KNOWLEDGE BASED ADVISORY SYSTEM FOR FLEXIBLE PAVEMENT ROUTINE MAINTENANCE

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By

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ABSTRACT

In recent years, pavement maintenance has become an area of major expenditure for many highway agencies. Making good maintenance decisions requires years of practical experience and judgement. Deciding on the best maintenance strategy is largely a subjective problem mainly because the benefits of a particular type of maintenance have not been quantified. Hence the problem does not lend itself to a traditional economic analysis where benefits and costs can be explicitly considered. As a result, the field seems perfectly suitable for an expert system application.

Only four systems in flexible pavement and one system in rigid pavement were reported in the literature, namely, PARADIGM, PRESERVER, ROSE, ERASME, and Concrete Pavement Evaluation. These systems are limited in their application to particular jurisdictions and environmental conditions. The only three systems which consider routine maintenance are PRESERVER, ROSE and ERASME. PRESERVER runs only on a mainframe using the specially developed expert system programming environment OPS5. ROSE is a knowledge-based computer program intended for selecting and recommending routing and sealing of cracks only. ERASME is of limited scope and applicable only to pavements in France. Therefore, it is essential to develop an expert system program to facilitate pavement maintenance decision making in Newfoundland.

This thesis describes the development of the Pavement Maintenance Advisory System (PMAS). It involves two areas of study. The first area is the process of knowledge acquisition. Knowledge was acquired for PMAS both from formal documents, documented case studies and from interviews with experts from the Newfoundland

Department of Works, Services and Transportation. The interaction with the experts was invaluable and their expertise, which was not available in any literature, was encoded in the system.

The second area of this study is the development of a computer program for selecting the appropriate maintenance strategies in cold/coastal regions. The system uses input including the type of distress, surface condition (severity and density), traffic volume, Riding Comfort Index, climate condition and outputs maintenance strategies with expected repair life in years as well as the associated total and unit cost of equipment, labors and materials. The cost comparison for the recommended maintenance strategies does not affect the internal decision making of the program. This feature simply allows the user to evaluate other maintenance options in case particular materials, laborers and equipment are available. The system is developed using two expert system shells; Exsys Professional on IBM-PC and compatibles and Instant Expert Plus on Apple Macintosh. PMAS utilizes backward chaining mechanisms to arrive at a conclusion. Confidence factors were introduced to indicate expert opinion on the suitability of the alternative maintenance strategies. The operational system was successfully tested by the experts through nine test case studies. PMAS can serve as a training tool for engineers who do not have much experience in selecting routine pavement maintenance strategies.

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Chapter 1

Introduction

One of the pressing problems facing the nation is the condition of its roadway infrastructure. In 1989, the total value of highway (roads and streets) construction was $6.2 billion which represented 5.8% of the total value of construction in Canada. At the same time, the total value of highway construction repairs was $1.56 billion, which represented 25.4% of the total value of highway construction [Statistics Canada Catalogue, 1989]. As the infrastructure ages, this expenditure is expected to rise further. Hence, pavement maintenance is becoming a major area of importance for highway agencies across North America.

Numerous studies have attempted to address pavement maintenance and pavement distresses. Selecting maintenance strategies is based on years of practical experience, however, often maintenance decisions are made by engineers who have limited practical experience [Ritchie, 1987]. Some forms of asphalt concrete distress, for example, can be prevented or delayed by using a good maintenance strategy [Brown, 1988].

Deciding on the best maintenance strategy is largely a subjective problem mainly because the benefits of a particular type of maintenance have not been quantified [SHRP, 1986]. Hence the problem does not lend itself to a traditional economic analysis where benefits and costs can be explicitly considered. As a result, the field seems perfectly suitable for an expert system application.

Expert systems, known also as knowledge-based systems, have been used as the means of conveying pavement maintenance knowledge, gained through research and field experience [Lemley, 1985]. An expert system is defined as an interactive computer program which documents judgement, experience, intuition and other information in order to provide knowledgeable advice [Gasching et al., 1981]. Knowledge is classified into public and private [Allez et al., 1988]. Public knowledge consists of information available through published literature (i.e., books, journals, etc.). Private knowledge, on the other hand, is possessed by human experts and it is gained through years of practical experience. By combining these two broad categories of knowledge, expert systems provide a logical approach for solving pavement maintenance problems.

