MRM including the decimal places.

4. Additional fields were added to the MRM.DBF that were required for import into dROAD. These fields are related to the location of the MRM and its address.

5. The additional fields were filled with the MRM location information.

6. Records in the file with an update code of "D' were deleted.

7. The MRM perspective, Logical data group, and data items were added to the dROAD database.

8. The locations of the MRMs were imported into dROAD using the Modify Element Location function (option 2.2.0.0.)

9. The data fields for each MRM were imported into dROAD using the Browse Data View function (option 2.4.2.2.)

9.1.3.3 The 1993 Planning File Perspective

Selected fields from the 1993 Planning File were provided to the consultant for loading into dROAD. This information would serve two functions. First, the 1993 Planning File would serve as a test case or model for further information being loaded into dROAD. At the time the 1993 file was supplied, the 1994 Planning File was not yet available. Second, the information from the 1993 Planning File would provide a historical reference for comparison once the 1994 Planning File was supplied and loaded.

The Planning File contains a great deal of information about the South Dakota highway network. Planning File segments are of varying lengths and are recorded from one MRM to another MRM. In general terms, the Planning File contains the following information:

- Identification data
- Geometric data
- Traffic data
- Structural data
- Railroad crossing data
- Structures data
- Deficiency data
- Improvement cost data
- Administration cost data
- Project information data
- Plan data
- Stopping sight distances
- Condition data for several distress types
- Rut depths

9.1.3.3.1 Description

The Planning File has been described in other documents available within SDDOT as well as earlier in this report. Therefore, it will not be fully described here. To serve as a test model for further data loadings and as a historical record, the following fields from the 1993 Planning File were loaded:

- Location information (used for importing)

Data class and highway number
Beginning MRM and displacement
Ending MRM and displacement
Section length

- Identification information

  Scenic road
  County
  Highway region
  Plan and development district
  Population code
  Federal aid route number
  Highway system code
  Municipal code
  Rural urban code
  Functional class code
  City code
  Maintenance responsibility code

- Geometric information

  Lane width
  Roadway width
  Number of lanes
  Left shoulder width
  Right shoulder width
  One way - two way code
  Divided - undivided code
  Median width
  Median type
  Terrain
  Right of way width

- Traffic information

  Average daily traffic
  Percent trucks

- Structural information

  Year graded
  Year last surfaced
  Year last sealed
  Surface type
  Surface width
  Surface thickness
  Shoulder type

9.1.3.3.2 Loading Process

To load the 1993 Planning File supplied by SDDOT, the consultant proceeded in the following manner:

1. A dBASE III+ file called RAWPLAN.DBF was created to contain all information from the 1993 Planning File. This file contained 11 fields each 250 characters wide.

2. Another dBASE III+ file called PLANFILE.DBF was created containing the fields required for import into dROAD. These fields are outlined in the previous section.

3. The data from the 1993 Planning File, HR46.H93 was appended into RAWPLAN.DBF.

4. A computer program was written to delete the records from the Planning File that contained a data class equal to county road, city road, or federal domain road. This resulted in the file containing state roads and frontage roads only. Out of 3294 records, 1605 records were deleted and 1689 records remained.

5. Another computer program was written to search through the 1689 remaining records and transfer the required fields of information to the PLANFILE.DBF. The program also filled the necessary location fields required for import into dROAD.

6. A final computer program was written to validate the file prior to import to check the location related information. This process produced errors which were caused by the following:

   a) Highways in the Planning File could not be located in the MRM file. The MRM file was used to determine the exact location of each planning section. These errors usually occurred due to the transfer of State maintained roads to a county or city jurisdiction.

   b) Sections in the Planning File referenced MRMs that did not exist in the MRM file. MRMs in the Planning File were located after the end of the road defined in the MRM file. The MRM file was used to define the length of each road in the network.

7. Through the help of SDDOT staff Daris Ormesher, these errors were corrected.

8. The 1993 Planning File perspective, logical data groups, and data items were added to the dROAD database.

9. The locations of the 1993 Planning File sections were imported into dROAD using the Modify Element Location function (option 2.2.0.0.)

10. The data fields for each 1993 Planning File were imported into dROAD using the Browse Data View function (option 2.4.2.2.)

9.1.3.4 The PCI Perspectives

The PCI files contain pavement condition information collected in 500 foot samples. The information from the 1990 data collection year was loaded into a perspective called PCI1990 and the 1993 data was loaded into a perspective called PCI1993.

9.1.3.4.1 Description

The PCI files for the 1990 and 1993 data collection years contained the following information:

Highway:

the data class, highway number, and highway suffix.

BMRM:

beginning mileage reference marker of the individual project or segment.

DISP:

displacement of individual project from BMRM.

EMRM:

ending MRM of the individual project or segment.

DISP:

displacement of the individual project from EMRM.

Length:

length of the project or segment.

Sample unit MRM:

beginning MRM where 500 foot sample was taken.

Sample unit displacement:

the displacement from the sample unit MRM where the sample actually began.

Sample unit station:

If present, the nearest station to the sample unit MRM at the beginning of the test section.

Date:

the date of the inspection.

Year constructed:

the year of the original construction.

Dowels:

Yes or no for the indication of dowels.

County:

the county where the test section is located.

Slab width:

the width of the individual slab not necessarily the lane width.

Reinforcing:

Mesh or CRCP.

Joint skew:

measured in feet of skew for the individual panel.

Slab thickness:

the thickness of the slab taken from the Planning File and verified at the time of inspection.

Surface texture:

Carpet drag, tining, etc.

Shoulder type:

the type of shoulder: gravel, curb and gutter, etc.

Type of sealant:

Neoprene, silicone, or hot pour, etc.

Shoulder condition:

A condition rating for the shoulder, good, poor, or amount of drop-off.

Year surfaced:

the year of the last major surfacing taken from the Planning File.

Comments:

Any comment about the test or the sample unit.

Distress information: (low, medium, and high severity)

Alkali Reactive
Blow up
Corner breaks
Cracking: longitudinal, transverse, diagonal
"D" cracking
Faulting / Settlement
Joint seal damage
Lane / Shoulder drop-off
Patching greater than 5 square feet
Patching / Utility cuts
Polished aggregates
Popouts
Pumping
Punchout
Scaling / Map Cracking / Crazing
Shattered Slab
Shrinkage Cracks
Spalling Corner
Spalling Joints
PCI Rating

9.1.3.4.2 Loading Process

To load the PCI data files supplied by SDDOT, the consultant proceeded in the following manner:

1. Two dBASE III+ files were created to contain all information from the PCI data files.
2. A computer program was written to search through the PCI files to fill the necessary location fields required for import into dROAD.
3. Another computer program was written to validate the file prior to import to check the location related information. This process produced errors which were caused by the following:

   a) Highways in the PCI files could not be located in the MRM file. The MRM file was used to determine the exact location of each sample unit.

These errors usually occurred due to the transfer of State maintained roads to a county or city jurisdiction.

b) Sections in the Planning File referenced MRMs that did not exist in the MRM file. MRMs in the Planning File were located after the end of the road defined in the MRM file. The MRM file was used to define the length of each road in the network.

4. Through the help of SDDOT staff Daris Ormesher, these errors were corrected.

5. The 1990 and 1993 PCI file perspective, logical data groups, and data items were added to the dROAD database.

6. The locations of the 1990 and 1993 PCI file sections were imported into dROAD using the Modify Element Location function (option 2.2.0.0.)

7. The data fields for each PCI file were imported into dROAD using the Browse Data View function (option 2.4.2.2.)

9.1.3.5 The 1994 Planning File Perspective

The Planning File contains a great deal of information about the South Dakota highway network. Planning File segments are of varying lengths and are recorded from one MRM to another MRM. In general terms, the Planning File contains the following information:

- Identification data
- Geometric data
- Traffic data
- Structural data
- Railroad crossing data
- Structures data
- Deficiency data
- Improvement cost data
- Administration cost data
- Project information data
- Plan data
- Stopping sight distances
- Condition data for several distress types
- Rut depths

The entire 1994 Planning File was loaded into dROAD for state maintained roads and frontage roads.

9.1.3.5.1 Description

The Planning File has been described in other documents available within SDDOT and will not be fully described in this report. For a full description of the logical data groups (LDGs) and database fields for the 1994 Planning File, please refer to Appendix II.

9.1.3.5.2 Loading Process

The loading of the 1994 Planning File supplied by SDDOT proceeded in the following manner:

1. A dBASE III+ file RAWPLAN.DBF was created to contain all information from the 1994 Planning File. This file contained 11 fields each 250 characters wide.

2. Another dBASE III+ file PLANFILE.DBF was created containing the fields required for import into dROAD. These fields are outlined in the previous section.

3. The data from the 1994 Planning File, HR46.H94 was appended into the RAWPLAN.DBF.

4. A computer program was written to delete the records from the Planning File that contained a data class equal to county road, city road, or federal domain road. This resulted in the file containing state roads and frontage roads only.

5. Another computer program was written to search through the remaining records and transfer the required fields of information to the PLANFILE.DBF. The program also filled the necessary location fields required for import into dROAD.

6. A final computer program was written to validate the file prior to import to check the location related information. This process produced errors which were caused by the following:

   a) Highways in the Planning File could not be located in the MRM file. The MRM file was used to determine the exact location of each planning section. These errors usually occurred due to the transfer of state maintained roads to a county or city jurisdiction.

   b) Sections in the Planning File referenced MRMs that did not exist in the MRM file. MRMs in the Planning File were located after the end of the road defined in the MRM file. The MRM file was used to define the length of each road in the network.

7. Through the help of SDDOT staff Daris Ormesher, these errors were corrected.

8. The 1994 Planning File perspective, logical data groups, and data items were added to the dROAD database.

9. The locations of the 1994 Planning File sections were imported into dROAD using the Modify Element Location function (option 2.2.0.0.)

10. The data fields for each 1994 Planning File were imported into dROAD using the Browse Data View function (option 2.4.2.2.)

9.1.3.6 The Distress Perspective

This project developed models and parameters necessary for SDDOT to perform a pavement management analysis. This section of the report explains how the database was changed to accommodate the foundation of those models, the pavement distress data.

Earlier sections of this report, notably sections 5.5, **The Condition** Indexes, and 8.2, **The Distress Survey**, presented a discussion regarding the individual pavement distress indexes; how they were collected in the field and how they are calculated in the office. **Table 11** on page 80 listed the pavement deficiencies which the SDDOT pavement management system would use in the analysis. To get these indexes, SDDOT first has to perform a pavement distress survey. Then, they must place the data from this survey into dROAD and perform the necessary calculations. Section 5.5.1, **Deduct Values**, on page 87, presents the deduct values used in these calculations.

To accommodate this capability in the pavement management system, the SDDOT database must store levels of extent for each level of severity and each distress. The consultant designed the DISTRESS perspective explained in this section to store these values. Also, dROAD must be formatted to perform the necessary calculations with these values to produce the condition indexes. The calculation capabilities in dROAD come in the form of *transformations*. The consultant developed a set of transformations to turn the raw distress survey values into condition index values for later use in the pavement management system. These transformations are reproduced in Appendices EE, FF and GG.