Computers are essential tools for many of the pavement management activities (e.g., design, planning etc.). These activities are usually well defined and have known procedural algorithms such as pavement design and highway alignment. Many problems in pavement engineering lack explicit mathematical solutions, so conventional computer tools are of limited use. These type of problems are considered a suitable candidate for an expert system solution. The development of such a system for Newfoundland is considered desirable in order to:

1 Facilitate the decision making process with regard to flexible pavement maintenance because similar existing systems that have been developed and successfully used in other jurisdictions (e.g. Ontario, California and Texas) are not applicable to Newfoundland weather conditions and types of maintenance used.

2 Provide portable experience in remote areas of the province.

3 Encode the private knowledge on pavement maintenance in an organized manner which is not available in the literature.

4 Serve as a training tool for engineers who do not have much experience in selecting pavement maintenance strategies.

1.1 Objectives

The objective of this study is three-fold. The first objective is to collect a body of knowledge related to flexible pavement maintenance strategies, for the three types of most serious distress problems in Newfoundland namely rutting, alligator cracking and transverse cracking [Sellers, 1991., McCarthy, 1985., Tam and Lynch, 1986]. The second objective is to develop a rational approach for modeling the decision making process of pavement maintenance strategies selection. The third objective is to develop a computer tool (i.e., *expert system*) which will provide expert advice on pavement maintenance strategies. This computer program will model and facilitate the decision-making process by encoding pavement maintenance knowledge.

1.2 Organization of thesis

This thesis is organized into six chapters. Chapter one introduces the problem and elaborates on the research objectives. Chapter two describes basic concepts and components of expert systems. This chapter also provides the advantages and the limitations of expert systems. Chapter three reviews known expert systems developed for pavement maintenance, and identifies major pavement distresses and the alternative maintenance treatments. Chapter four describes the methodology and the process of knowledge acquisition. Chapter five explains the procedure that was followed to develop the expert advisory system for flexible pavement maintenance. Finally, chapter six includes summary and conclusions.

Chapter 2

Expert System Concepts

Separate groups of British and American scientists led the development of the digital computer. In spite of the fact that computers were built as numerical tools, a small group of computer scientists continued to pursue the application of computers in manipulating non-numerical problems [Fenves,1986]. Over the years, scientists, concerned with symbolic processing and human problem-solving have formed the interdisciplinary subfield of computer science called artificial intelligence (AI). AI includes algorithms that provide answers by attempting to model human reasoning. AI evolved as a branch of computer science, parallel to other branches dealing with languages, data structures, operating systems and numerical algorithms [Fenves, 1986]. The collection of AI techniques that enable computers to help people to evaluate problems and make decisions are the basis of knowledge-based or expert systems.

AI programs can be subdivided into three relatively independent categories. The first category of AI is concerned primarily with developing computer programs that can read, speak, or understand spoken languages. This area is generally referred to as natural language processing. The second category of AI is concerned with developing intelligent robots. Scientists are particularly concerned with how to develop visual and tactile programs that will allow robots to observe and respond to the changes in their surroundings. A third category of AI is concerned with developing programs that use symbolic knowledge to simulate the behavior of human experts, called expert systems (ES).

ES are being developed to assist in complex planning and scheduling tasks, to diagnose diseases, to locate mineral deposits, to configure complex computer hardware and to aid mechanics in troubleshooting engine problems [Harmon and King, 1985].

As recently as 1980, ES research was still confined to a few university research laboratories. Today, the United States, Japan and the European Economic Community have initiated major research programs to develop and implement expert systems [Fenves, 1986]. A glossary of expert system terminology used in this chapter is presented in Appendix A.

2.1 Definition of Expert Systems

Many researchers have defined the term "Expert Systems." Among some of the most common definitions are:

1 "Expert system is a computing system capable of representing and reasoning about some knowledge-rich domain," [Peter, 1986].

2 "Expert systems are interactive computer programs incorporating judgment, experience, rules of thumb and other expertise to provide knowledgeable advice about a variety of tasks," [Gasching et al., 1981].