Also, dROAD has the ability to string individual transformations into one long transformation which can be run overnight. This ability is provided through a process called *batching*. Batching makes it much easier to execute a number of these transformations on a regular basis without requiring the user to remember which order to run them in. The consultant developed several batch transformations for calculating the condition indexes. These are reproduced in Appendix HH.

9.1.3.6.1 Description

The distress file to be loaded each year must contain the following information collected during the pavement distress survey.

Highway:
the data class, highway number, and highway suffix

Beginning MRM:

beginning MRM where the survey was taken.

Beginning displacement:

the displacement from the sample unit MRM where the survey actually began.

Ending MRM:

ending MRM where the survey was taken.

Ending displacement:

the displacement from the sample unit ending MRM where the survey ended.

Survey year:

The year of the current survey.

Fields containing the extent for each severity of each distress with the suffix '_L' indicating Low severity, and so on:

Transverse cracking:

TRANSCRK_L, TRANSCRK_M, TRANSCRK_H

Fatigue cracking:

FATIGUE_L, FATIGUE_M, FATIGUE_H

Patching:

PATCHING_L, PATCHING_M, PATCHING_H

Block Cracking:

BLOCKCRK_L, BLOCKCRK_M, BLOCKCRK_H

Rutting:

RUT_DEPTH

Roughness:

ROUGHNESS

D Cracking & ASR:

DASR_L, DASR_M, DASR_H

Joint Spalling:

JNTSPALL_L, JNTSPALL_M, JNTSPALL_H

Corner Cracking:

CORNERCR_L, CORNERCR_M, CORNERCR_H

Faulting:

FAULTING_L, FAULTING_M, FAULTING_H

Joint Seal Damage:

JNTSEAL_L, JNTSEAL_M, JNTSEAL_H

Punchouts:

PUNCHOUT_L, PUNCHOUT_M, PUNCHOUT_H

9.1.3.6.2 Structure

The consultant created the DISTRESS perspective to store the distress survey results in different years for each distress. The perspective has three logical data groups. These are summarized below.

RAW_VALUES:

The distress values from the distress survey are stored in this logical data group. Each year, the survey results are imported into this logical data group overwriting any existing data. Therefore, if SDDOT wants to keep the old raw values, they must be copied to another logical data group before entering the new values.

COND_INDEX:

This LDG contains the calculated condition index values for the current year. The calculated results of the transformations described in the next section are stored in this logical data group. dTIMS, the pavement management system will extract the condition index values directly from this logical data group.

INDEX_1994:

The condition index values are stored in this logical data group for historical purposes. After the survey is complete, and the transformations are calculated, the data is copied from the CUR_INDEX logical data group to the DIST_1994 logical data group.

It should be stressed that the RAW_VALUES and COND_INDEX logical data groups must always contain the most recent distress data, and their names should never be changed. The consultant developed a set of transformations to calculate the condition indexes from data in RAW_INDEX and place those calculated values in COND_INDEX. In order to prevent having to redefine the transformations each year, the raw data must be placed in the RAW_VALUES logical data group and the COND_INDEX logical data group must be ready to accept the calculated values. Similarly, dTIMS expects the most recent index values to be in the COND_INDEX logical data group which is where the transformation puts them. Therefore, to avoid redefining where dTIMS is to get the index values every year, they must always reside there. Keeping historical data is another matter altogether. Instructions for doing this will be given below during the discussion of the respective logical data group.

9.1.3.6.3 Raw Values LDG

The RAW_VALUES logical data group in the DISTRESS perspective contains the raw values from the distress survey. Data for this logical data group will be collected during the pavement distress survey according to the 1/4 mile segments in this perspective. Typically, the distresses require one extent for the predominant severity on the segment; as explained in section 8.2 starting on page 134. However, since the predominant severity is not known until after the survey, this logical data group has a field for each level of severity (roughness and rut depth are the only exceptions because they do not have severity levels).

Once the field collected distress information is loaded electronically into the RAW_VALUES logical data group, transformations are then used to fill the remaining data items in that same logical data group with the respective deduct values. The remaining fields for the RAW_VALUES logical data group are listed below. The naming convention is ?????_DV_x, where '?????' is the code for each condition and 'x' is one of L, M, H indicating the level of severity. Since roughness and rutting do not have variable severity levels, those field names do not have the '_x' suffix. The '?????' codes used for each condition are shown in Table 41. For example, there are three fields in the RAW_VALUES logical data group for fatigue cracking: FATIG_DV_L, FATIG_DV_M and FATG_DV_H.

Condition Index	Code
Transverse cracking	TRCRK
Fatigue cracking	FATIG
Patching	PATCH
Block Cracking	BLCRK
Rutting	RUTDPTH
Roughness	ROUGH
D Cracking & ASR	DASR
Joint Spalling	JNTSP
Corner Cracking	CRCRK
Faulting	FAULT
Joint Seal Damage	JNTSL
Punchouts	PUNCH

Table 41: Codes used for each condition in the RAW_VALUES logical data group.

A MATRIX transformation is used by dROAD to determine the deduct value for each level of extent and severity. These transformations are described in detail later in this report.

9.1.3.6.4 INDEX LDGs

The COND_INDEX logical data group contains the calculated condition index values for the current data collection survey. These values are used by dTIMS for all pavement management analysis on the highway network. The INDEX_1994 logical data group has an identical structure to the COND_INDEX logical data group, but, it contains the condition index values for the data collected during the 1994 survey year. Each year, SDDOT must add a new logical data group to the DISTRESS perspective to contain the data collected during that year. This logical data group should be called INDEX_xxxx, where 'xxxx' is the year of the survey. This will allow SDDOT to accumulate historical condition data.

The COND_INDEX and the INDEX_1994 LDGs contain the fields shown in Table 42. Each field has a numeric values from 0 (poor) to 5 (excellent) with a format of 9.99. Since one rating segment is either flexible or rigid, not all the values are applicable. If the condition index is not applicable to the segment, the missing data value is supplied. This value is equal to '9.99'. It is important to be aware that this is the missing data value so that it can be filtered out during a query. If it is not explicitly filtered out, dROAD will treat it as if it were a normal value.

Field Name	Condition Index
TRAN_CRACK	transverse cracking
FATG_CRACK	fatigue cracking
PTCH_DET	patching / patch deterioration
BLCK_CRACK	block cracking
RUT_DEPTH	rut depth
ROUGHNESS	roughness
DCRCK_ASR	D cracking and ASR
JNT_SPALL	joint spalling
CRNR_CRACK	corner cracking
FAULTING	faulting
JNT_SEAL	joint sealing
PUNCHOUTS	punchouts
COMPOSITE	composite

Table 42: Database field names used in the COND_INDEX and the INDEX_1994 logical data groups.

9.1.3.6.5 Calculating Indexes

Calculating the above condition indexes involves two distinct steps.

The first step involves calculating the deduct value for each level of severity. The consultant designed a set of three matrix transformations to calculate the deduct values for each condition index. Basically, this set of transformations work as if they were like the matrix shown in Table 43 as an example; with one transformation for each row. The transformation examines the value for the extent for that severity and assigns the deduct value accordingly. Note the first column is the missing extent value which has zeros for the deduct. These are there so that if the transformation detects a missing extent value, as it will for all but the predominant severity, it assigns the deduct value a zero. At the completion of three matrix transformations for each condition, the database contains a deduct value for low severity, medium severity, and high severity; two of which will be zero. These deduct values are then used to calculate the condition index value using a formula transformation explained below.

It should be pointed out that the consultant designed the distress survey to assign an extent only to the predominant severity as discussed earlier. If SDDOT changed the survey procedure to assign an extent to each level of severity, these transformations would not have to be changed.

Severity	Missing extent	Low extent	Moderate extent	High extent	Extreme extent
Low	0	0.4	0.8	1.4	2.0
Medium	0	0.6	1.7	3.1	5.0
High	0	1.1	2.7	5.0	5.0

Table 43: Example deduct values for the matrix transformation used for corner cracking.

The second step in calculating a condition index is to use a formula transformation to calculate the index based on the deduct values calculated above. Equation 11 shows the formula transformation for each condition except roughness and rutting.

$$DIST = MAX(5 - (low + medium + high),0)$$

Equation 11: Condition index calculation equation.

where:

DIST	is the condition value placed in the respective database field
MAX	is a dROAD function which selects the maximum of two values
low	is the deduct value for low severity for the respective condition
medium	is the deduct value for medium severity for the respective condition
high	is the deduct value for high severity for the respective condition

The formula takes the deduct values from the low severity, medium severity, and high severity condition and subtracts them from the highest value of 5. A maximum is taken to ensure that the lowest possible value for any condition index is 0 and not a negative number as may occur if deducts were assigned for each level of severity.

The condition index calculations are executed using batching. This allows all indexes to be calculated in one simple step. The formula and matrix transformations allow for quick and easy updates as the deduct values are updated.

9.1.3.7 The Pavement Type Perspective

The PAVETYPE perspective is used to define the pavement type of all the road sections. The pavement types are divided into two broad categories, one category for flexible pavements and one category for rigid pavements. The pavement type codes used in the software for both categories are repeated in Table 44 for convenience.

Pavement Type	Code
Full Depth	FD
Thick pavement	THK
Thin pavement on strong subgrade	TonS
Thin pavement on weak subgrade	TonW
Asphalt on concrete	AonC
Continuous reinforced concrete pavement	CRCP
Thick short jointed pavements	TKSJ
Thick short jointed pavements with dowels	TKSJD
Thin short jointed pavements	TNSJ
Mesh reinforced pavements	MESH

Table 44: Pavement type codes used throughout dROAD and dTIMS.

SDDOT provided the consultant, on paper, the above pavement types for all roads considered in the pilot project; those being the interstate highways and

US281. The starting MRM and displacement, the ending MRM and displacement, and the pavement type from the above table was provided for every section of road.

9.1.3.7.1 Description

The PAVETYPE perspective contains only one field, that being a table database field called PAVE_TYPE. The table decode values for this field are the same ones listed in Table 44.

9.1.3.7.2 Loading Process

The consultant was supplied with a paper copy identifying the pavement types for all roads in the project. The consultant typed this data into a dBASE III+ file. Next, the consultant imported this file into dROAD using option 2.2.0.0 to create the necessary sections in this perspective. Finally, the consultant imported the actual pavement types into dROAD using option 2.4.2.2.

9.1.3.8 The PMS Perspective

The PMS perspective is used by dTIMS as the master perspective which defines the section limits to be evaluated in the pavement management analysis. In other words, the section limits contained in the PMS perspective become the limits of the sections in the construction programmes generated by dTIMS.