3 "A tool which has the capability to understand problem specific knowledge and use domain knowledge intelligently to suggest alternate paths of action," [Kumara et al., 1989].

4 "An intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require human expertise for their solution," [Barr and Feigenbaum, 1982].

Expert systems are successfully used when the problem needs subjective reasoning for its solution [Davis and Lenat, 1980]. This feature was expressed in the first definition as "knoweledge-rich domain." The following section will demonstrate some other features of expert systems and compare them with conventional programming.

2.2 Conventional Programming Versus Knowledge Based Programming

Conventional programming systems are best suited to collect and process large volumes of data. They process this data by means of numerical algorithms.

Knowledge based systems are significantly different. They are highly interactive. A user can stop the processing at any time, and ask why an individual line of questioning is being persuaded or how a particular conclusion was reached. The single feature which distinguishes expert system programs from traditional ones is the separation of the control system from its knowledge base. Conventional programming languages, such as FORTRAN and BASIC, the control system and the database are integral parts of the program [Hall and Sporkin, 1986]. The main differences between an expert system and a conventional program are:

1 "The knowledge base of an expert system is readable, easy to change and highly interactive," [Maher, 1987].

2 "Conventional programs tend to depend on algorithms to provide their overall structure, whereas knowledge systems tend to depend on expertise for their structure," [Harmon and King, 1985].

3 "The job accomplished by an expert system was formerly performed by a knowledgeable human specialist," [Townsend and Feucht, 1986].

4 "Knowledge engineers and experts maintain knowledge systems. Conventional programs are maintained by programmers," [Harmon and King, 1985]. Knowledge

engineers concentrate both on the development of software for expert systems and on the analysis of ways in which human experts answer problems. Knowledge engineers interact with human experts to help them document their knowledge and provide the inference strategies, in terms that will allow the knowledge to be encoded [Harmon and King, 1985].

Expert system technology is not radical at all. It is simply an extension of basic computer science principles to new levels of sophistication. Expert systems address problems that normally require the expertise of a human specialist.

2.3 Components of Expert Systems

The structure of an expert system consists of five basic components shown in Figure 2.1: a rulebase or knowledge base, a working memory or data base, an inference engine, a knowledge acquisition module and an explanatory interface. These components are described next.

2.3.1 The Rulebase or Knowledge-Base

The knowledge base contains a large amount of knowledge in the form of rules. Each rule contains two parts. The first part, called the premise (IF), consists of conditions linked together by AND. The second part is the THEN part consisting of one or more conclusions or actions. That is, IF <situation or condition> and THEN <conclusions or actions>.

The knowledge of an expert system consists of facts and expertise about a specific domain. The facts constitute a body of information that is widely shared, publicly available and generally agreed upon by experts in that field (declarative knowledge). On the other hand, expert knowledge is mostly private, made up of objective rules of judgment that characterize expert-level decision making (procedural or expert knowledge).

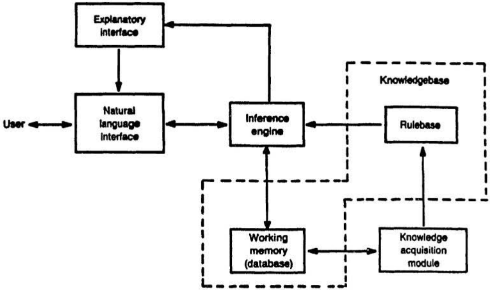


Figure 2.1: Components of Expert Systems [Townsend and Feucht, 1986]

Rules can represent either a fact or a decision. For example, extensive density of pavement distress is a fact that can be expressed in a declarative rule form as follows.

IF : The distress affected more than 30% of a pavement section

THEN : The density is extensive

Procedural rules, based on experience, are rules which relate the selection of a pavement maintenance strategy to a set of conditions. For example the following rule concluded in a decision to use hot or cold mix patching.