The PMS perspective has sections limits which the consultant automatically generated using one of dROAD's functions. All other perspectives in dROAD have their section limits defined prior to being loaded. Usually these limits were defined in order to keep the data being collected homogeneous across the entire length of the section. The sections in the PMS perspective also have to be homogeneous according to the data used in the pavement management analysis. Since none of the existing dROAD perspectives had sections that would allow the pavement management data to be homogeneous, this PMS perspective was required. It is important to note that even the Planning File could not give sections which were homogeneous enough for pavement management purposes. This was explained in section 4.3.3 on starting on page 43. Therefore, the sections in the PMS perspective are determined by dROAD based on a definition of data homogeneity supplied by the consultant as explained later in this section.

9.1.3.8.1 Description

The main purpose of the PMS perspective is to store the section limits required by dTIMS. However, the consultant put two database fields in this perspective. These two field define the 'from' and 'to' descriptions dTIMS uses to define the sections. The fields are called FROM_DESC and TO_DESC. They are filled with perspective transformations designed by the consultant.

9.1.3.8.2 Loading Process

As mentioned in the previous section, the main purpose of the PMS perspective is to store section limits and not data. Therefore, there really is no data loading process for this perspective. What there is, however, is a process to automatically create its section limits. The consultant used the dROAD automatic sectioning function (option 4.8.2.0) and a process defined below to generate these section limits.

As explained in great detail in dROAD's documentation[6, 37], the automatic sectioning function basically requires six pieces of information: (1) a committed section perspective, (2) a minimum section length, (3) a maximum section length, (4) a road list, (5) a filter criteria, and (6) an attribute criteria. Using these to define what 'homogeneity' means to the user, the function automatically goes through the database and creates a section limit whenever any of these criteria are satisfied.

For the SDDOT application, the consultant used the STIP perspective as the committed section perspective and did not need a filter criteria. However, through consultation with SDDOT staff, the consultant supplied the criteria listed in Table 45 to this dROAD function.

Characteristic	Change condition	Perspective
Committed sections	section limit	STIP
Length	min=0.25 , max = 10	PMS
Pavement type	any change	PAVETYPE
Pavement category	any change	DISTRESS
Road width	+/- 2 feet	PLAN1994
Composite condition index	+/- 15%	DISTRESS

Table 45: Characteristics used in dROAD to define homogeneous sections.

As a result of the above criteria, any section created in this process will not be less than 0.25 miles long or greater than 10 miles long, and the section will have a homogenous pavement type, pavement category, road width and composite condition index. This process generated approximately 550 sections in the PMS perspective. Appendices SS through to AAA show a dROAD strip map for each road in the pilot project. These strip maps displaying the data elements used in the automatic sectioning routine as well as several other database fields.

There was one complication that arose following the loading of the DISTRESS and the PAVETYPE data. That complication is as follows. Since DISTRESS contains a field called pavement category which is either "F" (flexible) or "R" (rigid) and PAVETYPE contains the pavement types, it is imperative that when the DISTRESS perspective says a road section is "F" that the PAVETYPE perspective have a pavement type from the flexible category and vice versa. The consultant saw that there was a problem in this regard following the printing of all the strip maps. Therefore, to highlight the differences between pavement category and pavement type, the consultant designed and executed a query in dROAD (List Values by Smallest Common Denominator - option 3.3.2.0). The result of this query is presented in Appendix BBB. The consultant went through this list, made the appropriate changes in the database and indicated the nature of the change on the strip maps in Appendices SS through AAA. The automatic sectioning routine was then rerun. This explains why the PMS sections on the strip maps do not match exactly with the final PMS sections in dROAD.

9.1.3.9 The STIP Perspective

The STIP perspective contains the sections limits of SDDOT's five year construction programmed capital projects on the interstate and US281. The consultant and SDDOT personnel entered each section by hand into dROAD. These sections were required to commit Programmed projects in dTIMS.

9.1.3.9.1 Description

The STIP perspective contains a logical data group which defines the characteristics of the committed projects. These characteristics are: (a) the type of treatment (COM_TRT), (b) the year the treatment will be applied (COM_YEAR), (c) the cost of the project (COM_COST), and (d) the budget category (COM_BUD).

9.1.4 Historical Data

Historical data can be accommodated in many different ways in dROAD, but first, it is necessary to examine the purpose and reason for storing such data historically. For example, ADT and total number of accidents are good examples of data fields that can be kept historically. This data can assist in predicting future volumes, future performance, and a deficiency in safety along the route. Items such as functional class, or divided / undivided status would not be good items to save historically because they rarely change from year to year. The functional class of a road three years ago is not as important as the functional class of the road today. This is an important issue when storing historical data and it is strongly recommended that only data needed for a historical or time dependent analysis should be kept from year to year.

The first method of storing data from different years is to store each year of data in its own perspective. This means that each year a new perspective is added to the dROAD database. Then, when comparing different years of data, dynamic segmentation can be used to compare previous years to the current year. The PCI and Planning Files serve as a good example of storing historical data using different perspectives. Each year, the Planning File will be loaded containing all current information into a new perspective. The previous year's data then is streamlined so to include only data needed for a historical or time dependent analysis. This method should only be used when section limits change from one year to the next.

Another way of storing historical information is to use different logical data groups in the same perspective. In the DISTRESS perspective, presented in the previous section, many years of data are stored in the same perspective but in different logical data groups. Each year, the data from the previous year’s distress survey is stored in a new logical data group and the current data is placed in that one. This was a special application of using different logical data groups which was required to avoid redefining the transformations, usually the most recent data is added to the database in a new logical data group.

The consultant has implemented the following in the SDDOT dROAD database to track historical information.

Condition values:

In the DISTRESS perspective, many different years of historical condition information will be kept in separate logical data groups. After the condition indexes are calculated for each year of the distress survey, they are transferred to a logical data group representing the year of data collection. As time passes, this information will be used to update the performance prediction models used in the pavement management system.

PCI DATA:

The PCI data for each year is stored in a different perspective. Currently the 1993 and 1990 surveys are stored in the database. If and when another PCI survey is completed, the new data should be entered into a new perspective.

Planning File Data:

The 1993 and 1994 Planning Files are stored in different perspectives. Planning Files from other years can be added to the database as well, each in its own perspective. Currently, the 1993 planning perspective contain 34 database fields, while the 1994 planning perspective contains 602 database fields. It is recommended that each year, the previous year's perspective be streamlined and only fields that are absolutely necessary be kept for more than one year.

In a broader sense, SDDOT will have to develop and maintain a historical database describing the work done on the road sections. This is not only required for ISTEA, as explained earlier, but, in order to assist in the refining of the performance curves. When a section is repaired its condition is improved. If this repair information is not available, then improvements in a road section's condition will be unexplainable when analyzing that condition for trends. Therefore, SDDOT should investigate implementing a work history database in dROAD as well. The dROAD documentation deals with explaining what features dROAD has to assist in this. The topic is listed under the heading 'Cross Section Graphics' because this is one of the products of building work history database in dROAD.

9.1.5 Custom Programs

The consultant wrote many custom programs during the duration of this project to take the raw data as provided by SDDOT and to put it in a format that can be imported into dROAD. The majority of these programs were needed for a one time run. In other words, once the data is loaded they are not required any more. However, there are 3 programs that SDDOT will need to use on a more frequent basis. These are described below.

9.1.5.1 PLANFILE.EXE

This program was used to load the 1994 Planning File and could be used to load any Planning File in the future. The actual steps taken to load the Planning File are described above in section 9.1.3.3.2.

The program developed by the consultant to load the Planning File is called PLANFILE.EXE. It requires several other files in order to run properly. These are listed in Table 46 along with the directory the must exist in (if no directory is given, then the files can exist in the current directory):

File name	Directory
DR0NET.DBF	dROAD's
DR0NET.NTX	dROAD's
DS001001.DBF	dROAD's
DS001001.NTX	dROAD's
DN001.DBF	dROAD's
DS002001.DBF	dROAD's
DS002001.NTX	dROAD's
DN002.DBF	dROAD's
RAW1994.DBF	current
ERRORFIL.DBF	current
PLAN1994.DBF	current
UNKN1994.DBF	current

Table 46: File names and locations required to run the PLANFILE program.

Any file beginning with a "D" can be found in the dROAD directory. Any other file can be found on the supplied diskette entitled "SDDOT Custom Programs". Because of hard coding, the '1994' must be used in the file name RAW1994.DBF even if the data is for another year. However, it is just used in the name and has no effect on the actual year of the data. The dBASE III+ file called RAW1994.DBF must be filled with the raw data from the Planning File supplied in ASCII format. In 1994, this ASCII file was named HR46.H94. The structure of RAW1994.DBF is given in Appendix JJ.

For readers familiar with dBASE, the consultant provided a file called RAWSTR.DBF. This file is a structure extended file and can be used to create the file structure for RAW1994.DBF. Once RAW1994.DBF is created, the records from the ASCII Planning File (HR46.H?? where ?? indicates the year) must be appended to this file. After all this PLANFILE.EXE can be run from DOS. The end result of running this program is a file called PLAN1994.DBF which is a section import file and data import file for the entire Planning File for the given year.

9.1.5.2 SURVEY.EXE

This file can be used as a data entry program for the distress survey collected in the field. As with PLANFILE.EXE, this program also requires several files during its operation. These files are listed below in Table 47, and are also contained on the supplied diskette entitled "SDDOT Custom Programs".

File name	Directory
MRM_DESC.DBF	current
SURVEY94.DBF	current
DR0SYS.DBF	current
DR0COLOR.DBF	current
DR0MSG.DBF	current
DR0MSG.NTX	current
DS001001.DBF	current
DS001001.NTX	current
DR0STAT.DBF	current
DR0LST.DBF	current
DR0LST.NTX	current

Table 47: File names and locations required to run the SURVEY program.

The two files, MRM_DESC.DBF and SURVEY94.DBF are created using dROAD. MRM_DESC.DBF is created by first running a batch transformation (option 2.4.3.5) called MRM_DESC, then a List Values by Perspective query (option 3.3.1.0) called MRM_DESC. SURVEY94.DBF is created by first running an automatic sectioning process (option 4.8.2.0) called SURVEY and then a List Values by Perspective query (option 3.3.1.0) called SURVEY. Once these steps are completed, SURVEY94.EXE can be executed. The end result of this program (following the data entry phase of the raw distress values) is a file called SURVEY94.DBF. This file is used by the next program described.

9.1.5.3 SURVEYIM.EXE

This program is used to take the data from SURVEY94.DBF and create a data import file for dROAD. The SURVEY94.DBF file cannot be directly imported into dROAD. Therefore, the only file that SURVEYIM.EXE requires is SURVEY94.DBF. After running SURVEYIM.EXE, a file named SUR94IMP.DBF will be created. It is this file that can be imported into dROAD .

9.1.6 Preparing Data for dTIMS

This section rather than describing the entire data loading procedure for dROAD again will summarize the three main batch transformations in dROAD that prepare the data for use in dTIMS. The discussion that follows assumes that the distress data, planning data, and pavement type data has been loaded and that the PMS sections have been created. The batch transformations that will be discussed can be found in dROAD option 2.4.3.5.