IF : The distress observed is single distress

and The type of distress observed is rutting

and The repair is needed this season

and The severity of rutting is severe

and The density of the distress is few

and The climate is coastal

THEN :

Hot mix patching, the expected repair life is three years

Cold mix patching, the expected repair life is two years

2.3.2 Working Memory or Data Base

The most basic function of the working memory is to contain a large amount of data usually in the form of values (user input). The data stored in working memory are dynamic and change for each consultation or computer run. The working memory functions as a temporary memory to store values for the consultation under consideration [Hall and Sporkin, 1986].

2.3.3 Inference Engine

The inference engine contains a control structure that uses input data, and attempts to search through the knowledge base to reach a conclusion. The control structure first examines the existing data in the working memory and the rules in the rulebase and then decides in which order the rules are to be "fired". If the premise (IF part) is true, the resulting conclusion (THEN part) must be true. The control component contains four functions namely, matching, selection, firing, and action. For example, in each run, the existing rules are scanned to see which ones have premises that match the known facts in the working memory. The rule is then fired, with the conclusion added to the working memory. In some systems the inference engine works in a "forward" process using the data in the memory to reach a conclusion. In other systems, the inference engine works in a "backward" process, trying first one conclusion and then anothers until it can find supporting facts for a particular conclusion [Townsend and Feucht, 1986]. The functions of these processes will be explained in detail in Section 2.4.

2.3.4 Knowledge Acquisition Module

The purpose of this component is to assist the procedure of entering the knowledge into the knowledge base. This component acts as an editor for entering the rules to the rulebase, modifying existing rules, and saving the rules in the rulebase in a form that can be used by the inference engine, [Townsend and Feucht, 1986].

2.3.5 The Explanatory Interface

The component of the knowledge system that explains how the conclusion is reached is the explanatory interface. The explanatory interface provides a user friendly interface between the user and the machine. One of the basic features of any explanatory interface is its ability to respond to questions like "Why" and "How." Some systems explain "How" they reached certain conclusions, by displaying the fired rules in a sequential manner. This facility also allows the system to present information in a readable form.

2.4 Control Strategies

Control strategy is the part of the inference engine that decides the sequence in which the rules are examined and fired. Forward or backward reasoning control strategies are usually used in the development of expert systems.

In a forward reasoning strategy, the inference engine starts with the facts, and tries to reach a conclusion by going to the rules in the working memory and looking for similar facts in which a conclusion has already been formulated. The rules in forward reasoning are of the form, "IF conditions THEN conclusions". A forward reasoning strategy is generally practical in circumstances where there are many solutions and few input data or facts (e.g., diagnostic system).

In a backward reasoning strategy, the inference engine starts with the conclusion and tries to find a fact which would support this conclusion from the working memory. The rules are of the form "IF conclusion THEN condition." A backward reasoning strategy is usually used in circumstances where there are few conclusions and many input facts.

2.5 Knowledge Representation

Humans possess knowledge in a variety of forms. Several attempts have been made to simulate how knowledge is represented in the human brain. Some of the most popular knowledge representation schemes are discussed in the following sections. There are several other representation schemes which are beyond the scope of this thesis such as object oriented representation and blackboard systems [Townsend and Feucht, 1986].

2.5.1 Semantic Networks

Semantic networks attempt to describe the word in terms of objects (nodes) and links relations (labelled edges). According to a semantic network representation, the knowledge is a collection of objects and associations represented as a labelled directional graph [Harmon and King, 1985]. The nodes are represented by a labelled boxes. The links between the circles represent relationships between nodes. Figure 2.2 depicts the structure of a semantic network. Semantic networks are easily understandable, but difficult to implement. For example, one fact or rule can be represented by a big number of nodes and links. As a result, large knowledge base will be difficult to develop and manage.

2.5.2 Frames

A frame is a data structure for representing a typical situation arranged in slots and filler format. The slots store knowledge such as type, cause and maintenance strategy for each distress. Slots can be used to store values, procedures or rules. The fillers are the accompanying explanation of the slots [Kumara et al., 1989]. Figure 2.3 gives an example of the structure of a frame. A frame is similar to a semantic network; the main difference is that the nodes in a semantic network represent simple ideas, whereas the slots in a frame structure represent compound concepts.

2.5.3 Knowledge Representation with Rules

Rule based systems are the most widely used representation schemes [Maher, 1987, Townsend et al., 1986, ESCAD, 1986]. In a rule based system, commonly referred to as a production system, the complete knowledge base is programmed in an IF-THEN rule format. There are two types of rules used to represent knowledge. The first type of rule is referred to as "declarative" which expresses facts and assertions about the problem. Declarative rules are used to represent static knowledge. If the fact is true then the conclusion is true. The second type of rule is referred to as "procedural". In procedural rules, the left hand side of the rule is called the "condition" and the right hand side is called the "action". Using the procedural rules, the action part of the rule may be achieved whenever the condition part is true [Kumara et al., 1989].

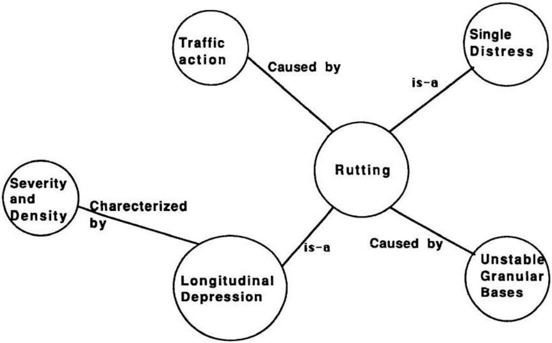


Figure 2.2: Example for Semantic Network Representation

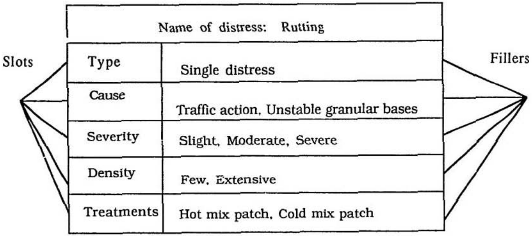


Figure 2.3: Example for Frame Representation

2.6 Languages and Tools for Building Expert Systems

Knowledge systems can be written using almost any type of computer language. A number of specialized languages are presently available for building expert systems. These languages can be classified into three categories, namely, Artificial Intelligence Programs, Programming Environment Languages, and Knowledge Based Engineering Tools [Townsend and Feucht, 1986, Harmon and King, 1985].

Artificial intelligence programs commonly use high-level specialized languages such as LISP (list processing) and PROLOG (programming in logic). PROLOG contains features that facilitate the writing of programs which manipulate logical expressions. PROLOG is one of the most widely used programming languages for ES development [Frederic, 1983]. AI languages provide maximum flexibility, but it is difficult to develop a prototype because the programmer has to develop the inference component.

The programming environment languages are programming languages developed specifically for knowledge engineering. They are much less flexible than AI languages because they have a predesigned inference engine. OPS5 and KEE are examples of programming environment languages [Harmon and King, 1985].

Knowledge based engineering tools provide the expert system builder with an inference engine, from which the application can be built by adding domain specific knowledge. Expert system shells fall under this category. An expert system shell is a fully developed expert system with its knowledge base removed. It contains a variety of user friendly modules to assist with the input of the knowledge base.

2.7 Who is the Expert?

The expert has developed the ability to organize a large amount of information in a particular area. A typical expert in a specific field will know 50,000 to 100,000 pieces of information, that can be applied to decisions in his/her specific domain of expertise. The accumulation and indexing of this much data in the human mind takes between 10 and 20 years [Townsend and Feucht, 1986].

2.8 Expert Systems Classifications

A useful guideline for classifying expert systems in terms of performance and utility is the level of expert system evaluation and development. Six levels were defined by Waterman [Waterman, 1986]. These are:

1 Conceptual prototype: These systems are at an early stage of development and represent conceptual or preliminary designs for expert systems.

2 Demonstration prototype: These systems are also in relatively early stages of development. They have reached the stage of a working prototype.

3 Research prototype: These systems address the entire problem undertaken, displaying credible performance, but have not been substantially validated or refined.

4 Field or operational prototype: These systems display good performance, with adequate reliability, and have been revised by extensive testing.