The first batch transformation that will be run is one called INDICES. This transformation assigns all the deduct values based on the raw severity and extents for each condition and then calculates a condition index for each condition.

The second batch transformation to be run is one called PAVE_TYPE. This assigns values to various fields needed by dTIMS, for example, number of trucks, minimum resurfacing width and pavement ages. This transformation requires a user input at the end. The transformation will pause and ask for the first year of analysis used in dTIMS. This is usually the first year dTIMS will generate a construction programme for.

Finally, the third batch transformation to be run is called PMS_DESC. This fills the FROM and TO description fields in the PMS perspective. These are used in dTIMS to clearly denote the location of the section limits. The one point to remember is that prior to running this transformation the Location Reference Method (LRM) in dROAD must be set to "MRM" (Mileage Reference Marker). This can be set in option 2.2.0.0 using the F9 - LRM method button. Once the transformation is complete, the LRM can be reset to the default LRM "ROADS". These batch transformations are shown in Appendix HH.

9.2 *dTIMS: The Analysis Software*

9.2.1 Overview

dTIMS is a microcomputer software pavement management analysis package. It has successfully merged project and network level pavement management into one system. dTIMS can assist a user to analyze the impacts of how they spend money on their entire infrastructure. It is completely modular and totally generic. dTIMS uses the data a user already has. It rarely requires the user to collect any more data. dTIMS has one purpose: to make a user's job of managing pavements easier. dTIMS provides valuable information. The kind of information any user needs to make informed long-term programming and budgeting decisions. dTIMS also provides charts and graphs to vividly communicate pavement funding needs to politicians.

dTIMS uses the data from a dROAD database to analyze each road section. It analyses the road network for anywhere from one to twenty years. During this analysis, dTIMS creates a list of all possible repair strategies for each section. dTIMS calculates and saves the life cycle costs and benefits for each strategy on this list. dTIMS then uses the incremental benefit cost optimization procedure (As recommended by The World Bank). It also utilizes a set of user-supplied budgets. These budgets allow dTIMS to select which of these strategies is the most cost-effective. The result of the optimization analysis, yields one "selected" strategy for each section. The collection of these "selected" strategies for all the sections is called, the recommended construction programme.

A computer-generated recommended construction programme is seldom realistic. This is due to a whole set of constraints that are difficult to quantify, and therefore, were not involved in the optimization analysis. However, dTIMS provides a user with the tools necessary to use his knowledge. The knowledge of these other constraints is used to develop a realistic construction program from the recommended one. dTIMS allows the user to interactively change the "selected" strategy. The user can change the strategy for any or all sections. The strategies are changed while showing the budget impacts of that switch right on the screen.

Flexibility is the hallmark of dTIMS. Virtually everything that could be made user definable in dTIMS, was. For example, a user can define one alternative or thousands, one condition index or thousands, one performance curve or thousands, one budget level or thousands, and so on.

dTIMS has a wide variety of reporting options. These options can be divided into four categories:

Parameter reports:

A set of standard reports that describe how dTIMS parameters have been configured, such as performance curves, alternative treatments, trigger limits and so on;

Strategy reports:

A set of user-definable reports that illustrate data describing the list of strategies for any or all sections in the analysis;

Program reports:

A set of user-definable reports that describe the "selected" strategy for each section;

Program impact reports:

One of four powerful graphical summaries of the long-term impact on the network resulting from the construction program.

dTIMS provides a selection of graphic tools. These graphic tools illustrate the impacts with full color charts and graphs (not pages and pages of tabular output). Often, one graphic display can dramatically show the long-term effects of different budget levels. The six types of graphical outputs are:

Performance curves:

after the desired parameters have been entered to describe performance curves, the press of a button will show the shape of each curve;

Future condition:

to illustrate how the strategy will affect the future condition of each road section;

Condition distribution by length:

a colorful bar chart will illustrate how the percent of total miles of road in poor, fair, good, and excellent condition will change over time as a result of implementing that construction programme;

Condition distribution by travel:

A colorful chart will illustrate how the percent of total travel on roads in poor, fair, good, and excellent condition will change over time as a result of implementing that construction programme;

Average future condition:

the user can plot, on the same graph, how each different budget affects the average condition of all roads in the network over time;

Future backlog:

the user can plot, on the same graph, how each different budget affects the backlog of needs over time.

9.2.2 SDDOT's Analysis

This section describes the dTIMS parameter loading process for the South Dakota Department of Transportation (SDDOT). It briefly describes the type of data that dTIMS requires to perform an analysis and then goes on to describe how that data was implemented in the system for use by SDDOT. This chapter assumes the reader has reviewed the dTIMS User Manual.

9.2.2.1 Source Data

The data item sources option in dTIMS, tells dTIMS what raw data to use and where to go to retrieve it. dTIMS can be set up to run directly linked to dROAD, or dTIMS can be set up to run independent of dROAD. If it is independent, the user must create a file called DT2699.DBF which stores all of the raw data that dTIMS will use. The dTIMS system documentation describes the layout and content of this file in detail[3]. The dTIMS for SDDOT was set up to run directly linked to dROAD. Therefore, in the data item sources option, each data item that dTIMS uses is supplied with a dROAD perspective, LDG and database field name. This tells dTIMS where in the dROAD database to look for each data item's value.

The dTIMS data item sources are sub-divided into one of three categories: (1) base data items, (2) performance data items, and (3) other data items. A base data item is an item that cannot be removed or added to dTIMS. The user must tell dTIMS where to look in dROAD for each item. However, some of these items are optional, and the user can supply dummy values for them if they are not needed in his analysis.

The second category of data items are performance data items. A performance data item is a label which tells dTIMS to store yearly values for this item. A performance data item always requires a mechanism for dTIMS to calculate its values into the future. Performance curves such as those developed for the condition indexes are excellent examples of this mechanism, but, are not the only examples. Performance data items give dTIMS the ability to project and monitor any value over time.

The final category, other data items, are used for a variety of reasons. Basically, an other data item is a item that is not a base or performance item that a user wants to include in dTIMS for use during the analysis. These data items provide additional information for use in triggers or calculations. They are most often included in expressions and groupings which are discussed later.

All data items used in dTIMS are described in the following paragraphs. Appendix KK of this report contains the dTIMS data item sources report.

9.2.2.1.1 Base data items

A list and brief description of base data items used in dTIMS for SDDOT is provided in Table 48. Any marked as optional are currently not being used in the analysis.

Type of data	dTIMS' name	Description
MASTER PERSPECTIVE	FSECTION	name of the section perspective in dROAD which defines the limits of the sections dTIMS will analyze
SECTION LENGTH	FLENGTH	length of analysis sections
ROAD NAME	FNAME	name of road
ROAD TYPE	FTYPE	type of road (optional)
ROAD DIRECTION	FDIRECTION	road direction (optional)
BEGINNING OFFSET	FOFFFROM	starting milepoint of section
ENDING OFFSET	FOFFTO	ending milepoint of section
BEGINNING DESCRIPTION	FDESCFROM	description for start of section
ENDING DESCRIPTION	FDESCTO	description for end of section
AVERAGE ANNUAL DAILY TRAFFIC	AADT	traffic count
CUMULATIVE ESALs FROM LAST WRK	CUM_ESAL	cumulative ESALs (optional)
AXLE EQUIVALENCY	AXLEQUIV	optional
LEFT - RIGHT DIRECTIONAL SPLIT	LRSPLIT	optional
STRUCTURAL INDEX	SI	optional
COMMITTED TREATMENT CODE	COM_TRT	four character treatment code
COMMITTED TREATMENT COST	COM_COST	cost of project in $,000
COMMITTED TREATMENT YEAR	COM_YEAR	year of project
COMMITTED TREATMENT BUDGET	COM_BUDG	budget category for the committed project
PAVEMENT TYPE	PAVETYPE	surface or pavement type
REHABILITATION TYPE FLAG	REHAB	optional
RECYCLE FLAG	RECYCLE	optional
DESIGN STANDARD	DES_STD	optional
TRAVELLED WAY WIDTH	TRAV_WAY	width of section
PERCENT COMMERCIAL VEHICLES	PCT_COMM	optional
YEAR OF LAST WORK	YR_LSTWK	year of last major rehab
THICKNESS OF PAVEMENT/SURFACE	THICK	optional

Table 48: List of the base data items required for a dTIMS analysis.

9.2.2.1.2 Performance data items

A list which shows the name of the performance data items used in dTIMS is given in Table 49. The type of pavement that each index is for is also shown. With the exception of the composite index, all of these indexes are calculated in dROAD using the transformations described in Section 7.2 of this report. The composite index is taken as the mean of the indexes minus 1.25 times the standard deviation of the indexes. There is a composite index for both flexible and rigid pavements.

Type of data	dTIMS' name	pavement type
TRANSVERSE CRACKING	TRCR	flexible
FATIGUE CRACKING	FTCR	flexible
PATCH DETERIORATION	PTCH	flexible
BLOCK CRACKING	BLCR	flexible
RUT DEPTH	RUT	flexible
ROUGHNESS	RUFF	both
D CRACKING & ASR	DASR	rigid
JOINT SPALLING	JTSP	rigid
CORNER CRACKING	CRCR	rigid
FAULTING	FLTG	rigid
JOINT SEAL DAMAGE	JTSL	rigid
PUNCH OUTS	POUT	rigid
COMPOSITE INDEX	CMP	both
X AGE (independent age variable # 1)	XAGE	both
Y AGE (independent age variable # 2)	YAGE	both

Table 49: Performance data items used in dTIMS.

9.2.2.1.3 Other data items

A list of the other data items required in the dTIMS analysis is given in Table 50. These items are required for use in either groupings or to calculate a strategy cost (e.g. number of structures). They either come directly from the Planning File in dROAD or are filled in dROAD by way of a transformation.

Description	dTIMS' name
Pavement category code	PAV_CTEGRY
Number of Structures	NO_STRUCT
Rural / Urban code	RUR_URBAN
Functional class	FC
Divided highway code	DIV_CODE
Number of trucks	NO_TRUCKS
Is pavement doweled code	IS_DOWELED
Minimum resurfacing width	MIN_RES_WD
Roadway width (incl. shoulders)	RD_WID

Table 50: Other data items defined which are required for the dTIMS analysis.

9.2.2.2 Parameter Data

9.2.2.2.1 Groupings

dTIMS employs a fundamental concept which allows it to be as flexible as it is. This concept is called *groupings* . A grouping allows a user to define a criteria which when satisfied says that the pavement section is part of this group. A pavement section can be a part of only one group, or, all groups depending on the criteria and on how the characteristics of the section fit that criteria. A grouping consists of a name and a filter. The filter is a Boolean logic statement such as 'AADT > 500 .AND. WIDTH < 32'. When a section's current values for AADT and WIDTH are fed into this statement, dTIMS evaluates the statement. If the evaluation returns a 'true', the section is part of the group. If it returns a false, the section is not part of that group.