5 Production Models: These are expert systems that exhibit high quality, reliability, speed and efficient performance.

6 Commercial systems: These systems are production models that are used on regular commercial basis.

2.9 Expert Systems Limitations

Expert systems are limited by the information in their databases and by the nature of the process for inputting that information. Expert systems can not report conclusions that are not already implicit in their databases. Large databases are likely to be difficult to modify and to maintain. As a result, expert systems are more appropriate to narrow domains of expertise [Denning, 1986]. Bruce Buchanan of

Stanford University's Heuristic Programming Project and Randy Davis of the Massachusetts Institute of Technology's Artificial Intelligence Laboratory in Cambridge have pointed out limitations on expert systems [Gevarter, 1983]. Among them are:

1 Narrow domain of expertise. Building and maintaining a large knowledge base is difficult; only a few expert systems cover a significant range of knowledge.

2 Limited knowledge-representation language for facts and their relation. Certain types of knowledge, particularly those without immediate IF-THEN consequences, can be quite difficult to represent efficiently in current knowledge-representation languages.

3 Relatively stylized languages for input and output. Users must describe problems in a strictly defined language.

2.10 Summary

In this chapter the essential concepts and key words have been discussed, and the basic concepts of expert systems have been explained. The knowledge of an expert system consists of facts and expertise about a specific domain. The working memory contains a large amount of data. The inference engine consists of two components, namely, inference and control. The knowledge acquisition module acts as an editor for entering the rules. The explanatory interface provides a friendly interaction between the user and the machine. Some methods of representing knowledge and the limitation of expert system have been presented. The following chapters will describe the development of a prototype system in detail and should clarify the concepts.

Chapter 3

Literature Review

This chapter summarizes the current operational prototype systems in the area of pavement maintenance. The demonstration of their applications and limitations are addressed. This chapter also provides the background of pavement distresses and maintenance strategies in detail.

3.1 Review of Pavement Maintenance Expert Systems

Little work has been reported in the literature with regard to expert system applications in the flexible pavement area. There are no expert systems known to have reached the commercial level of development. The majority of the recently developed systems are demonstration and research prototypes [Che-I Yeh et al., 1987].

A computer search at the Queen Elizabeth II Library at Memorial University of Newfoundland revealed four expert systems dealing with flexible pavements, namely, PARADIGM, PRESERVER, ROSE and ERASME and one system dealing with rigid pavements namely, Concrete Pavement Evaluation.

3.1.1 PARADIGM

PARADIGM was developed by Professor Ritchie at the Department of Civil Engineering and Institute of Transportation Studies, University of California, in association with the University of Washington and the Washington State Department of Transportation. PARADIGM (PAvement Rehabilitation Analysis and DesIGn Mentor) is a microcomputer-based program that was developed to integrate several knowledge-based expert systems and algorithmic models to address the following problems:

- Evaluation of pavement surface condition
- Evaluation of the pavement's structural adequacy
- Identification of feasible rehabilitation strategies
- Detailed design of feasible rehabilitation strategies
- Life-cycle costing of alternatives

The knowledge base of PARADIGM contains over one hundred forty rules and consists of four expert systems modules. These are :

- SCEPTRE (Surface Condition Expert for PavemenT REhabilitation)
- OVERDRIVE (OVERlay-Design heuRIstic adVisEr)
- Two similar systems for utilizing project level information generated by either SCEPTRE or OVERDRIVE to perform network optimization

3.1.1.1 SCEPTRE

SCEPTRE, Surface Condition Expert for Pavement Rehabilitation, is the first knowledge-based expert system developed as part of the PARADIGM project. It is an advisory tool for evaluating pavement surface conditions and recommending rehabilitation strategies at the project level. SCEPTRE version 1.4 contains one hundred forty rules in its knowledge base. The knowledge base has been constructed using the combined expertise of two pavement specialists, with extensive experience in pavement rehabilitation in the states of Washington and Texas [Ritchie et al., 1990]. The system has been developed using the Exsys expert system shell. It runs in an IBM PC environment [Ritchie et al., 1986, 1987]. The specific types of surface distress considered by SCEPTRE are:

1 Alligator (fatigue) cracking in wheel paths

2 Rutting

3 Longitudinal cracking in wheel paths

4 Transverse cracking

SCEPTRE considers ten basic rehabilitation strategies as follows:

1 Do nothing

2 Fill cracks

3 Fog seal

4 Friction course

5 Chip seal

6 Double chip seal

7 Thin asphalt concrete overlay(thickness < 0.1 ft)

8 Medium asphalt concrete overlay (0.1 Ft< thickness< 0.25 ft)

9 Thick asphalt concrete overlay(thickness > 0.25 ft)

10 Mill and replace

These distress manifestations are compatible with those used by Washington State Department of Transportation. SCEPTRE uses a rule-based system for representing knowledge expressed as IF condition THEN action statements. The system reaches a conclusion by utilizing a backward chaining inference method.