Groupings are used for triggering treatments, growing traffic, analyzing subsets of the network, and for defining families of performance curves. The consultant created many groups in dTIMS for this project. Their names and filters are listed in Appendix MM. The naming convention for performance curve groupings is "P_" followed by the pavement type code. The naming convention for trigger limits is "TRGF_", for flexible, and "TRGR", for rigid, followed by the pavement type code.

9.2.2.2.2 Expressions

In dTIMS the user has plenty of flexibility when it comes to defining most objects. One of the best mechanisms providing this flexibility is the expression. Expressions are similar to groupings in that they consist of two things: a name and a mathematical formula. The mathematical formula can be anything which evaluates to a numerical result (groupings evaluate to a logical result). Throughout the following discussion, the report will make reference to the expressions set up in dTIMS by the consultant.

The naming convention for cost expressions is "C_" followed by the treatment code, and for performance curves is "P_" followed by the pavement type code.

9.2.2.2.3 Condition Indexes

Condition indexes are what dTIMS uses to monitor the condition of the network and to trigger treatments. Barring any maintenance or rehabilitation work, a section of road will deteriorate over time. Condition indexes are used to tell dTIMS the rate of this deterioration. dTIMS has two classes of condition indexes, composite and non-composite. The 'composite index' developed for SDDOT and presented in Equation 9 is of the composite index class in dTIMS; it's unfortunate the two have the same name however. Actually the term composite index is a generic one in dTIMS referring to an index which is made up by combining other indexes. Because of this, a composite index in dTIMS does not require an initial value from the database. The composite index developed for SDDOT is calculated in dTIMS using the COMP function. This function, when supplied with the proper parameters, actually performs the calculation of Equation 9.

A non-composite index, on the other hand, is one that is measurable in the field and requires a performance curve to project its value into the future. All of the condition indexes used for SDDOT except for the 'composite index' of Equation 9 are classed as non-composite. Therefore, they all require an initial value to be supplied from the database.

The indexes in dTIMS for SDDOT were divided into two categories based on pavement type, one set for flexible pavements and one set for rigid pavements. The indexes used for each pavement type are discussed in section 5.5.2 on page 93 of this report. The data item sources report in Appendix KK contains some additional details for each index.

In addition to the condition indexes, the consultant created two other performance data items in dTIMS: XAGE and YAGE. The XAGE and YAGE performance data items are used as independent age variables in the other condition indexes' performance curve expressions. The performance expression for these age variables cause them to increase by a value of one in each year. The XAGE and YAGE indexes are used as opposed to the internal dTIMS age variables (GAGE_REHAB, GAGE_PERIODIC, and GAGE_MTCE) because some treatments affect the age of the pavement for certain condition indexes only.

For example, a Pavement Restoration Two treatment resets the age to zero for the faulting index but has no effect on the corner cracking index. If both the faulting index and the corner cracking index used the same age variable in their performance expression, and if that age variable were reset to zero after a Pavement Restoration Two treatment was applied, then the performance after the treatment would be calculated incorrectly for corner cracking. Therefore, these two independent age variables, XAGE and YAGE, are needed as well as the dTIMS' internal age variables.

9.2.2.2.4 Performance Curves

In dTIMS, each condition index requires a performance curve. A performance curve calculates the rate of deterioration for each condition index. This curve is the mechanism dTIMS uses to project the condition indexes into the future. The performance curve can be supplied to dTIMS as either a series of condition versus age, AADT or ESALs points, or as an expression. For each condition index in dTIMS for SDDOT, the consultant used an expression for the performance curve because expressions execute faster in the analysis. These expressions were developed specifically for this project as explained in section 5.6.2 on page 103. The expressions entered into dTIMS by the consultant are provided in the Appendix LL.

Since each condition index has a different performance curve for each treatment type, the concept of *groupings* is used in dTIMS to distinguish one curve from another.

9.2.2.2.5 Treatment Alternatives

The treatment alternatives are the types of maintenance and rehabilitation that dTIMS will perform on road sections to improve some condition index. Treatment alternatives are triggered by one or more condition indexes; and, when applied, improve the condition of the road section by some amount. The treatments in dTIMS are divided into two categories based on pavement type. Some treatments will only be applied on flexible pavements and some only on rigid pavements. The treatments used in dTIMS, the type of pavement they will be applied on, and the code used in dTIMS are repeated in Table 51 for the reader's convenience.

Treatment Description	Treatment Code	Type of pavement
Reconstruction	RECF	Flexible
2" AC Overlay	2ACO	Flexible
Mill 1" w/ 2" AC Overlay	M120	Flexible
Mill 1" w/ 3.5" AC Overlay	M135	Flexible
2" Mill and Replace	2MAR	Flexible
Cold In-place Rec w/ 3" Ovl	CPR3	Flexible
Rout and Seal	RAS	Flexible
Chip Seal	CS	Flexible
Reconstruction	RECR	Rigid
Crack & Seat w/ 4.5" AC Ovl	CS45	Rigid
4.5" AC Ovl (no Crk & Seat)	45AO	Rigid
Pavement Restoration 1	PR1	Rigid
Pavement Restoration 2	PR2	Rigid
Pavement Restoration 3	PR3	Rigid
Saw and Seal Joints	SASJ	Rigid
Unbonded Concrete Overlay	UBCO	Rigid
Bonded Overlay	BO	Rigid

Table 51: List of the treatments and codes used in dTIMS.

All of these treatments are rehabilitation type treatments except for the Chip seal, Rout and Seal, and Saw and Seal Joints which are periodic treatments. Rehabilitation type treatments are evaluated each year to determine if they can be performed or not. Periodic treatments are evaluated on a fixed interval, every two years for example. The Chip Seal treatment is evaluated three years after any overlay and every six years thereafter. The Saw and Seal Joints treatment is evaluated on a ten year cycle. The Rout and Seal treatment is evaluated in the second year following the application of any overlay. These periodic treatments are evaluated only after a major rehabilitation has been performed based on the age since the last rehabilitation treatment and based on the time interval of the periodic treatment.

There are six treatments that appear in the treatment report in Appendix NN that are not listed in Table 51. These are called *ancillary* treatments. An ancillary treatment is one that is applied at the same time as a rehabilitation treatment. In the SDDOT dTIMS configuration, these ancillary treatments are applied only in conjunction with the two reconstruction treatments. There are three ancillary treatments for the reconstruction of rigid pavements and three for the reconstruction of flexible pavements. Their purpose is to adjust the cost of the reconstruction treatments. They are required because the cost of a reconstruction varies depending on the pavement type, the functional class, the road's divided status, the volume of traffic and number of trucks. Therefore, the total cost of a reconstruction is the cost of the rehabilitation treatment (determined by the cost expression for the reconstruction) plus the cost of the ancillary treatment applied (determined by the above factors and the cost expression for the ancillary treatment).

The application of any treatment has an effect on one or more of the condition indexes. This effect manifests itself in dTIMS with the treatment resets. Each treatment in dTIMS has a condition index reset for every condition index in the system. The reset for any index can be reset by either an absolute value, a percent of the original value, a relative amount, an expression, or not reset at all. For example, the application of a saw and seal joint treatment has no effect on the fatigue cracking index. These resets are what distinguishes the performance curve for a strategy from that of the do-nothing strategy. Any positive treatment reset is shown as a vertical jump in the performance curve indicating a major improvement to the road's condition. The treatment resets for each treatment and condition index have been listed in Table 33 and Table 34 . How they are implemented in dTIMS is shown in the treatment report and the condition index reset report in Appendix NN and Appendix OO.

The cost of a treatment is usually determined by many factors. In dTIMS, the cost of a treatment can be supplied as a discrete dollar amount for some unit measure, or as an expression. If it is supplied as a dollar amount, the total cost of the treatment is dependent on the length and width of the section and possibly the thickness of the treatment. If the cost of the treatment is supplied as an expression, the total cost of the treatment can be dependent on any number of factors. For SDDOT, most treatment costs were supplied as expressions since the cost of most treatments were dependent on such things as the type of treatment, the number of structures, and the length of the section. The cost table is shown in the treatment costs section in Appendix PP. This table shows the dollar figures and some of the factors that govern the total cost of a treatment. The expression report in Appendix LL shows the resulting cost expression for each treatment.

The consultant developed a cost expression for each treatment. This expression calculates the cost for the surfacing as well as all other costs associated with the treatment. These expressions are complicated, therefore, are not reproduced here. Rather, the reader is referred to Appendix LL which lists all of the expressions used to set up the software. The list in Appendix LL includes all expressions in the software; not just the cost expressions. The name of all cost expressions begin with "C_". This prefix is then followed by the treatment code.

9.2.2.2.6 Trigger Limits

Trigger limits are used by dTIMS to indicate when to apply a certain treatment. Every treatment is eligible to be applied at some level of condition. If not, there would not be a need to have that treatment in the system. For every treatment, there is at least one trigger limit (or rather trigger zone). In this dTIMS setup, the trigger zones are divided into two broad categories, rigid and flexible pavements. This is necessary because rigid pavements are eligible for a different set of treatments than flexible pavements. Then, for each of the treatments within a pavement category, the trigger zones for each specific treatment are divided into more discrete categories based on the pavement type. Presumably, the thinking here is that a 2 inch AC overlay will be triggered at a different level of cracking on a full depth asphalt pavement than a thin on strong subgrade pavement. Not all treatments have a different trigger zone for each pavement type. The trigger limit report in Appendix QQ shows the different trigger limits for each treatment and pavement type. Also in the appendix is a spreadsheet showing the trigger zones by treatment and pavement type. These were developed using the procedure described in section 6.3 on page 111.

9.2.2.2.7 Traffic Growths

The traffic growth rate is used to adjust the traffic volume (AADT) and ESALs each year from the original year. This is required because the AADT is often used in the calculation of benefits. Therefore, since benefits accrue over many years, dTIMS adjusts the AADT each year so that it is current in every year. The traffic growth rate is an annual percentage increase in the AADT. It can be applied for the entire road network equally or the user could supply different rates for different parts of the network. In this analysis, a nominal increase of 1.5 % per year was applied for the entire network. This number can be adjusted at any time prior to an analysis.

9.2.2.2.8 Economic Parameters

dTIMS requires various quantities of economic information during its operation. This information is used during the strategy generation phase and the optimization phase. This economic data can be divided into two categories. The first category is the annual budget levels. For each year that treatments can be applied, dTIMS requires an annual budget. dTIMS can also accommodate up to 5 different budget scenarios. This allows a user to perform various "what if" scenarios. The user can run one analysis and have dTIMS generate the optimal construction programme given up to 5 different annual budget amounts.

The initial set up of dTIMS has one budget scenario with an annual budget of 0 (that is, the do-nothing scenario) and four non-zero annual budgets at $10 million per year, $15.8 million per year, $20 million per year, and $25 million per year.

The second category of economic information is a set of analysis parameter data. Table 52 shows the economic parameter data required by dTIMS and its current setting in the SDDOT pavement management system. Each data item is explained in detail in the dTIMS user manual.

Parameter	Current setting
IBC cutoff value	0.1
Min allowable B/C	-11
Efficiency range	10% of benefit
Geometric traffic growth	N
Equation for VOC calc	N/A
Economic agency costs	N
Use committed trtmnts	Y
Use annualized costs	N
Analysis period	1994 to 2029
End yr of trtmnt application	2014
Inflation rate	0%
Discount rate	3%
Type of benefit	Area under curve
Fill budget after optimization	Y
AADT exponent in effectiveness calculation	1.0

Table 52: Economic and other parameters used in the dTIMS analysis.

9.2.3 Testing and Verifying

Once the parameters have been loaded into dTIMS, they should be checked to determine if they are working as expected. This was done following the initial setup. However, this process should be thought of as an ongoing one. Whenever, any change is made to any of the parameter data, everything should be re-checked to verify that the change has taken place and is producing the desired results. This section explains how one might test and verify the parameter data.

Using a representative sample of data, test and verify that the parameters are operating as expected. A dROAD query report, dBASE or Quattro Pro can be used to create an external test file to test dTIMS. This test does not have to be very large, it can be done with fifty road sections. Generate a small analysis and check each strategy against desired performance. Look for:

Condition indexes

Are they deteriorating properly? Does the performance curve for a strategy cross below the performance of do-nothing?

Treatment costs

Do they match expectations

Treatments

Are they triggered when desired?

Benefits

Are they indicative of the treatment? Do they vary the various treatments the system considers?

Budget levels

Is the condition level indicative of the budgeted amount?

Once the above has been completed, execute the analysis using network data for the whole system. Re-evaluate the performance of the system with respect to desired or expected results. If necessary, change required parameters and generate the analysis again. This may be a somewhat continual process until dTIMS has successfully modeled the performance of the pavements in the field using the computer in the office.

9.3 dMAP: The Mapping Software

9.3.1 Introduction

dMAP uses data in the dROAD database and displays it on a map in different colors. dMAP also allows users to access the data in the database by selecting sections from a map. dMAP is an inexpensive, sophisticated tool for representing any data in a database on real maps according to the engineers' own demonstration concepts.

dMAP is a microcomputer software package that runs under AutoCAD and is used to display the attributes of any element in the infrastructure on a map. dMAP as an automated mapping system uses data already stored in a dROAD database. It displays the results of a query performed on all or a group of data selected from the database using any visual identifier desired. dMAP also allows access to the data in the dROAD database through the map itself. It is possible to select one or more road sections from the map and view or edit any data in the dROAD database for the selected section(s).

dMAP's main advantage is that it has a two-way link with the most sophisticated infrastructure database system, dROAD. The link from the database to the map involves dROAD performing dynamic segmentation between the various road sections' data and passing the results to dMAP for plotting. The link from the map to the database involves dMAP allowing a user to select one or more road sections from the map. dMAP then calls dROAD to give access to any data associated with those sections for viewing or editing.

dMAP lets a user produce electronic maps that are similar to conventional maps. However, in dMAP the user has more flexibility, power and speed than with a paper based system. dMAP gives the following advantages compared to conventional mapping:

1. it takes less effort to process spatial data and create a base map of the road network;
2. the base map can be easily maintained following any changes in the road network;

3. the link between the data in the database and the base map only has to be defined once;
4. different values of certain attributes can be distinguished using the standard features of AutoCAD such as colors, line widths, shading and so on;
5. maps can be displayed and edited on the screen before printing or plotting;
6. different maps can be saved in electronic and/or hard copy format.

9.3.2 Retrieving the Map File

This section describes the process required to implement dMAP for SDDOT.

The following material was provided to the consultant by SDDOT:

AutoCad drawing of the State highway system

Report indicating the different layers in the above drawing

Official State highway map

Intersection report from RES

SDDOT originally had the map file in Intergraph format. The dMAP software is AutoCad based meaning the format of the map file must be AutoCad. The consultant visited SDDOT and viewed the Intergraph file. SDDOT assured the consultant that the map could be translated into AutoCad format. The consultant made some recommendations about the information to include in the AutoCad map file. In other words, not all the information in the Intergraph file was relevant for dMAP purposes. The information listed in Table 53 was deemed necessary in the AutoCad file. This information is provided on different layers in the drawing.

Layer	Contents
3	U.S. Highway System
4	State Highway System
5	Interstate System
9	MRM's
12	North arrow
15	All U.S., Interstate and State Highway Shields
25	Region Boundaries

Table 53: Layers of information extracted from the Intergraph system to include in dMAP.

The consultant then loaded the AutoCad file provided by SDDOT. The next section describes the steps taken to verify the map and then link the map to the database.

9.3.3 Loading the Map File

The steps taken to verify the map file and link it to the database are discussed here. The points that the consultant was looking for to verify the map for use in dMAP are the following:

1. all highways must be **complete** polylines
2. all polylines must be drawn in the same direction as the highway is defined in dROAD
3. no polyline can break at a highway shield
4. no polyline can break at a region boundary

The steps the consultant performed were:

1. A Data Reference Point (DRP) report was printed from dROAD . This report shows for all roads in the database, the route's starting MRM and all MRM's on that route. This information was loaded from the RES-MRM file. This report is used as an aid to link the map to the database.
2. The polylines in the drawing file were verified to be contiguous at all points. In other words, the polylines did **not** break at the highway shields or the region boundaries.
3. The polylines in the drawing file were verified to be drawn in the same direction as the highways are defined in dROAD. The DRP report was required for this step. Any polylines that were drawn in the opposite direction were adjusted accordingly.
4. At this step the drawing file was deemed ready for linking to the database. A map is linked to the dROAD database by these steps (all of these steps are functions in dMAP):

   a) Export:

   Export dROAD's atoms to create a file containing road information for use by the split function in dMAP.

   b) Split:

   In this step each road in the map is identified and sub-divided at each DRP (from the DRP report) that is identifiable on the map, e.g. road intersections.

c) **Import:**

Import the split roads into dMAP and create dMAP handles for each road segment.

5. Once the above step was completed, the map was linked to the dROAD database and queries were run and displayed on the map for testing and verification purposes.

10. Training and Documentation

Provide training, documentation and a comprehensive user's manual for the enhanced pavement management system.

10.1 Software Documentation

All three pieces of software supplied through this contract have very extensive user manuals.[3,6,37,38] Four complete sets of manuals have been provided to SDDOT for their reference.

As expressed earlier in this report when discussing institutional issues, the consultant expressed the fact that a pavement management system is really a tool. The software packages (dROAD, dTIMS, and dMAP) are the means through which that tool can be used. As such, each one has a very strict vocabulary to precisely explain: (a) everything it can model, (b) the functions it uses to model those things, and (c) the information it produces because of the models. Persons who are not familiar with that vocabulary, can easily misinterpret it. Therefore, it is imperative that persons using the system are familiar with the terminology of the information they are using. This familiarity comes from training and from reading the manuals.

The consultant provided the following manuals:

dROAD 5 Technical Guide

Contains the complete civil and information engineering background to the dROAD software and the data model on which it is based. The PMS System Administrator must understand the contents of this document completely; including both engineering sides. Even the most casual user must understand parts of this manual. dROAD is a very flexible and powerful tool. Consequently using it properly requires a precise understanding of what it does and how it does it. This manual provides the necessary information to acquire that understanding.

dROAD User Manual

Describes all the functions in dROAD.

dTIMS User Manual

Combines the technical guide similar to dROAD's with a description of all the functions in dTIMS.

dMAP User Manual

Combines the technical guide similar to dROAD's with a description of all the functions in dMAP.

10.2 Software Training

Throughout the project, staff of SDDOT have been trained in the use of the software. The consultant attended SDDOT twice specifically for the purpose of training SDDOT staff.

As well, the advanced dROAD training course has been delivered as part of this project so that users can train themselves in the use of this software. This training course consists of a set of training videos, a work book, and an example database.

The training videos for dTIMS were not supplied as part of this contract. However, they too are an excellent and affordable way for SDDOT to train future pavement management engineers in the basics of the engineering behind dTIMS.

11. Final Presentations

Make an executive presentation to the Department's upper management and Research Review Board.

During the final weeks of the contract, the consultant presented the project to two groups of SDDOT personnel. The first group consisted of various SDDOT engineers. The second group was the Executive Team.

During these presentations the consultant explained the models and how they were developed, and demonstrated parts of the software. The consultant also answered any and all questions directed to him.

12. Conclusions and Recommendations

Develop recommendations for pavement management policies, procedures, and software design consistent with SDDOT's technical and organizational requirements.

12.1 Introduction

This section summarizes the entire project by presenting the recommendations developed by the consultant and some concluding remarks including how the original objectives were achieved. The recommendations are all based on investigations and situations the consultant encountered during the course of the project. In relevant cases, proper reference is made back to the section of this report where the situation causing the recommendation was first discussed. However, it is assumed the reader has reviewed all previous discussion and is familiar with the issues.

12.2 Recommendations

12.2.1 Historical Database

SDDOT should use dROAD as its pavement management historical database and should develop procedures which will ensure that this database gets loaded with road condition and construction data every year.

Currently SDDOT does not have a historical pavement management database. dROAD is capable of storing all data necessary to maintain a pavement management historical database. It does not require any programming on behalf of SDDOT. In a sense, it is ready to store all the historic data SDDOT needs for pavement management purposes, both now and in the future. To be useful, however, this capability must be exploited by SDDOT. Otherwise, dROAD will just end up being like the Planning File and the RES database whose one-year snap-shot pictures of the highway network are not sufficient to support a multiyear life cycle cost analysis.

To exploit this capability, SDDOT must develop a set of procedures which would formalize the tracking and storing of both the construction history, and the pavement condition as discussed in section 9.1.4 on page 186. Without these procedures, SDDOT will not end up with a historic pavement management database.

12.2.2 Enhanced PMS

> *SDDOT should supplement existing van tours and project selection procedures with the information and procedures developed under this project to evaluate candidate projects.*

The consultant strongly recommends that SDDOT incorporate the individual pavement condition indexes in the pavement management system into their pavement management procedures. They are the only indexes that can be truly predictive with time in a way that provides the most efficient array of pavement rehabilitation options for the most efficient project timing and scope identification.

The composite index which was developed to represent the most critical condition at any given time in the projects life cycle, rather than average the best with the worst conditions, is to be used to represent the general condition of the system. It can also be used to indicate the condition of the individual project to the public and elected officials in a simple manner. The composite index should be used to show the relative "health" or condition of the pavements; not to trigger treatments or calculate timings. It should not be used to prioritize or select projects. It is not an index that can be used to predict individual project pavement condition with time, nor is it able to help define the general needs of a project thus its general scope.

The life cycle cost analysis capabilities of the system developed here for SDDOT is a far better way to evaluate individual project needs with network constraints in mind.

12.2.3 Priority Planning System

After a period of validation and verification, SDDOT should replace the existing priority planning system with the enhanced pavement management system developed under this project, and should distribute this new information to the regions.

Pavement Management Systems require pavement condition indices to describe the state of being of the pavement relative to those basic pavement attributes that cause the agency to take action. Many agencies have used pavement smoothness (ride) as the single or predominate attribute on which to base action. It is now generally recognized that the use of this single attribute limits the full utilization of a pavement management system and restricts the system to work only with more deteriorated pavements with less cost effective treatments. It is now generally recognized nationwide that pavement condition assessment must consider not only ride, but also the individual pavement distresses that aid early identification and action on those distresses that ultimately cause pavement smoothness to change.

Pavement condition information is used to evaluate the current condition, determine the rate of deterioration, project future condition, determine maintenance and rehabilitation needs, and determine the costs to repair pavement segments. It is also used to establish maintenance and rehabilitation strategies and to help prioritize both maintenance and rehabilitation fund expenditures.

SDDOT has used several different condition indexes such as PSR, a sufficiency rating and a priority ranking. Only the priority ranking was ultimately used to select projects for the construction programme. The consultant performed a sensitivity analysis on this ranking number. Though the ranking number considered many pavement related attributes, it was found to be largely affected by changes in pavement smoothness and traffic at any specific location. Because of the questionable application of this ranking number in a modern pavement management system, the consultant recommends that SDDOT use individual pavement condition indexes in their system that reflect the individual pavement deterioration experienced in South Dakota.

However, the replacement of the old pavement management system with the new should be phased in. SDDOT should learn the new system by using it concurrently with the old system for a period of time. SDDOT should switch only when they develop a level of comfort with the information from the new system. When this happens, SDDOT should find ways to spread the information throughout the agency, including the regions, so that they too can take advantage of its value in assisting with decision making.

12.2.4 Distress Surveys

SDDOT should perform a detailed distress survey (similar to the one performed on the pilot study roads) for the remainder of the road network. Also, SDDOT should adopt this distress survey as part of their regular data collection program.

Early in the execution of this project, the consultant determined that the distress data available in SDDOT was insufficient to meet the needs of the new South Dakota PMS (see section 4.4.3 on page 59). The consultant designed and pilot tested a distress survey (see chapter 0 on page 131) to remove this problem and to acquire sufficient data to test the enhanced pavement management system. The results of this distress survey look promising.

Therefore, the consultant recommends that SDDOT officially adopt a policy that requires this distress data be collected. The amount, timing and frequency of this survey can be determined later. It should be noted, however, that the cost of this survey is trivial compared to the amount of money SDDOT could save by making more proactive decisions.

12.2.5 PMS System Administrator

SDDOT should officially recognize the role of a PMS System Administrator and designate one full-time person in the pavement management unit of Planning and Programming to this role.

The South Dakota PMS should be regarded in the same way as a living thing. In other words it requires constant care. Generating special reports, supporting part-time users, loading data, distributing data, and modifying the models are only a few of the tasks which will have to be performed constantly on the software. Most software books go into great detail describing the need for, and role of, a System Administrator. Rather than reiterate those details here, the consultant recognizes that the need for a PMS System Administrator is real, and that the position is key to the long term success of this new software.

12.2.6 Data Sources

SDDOT should initiate a management system project which would result in the data which feeds the new PMS historical database originating from the RES file(s) instead of the Planning File.

Recall that considerable discussion was dedicated earlier in this report to describing the existing RES database and the Planning File (see sections 4.3.2 and 4.3.3 starting on page 39). During the course of the project, the consultant recognized that the data in the Planning File was too coarse to perform this type of analysis with (see section 4.3.3, Figure 1 on page 45). Therefore, the consultant recommends that SDDOT initiate a project which would result in the data that feeds the PMS historical database come from the RES file. This project will likely require a great deal of effort from the computer department in SDDOT.

12.2.7 Future Model Development

SDDOT should fully examine the models developed in this project continuously for the next year, and re-examine them every five years thereafter.

As discussed earlier in the report, and as mandated by ISTEA, it is essential that SDDOT keep reviewing the models on a periodic basis to keep them current with

SDDOT policy and procedures. Coordinating this activity should be one of the responsibilities assigned to the PMS System Administrator.

12.2.8 Pavement Management Task Force

SDDOT should keep the Pavement Management Task Force and should supplement it with representation from all the regions. This group should review the pavement management models as needed and should oversee the implementation of the new pavement management system.

Through the development of the enhanced pavement management system the PMS Advisory Team has provided significant information and direction; without which the project could not have been successful. The consultant strongly recommends that this team be continued as a PMS Implementation Committee. After the implementation of the enhanced pavement management system, the committee should go on to become the PMS users support group. For both the Implementation Committee and future users support group, the consultant recommends that there be somewhat more participation from individual Region representatives.

12.2.9 Institutional Issues

SDDOT should ask for and obtain a commitment from upper management to support the new pavement management system at all times, and to use and promote its information.

SDDOT appears to strongly support and take justifiable pride in their existing PMS and their efforts in this area. Upper level management in SDDOT has clearly supported ongoing efforts to make use of and improve these processes. This continued support is critical for the full implementation of the new pavement management system in providing clear and well defined goals and policies as well as adequate funding and workforce to reasonably meet those goals.

This commitment from upper management did not seem as clear as it should be to dirêct and empower the PMS Task Force to fully and effectively implement a new pavement management system. We recommend that the PMS Task Force formally ask for and obtain a commitment from upper management to support the task force's efforts to implement a new pavement management system.

12.2.10 Location Referencing

Since a historical database requires location stability over time, SDDOT should initiate a study to end any debate regarding locations and addresses of features South Dakota as given by the MRM location reference system. SDDOT should adopt a policy where all employees are required to be knowledgeable about SDDOT's location reference system.

Although location referencing in SDDOT is not as big an issue in SDDOT as it is in other state DOTs, the issue is not completely addressed. With the spread of newly available information, comes the need for the receivers of that information to understand where in the network it relates to. Although it seems obvious to some people, to others the MRM and offset concept is not fully understood. As well, custodians of various systems throughout SDDOT do not seem to be aware of how essential address stability really is (see section 4.4.1 starting on page 48). Without this quality, the hope for a historical database is lost.

Therefore, the consultant recommends that SDDOT initiate a study to once and for all end any debate regarding locations and addresses in South Dakota. One of the deliverables of this project would be to update the video describing the location reference system. Also, the consultant recommends that SDDOT adopt a policy whereby <u>all</u> employees who collect data for, or receive information from, the pavement management system must attend and pass a course in SDDOT location reference system.

12.2.11 Deflection Survey

SDDOT should consider using the deflection based subgrade and pavement stiffness values to help select rehabilitation treatments in their treatment selection processes, and discontinue their use in setting network priorities.

The consultant does not recommended that any deflection based indicator of pavement stiffness be used to make project timing decisions. Pavement stiffness is very dependent on construction processes, material properties, and environment which combine to make it very difficult, if not impossible, to predict the timing of significant changes. Over time all asphalt concrete pavements initially stiffen as the asphalt films age and oxidize. The resilient modulus values of most ACP mixes are in the range of 400 ksi to 600 ksi following construction. As the asphalt films in the ACP age over 5 to 10 years it is not uncommon to see the resilient modulus values increase to values in the range of 700 to 1,000 ksi. When the pavement starts to fatigue crack or deteriorate from stripping the resulting resilient modulus values will drop. In the case of stripping pavements the values will typically drop to a range of 200 ksi to 400 ksi. For fatigue cracking the resilient modulus values may drop as low as 80 ksi to 150 ksi for full fatigued pavement. The problem is that it is almost impossible to predict the timing of these changes until there is a clear pattern of deterioration. In many cases it is then too late to apply the most cost effective rehabilitation treatments.

The use of deflection-based pavement stiffness values are most practical when the pavements have all deteriorated to the point where the surface reflects only a series of deteriorating patches and it is difficult to differentiate one badly patched roadway from another. Here, then, where the pavements cannot be distinguished by low visual distress and roughness values, deflection-based structural stiffness values could be used to differentiate the pavement needs.

The pavement conditions in South Dakota are clearly much better than that just described. The consultant recommends that SDDOT consider only using the deflection based subgrade and pavement stiffness values to help select rehabilitation treatments in their treatment selection process.

In the past, SDDOT collected network pavement deflection data using a Dynaflect for input into its pavement ranking processes. In the last year or so they obtained a Falling Weight Deflectometer which is a much more accurate tool for pavement deflection testing. This specific tool has many uses usually ranging from a very accurate research tool to an equally accurate pavement design tool. It may also be used in pavement management but the high quality and accuracy of the tool may be somewhat under utilized in that use.

In the existing SDDOT pavement management processes, the deflections collected from this tool are converted back to equivalent deflections from the

Dynaflect and a very simple single deflection analysis is used as one of many items in a pavement ranking procedure. In developing a new pavement management system, the consultant did not see a clear need for the simple deflection analyses currently in use.

The consultant does not recommend that the existing structural analysis be included in any of the new pavement management system project ranking procedures. If the network deflection testing is continued then there are some fairly accepted procedures that provide a more meaningful assessment of the relative stiffness of the composite pavement layers and the stiffness of the subgrade soils from the deflection tests. The analysis procedures which consist of a simple set of basic computations are described in (section 4.4.2 starting on page 50). There may be some merit in using these basic stiffness values in the selection process for rehabilitation treatments.

There is a concern, however, in the size of the network sample. Does the test, which represents the stiffness in only 3 ft. to 5 ft, represent the relative pavements structural response for the entire mile segment when only one test is conducted per mile. This sampling rate represents a little less than a 0.1% sample which is an extremely small sample for any use. The consultant recommends that SDDOT compute these stiffness values from the existing deflection tests and judge whether they reasonably represent the performance and thus implied stiffness of the pavement over the one mile segments. If it can be shown that the information represents conditions found in each specific section then the values may be used to help select or limit rehabilitation treatments for each pavement section. Specifically, it may have a valid use in limiting the treatments that are not structurally justified for the performance assumed.

12.2.12 Security

> *SDDOT should put in place a security mechanism which will ensure that only authorized persons get access to the database. The software's own internal security mechanisms coupled with the security features of the network software will make this possible.*

The database and analysis data will be kept on a network file server. The software (dROAD and dTIMS) has built in security to prevent unauthorized people from using it. However, the files all exist on the hard drive of the file server. And, anyone with a moderate degree of computer knowledge could access them. This opens up the possibility of having other people looking at and possibly damaging the files.

Therefore, the consultant recommends that SDDOT put in place a security mechanism which will ensure that only authorized persons get access to that part of the file server. This can be facilitated using the security features of the networking software.

12.2.13 Hardware

The current hardware at SDDOT may be inadequate to perform the required analysis in a timely manner. A dedicated micro computer with at least 20 Mb of RAM, a 1 gigabyte hard drive and a pentium 66 MHz processor or higher is required. Any analysis that is performed should be performed on this computer and not on a file server.

The current size of the historical pavement management system database for South Dakota is approximately 23 megabytes. To handle the historical data, this database will continually grow. And, it is conceivable that more data items could be added in the future. Therefore, it is not unreasonable to assume the database will grow to 50 or 100 megabytes.

Similarly, the size of the database which stores the information describing the strategies is currently 48 megabytes for the pilot study of approximately 550 sections. By extension, therefore, when the analysis is performed on the entire network, this database could grow to be 180 megabytes or more.

In addition, the length of time to perform an analysis on the pilot network was 20 hours. This was performed on a micro computer with a 66 MHz 486 processor with 16 megabytes of RAM. This means that an analysis for the entire network would take approximately 50 hours on the same computer. It would also be significantly longer in a network environment. Although eventually the analysis will only have to be performed a few times a year, the amount of time to wait for this is incredible. And, since the first few years of use require a lot of iterations, the time problem becomes significant.

In the long run, the solution to the time problem will come from two sources. First, as SDDOT further refines the models for the analysis, chances are these will be simplified rather than made more complicated. This simplification will save time. Second, the consultant is continually working to improve all aspects of the software including speed. In the short run, the solution to the time problem can only come from purchasing the fastest hardware available.

Therefore, the consultant recommends that SDDOT purchase a dedicated micro computer which has at least 20 megabytes of RAM, a 1 gigabyte hard drive, and a Pentium 66 MHz or higher processor. Furthermore, whenever an analysis is performed by generating a new set of strategies the consultant recommends that SDDOT perform this analysis on this computer. Also, the consultant recommends that SDDOT review the maintenance contract annually so that they will receive future enhancements to the software whenever they are made.

12.3 Concluding Remarks

To determine the success of this project the consultant has repeated the original objectives from the RFP. Then, below each objective, the consultant discusses how it was satisfied.

1. *To determine how the content and organization of the Department's pavement management database can support a historically based, multi-year optimizing pavement Management System and to identify needed improvements.*

   The consultant identified that the existing database had no historical qualities. As such, the consultant recommended that SDDOT use dROAD and a set of updating procedures to develop and maintain a historical pavement management database.

2. *To develop fundamental pavement management components, including historically based pavement performance curves, appropriate strategies for maintenance, rehabilitation and reconstruction, and formal definitions of current pavement management policy objectives.*

   The consultant designed a questionnaire to extract expert opinion regarding the pavement rehabilitation practices and experiences in South Dakota. Using information from that questionnaire, the consultant developed a set of engineering models which effectively model those experiences mathematically.

3. *To provide operational software incorporating these fundamental components and full pavement management functionality for database management, comprehensive analysis and report generation.*

The consultant then took his existing software and configured it according to the models developed above. He tested these models for reasonableness, and with the guidance of SDDOT's pavement management engineer modified them to produce reasonable results.

4. *To recommend policies and procedures and provide training necessary to maintain and operate the system.*

   The consultant included in the first section of this chapter a list of some thirteen recommendations designed to help modify SDDOT's policies and procedures regarding pavement management. The consultant also documented the steps carried out in this project so that SDDOT personnel could duplicate the effort in future years. Finally, the consultant spent a number of days training SDDOT personnel in the use of the software, and left with them the documentation and training videos necessary for them to increase their knowledge and proficiency with it over time.

With the completion of this research project SDDOT will have a pavement management system that is technically complete. This system is capable of providing all of the standard analysis and model development needed to provide the most efficient pavement rehabilitation program information. It meets both the AASHTO Guidelines and the new FHWA requirements for pavement management systems.

The system has a very strict vocabulary to precisely explain: (a) everything it can model, (b) the functions it uses to model those things, and (c) the information it produces because of the models. Persons who are not familiar with that vocabulary, can easily misinterpret it. SDDOT must make sure each person involved understands that vocabulary to the extent it is required to understand what he is doing.

A pavement management system is really just a tool. The models and the software are the means through which that tool can be used. Both must be monitored, and both must be adjusted. This means that in the same sense as this report marks the end of the consultant's work, it marks the beginning of SDDOT's. This project not only had an objective to provide a product, it had an objective to start a trend. It is now SDDOT's turn to make that trend continue.

With that in mind, it seems appropriate to end the document quoting from the same reference with which the document began, the ISTEA Rules and Regulations.

> *(3) Update. The PMS shall be evaluated annually, based on the agency's current policies, engineering criteria, practices, and experience.*[1]

[1] ISTEA legislation, Rules and Regulations 01 December, 1993.

[2] Botelho, F., National Perspective on Pavement Management, TR News Number 173, Washington, D.C., July-August, 1994.

[3] Deighton Associates Ltd., dTIMS User Manual, Bowmanville, 1994.

[4] Deloitte & Touche, Information Systems Plan (SD 91-14), SDDOT, Pierre, September 1991.

[5] RE/SPEC Inc., Historical Database Feasibility Study (RSI-0383), SDDOT, Pierre, January 1991.

[6] Deighton Associates Ltd., dROAD 5 Technical Guide, Bowmanville, 1994.

[7] Blake, D., Deighton, R., Enhancement of Utah's Location Reference System, Conference proceedings Third International Conference on Managing Pavements, National Academy Press, Washington, D.C., 1994.

[8] AASHTO, Guidelines for Design of Pavement Structures, AASHTO, Washington, 1993.

[9] Livneh, Moshe, Repeatability and Reproducibility of Manual Pavement Distress Survey Methods, Conference proceedings Third International Conference on Managing Pavements, National Academy Press, Washington, D.C., 1994.

[10] Lepert, P., Guillemin, R., Bertrand, L., Evaluation of French National Highway Network Based on Surface Damage Surveys, Conference Proceedings Third International Conference on Managing Pavements, National Academy Press Washington, D. C. 1994

[11] Seminar Notes, Pavement Condition Data Collection, Third International Conference on Managing Pavements, San Antonio, Texas, 1994.

[12] Peterson, D. E., Pavement Management Practices, NCHRP Synthesis of Highway Practice 135, TRB, Washington, D.C., 1987.

[13] AASHTO, Guidelines for Pavement Management Systems, ASSHTO, Washington, D.C., July 1990.

[14] Deighton, R.A., Blake, D. G., Database Module, Course Notes, An Advanced Course in Pavement Management Systems, FHWA, AASHTO, TRB, Washington, D.C., 1990.

[15] Smith, R. E., Hall, J. P., Overview of Institutional Issues in Pavement Management Implementation and Use, Conference Proceedings Third International Conference on Managing Pavements, National Academy Press, Washington, D. C., 1994

[16] Hall, J. P., Institutional Issues Module, Course Notes, An Advanced Course in Pavement Management Systems, FHWA, AASHTO, TRB, Washington, D.C., 1990.

[17] SHRP, Distress Identification Manual for the Long-Term Pavement Performance Project, SHRP-P-338, Strategic Highway Research Program National Research Council, Washington, D.C., 1993

[18] Hill, L., Cheetham, A., Haas, R., Development and Implementation of a Pavement Management System for Minnesota, Transportation Research Record No. 1311 Pavement

Management: Data Collection, Analysis, and Storage, National Academy Press, Washington, D. C., 1991

[19] Sayers, M. W., Profiles of Roughness , Transportation Research Record No. 1260 Pavement Management and Rehabilitation, National Academy Press, Washington, D. C., 1990.

[20] Long, R. R. Jr., Pavement Management System for Concrete Roadways in Virginia: Phase 1 - Condition Ratings, Transportation Research Record No. 1272 Pavement Management and Rehabilitation, National Academy Press, Washington, D. C., 1990.

[21] Nelson, T. L., LeClerc, R. V., Development and Implementation of Washington State's Pavement Management System, Research Report No. WA-RD 50.2, Olympia, 1982.

[22] Shahin, M. Y., Kohn S. D., Pavement Maintenance Management for Roads and Parking Lots, Construction Engineering Research Laboratory Technical Report M-294, 1981.

[23] Baladi, G., Snyder, M., Highway Pavement Training Course, Michigan State University, FHWA, NHI, Publication No. FHWA HI-90-026, Washington, D.C., 1992.

[24] Fitch, T. F., Yu H. T., Shahin, M. Y., Evaluation of Field Inspection Devices for Use with the PAVER Pavement Management System, Transportation Research Record No. 1311 Pavement Management: Data Collection, Analysis, and Storage, National Academy Press, Washington, D. C., 1991

[25] Rodriguez, L., Harris, R. L., Test and Evaluation Project No. 21 "Automated Pavement Distress Survey Equipment", November 15 - 19, 1993 Austin , Texas, Second Draft Final Report.

[26] Paterson, W. D., Proposal of Universal Cracking Indicator for Pavements, Presented at the Transportation Research Board Annual Meeting, Washington, D. C., 1994.

[27] Gulen, S., Woods R., Weaver, J., Anderson, V. L., Correlation of Present Serviceability Ratings With International Roughness Index, Presented at the Transportation Research Board Annual Meeting, Washington, D. C., 1994.

[28] Barros, R., Assessing Composite Distress Evaluations, Transportation Research Record No. 1311 Pavement Management: Data Collection, Analysis, and Storage, National Academy Press, Washington, D. C., 1991

[29] Jackson, N, Kay, K., Mahoney, J., The WSDOT Pavement Management System - A 1993 Update, Report No. WA-RD 274.1, Washington State Transportation Center, WSDOT, 1993.

[30] Ben-Akiva, M., Humplick, F., Madanat, S., Ramaswamy, R., Latent Performance Approach to Infrastructure Management, Transportation Research Record No. 1311 Pavement Management: Data Collection, Analysis, and Storage, National Academy Press, Washington, D. C,. 1991

[31] Butt, A. A., Shahin, M. Y., Feighan, K. J., Carpenter, S. H., Pavement Performances Prediction Model Using the Markov Process,Transportation Research Record No. 1123 Pavement Management and Weigh-in-Motion, National Academy Press, Washington, D.C., 1987.

[32] Shahin, M. Y., Nunez, M. M., Broten, M. R., Carpenter, S. H., Sameh, A., New Techniques for Modeling Pavement Deterioration, Transportation Research Record No. 1123 Pavement Management and Weigh-in-Motion, National Academy Press, Washington, D.C., 1987.

[33] Northwest Pavement Management Systems Users Group, Kay, K., Pavement Surface Condition - Rating Manual, Washington State Transportation Center-University of Washington for Northwest Technology Transfer Center, WSDOT-Local Programs Division, 1992.

[34] Letter from Dr. Joe Mahoney to Newton Jackson dated Sept. 10, 1993. See Appendix RR for a copy of this letter.

[35] Mahoney, J. P., Ph.D. Thesis, Texas A. & M. University, College, Station, 1978.

[36] Texas Transportation Institute, Pavement and Road Surface Management for Local Agencies - Course Notebook, National Highway Institute, Washington, D.C., 1994.

[37] Deighton Associates Ltd., dROAD User Manual, Deighton Associates Ltd., Bowmanville, 1994.

[38] Deighton Associates Ltd, dMAP User Manual, Deighton Associates Ltd., Bowmanville, 1994.