The selection of feasible rehabilitation strategies is based on six factors, namely:

1 Type of surface distress

2 Amount of surface distress

3 Severity of surface distress

4 Existing pavement performance

5 Traffic levels (800 veh/lane or less, between 800-4000 veh/lane and more than 4000 veh/lane)

6 Climate (marine dominance and high solar radiation).

3.1.1.2 OVERDRIVE

OVERDRIVE (OVERlay Design heuristic adVisEr) is an expert system for the design of flexible asphalt concrete overlays on flexible pavements. The system is applicable to existing pavement structures containing up to three pavement layers, excluding the subgrade. OVERDRIVE is rule-based and uses a forward chaining inference method. The system has been developed using the Exsys expert system software package. The system contains about one hundred eighty rules. The knowledge-base of OVERDRIVE is the result of knowledge engineering efforts with a pavement specialist combined with a synthesis of state-of-the-art reports, papers and manuals mainly, the Asphalt Institute Thickness Design-Asphalt Pavements for Highways [Ritchie and Mahoney, 1989]. OVERDRIVE determines two design parameters, namely the subgrade modulus and the design traffic loading (number of equivalent single axle loads). It allows the user to utilize default parameter values for design purposes when actual values are not available. The full depth design thickness is found by interfacing the knowledge base to an external Pascal program which contains the Asphalt Institute Design Curves [Ritchie, 1987]. An effective thickness analysis requires knowledge of the following pieces of input:

1 Number of existing layers

2 Thickness of each layer

3 Layer material type

4 Layer condition

This input can be obtained from construction or survey records, or by limited sampling and testing of in-place materials. The system presents one of the following three outputs:

1 The existing pavement section is not structurally adequate and an overlay is required to provide greater structural capacity. The thickness of asphalt concrete overlay required is approximately 3 inches.

2 The existing pavement section is structurally adequate and no overlay is required.

3 The severity of rutting is such that reconstruction, or milling and overlay, of the existing pavement section is required. Determination of the required overlay thickness in this case is beyond the scope of this prototype. This conclusion is output only when the rut depth is over 1.5 inches.

3.1.1.3 Network Optimization

This module describes how the project-level results from the rehabilitation model can be used for network-level pavement management. The problem involves selecting the optimal set of rehabilitation strategies for a pavement network. This problem can be formulated as an integer program with binary decision variables. Network optimization is performed by an external programming in C language. The input data includes segment identification, strategy identification, construction cost and net present value. The output of the program is a list of pavement sections and the proposed rehabilitation strategies that would be part of the optimal solution for the project to be constructed in the coming year [Ritchie et al., 1990].

3.2 PRESERVER

PRESERVER is a knowledge based system which recommends the single most cost effective maintenance treatment action for each pavement project. The system uses maintenance treatment actions designed for Ontario road conditions. The system developed using OPS5 representation language on a VAX mainframe. OPS5 is a programming language for producing rule-based systems. OPS5 is a useful development environment because of the flexibility built in the control structure. The default control strategy for OPS5 is forward chaining. If a more complex control strategy, such as backward chaining is desired, it can be implemented by the knowledge engineer. The control is illustrated in Figure 3.1 which directly represents the main flow of operation, and symbolically introduces the control strategy within each main step.

PRESERVER knowledge base is limited to those considered by the Pavement Maintenance Guidelines manual of the Ontario Ministry of Transportation and Communications. This manual was the principal source of knowledge for PRESERVER. Rules have been implemented for three distress conditions:

1 Alligator cracking

2 Progressive edge cracking

3 Distortion (frost related bump)

An example of one of these rules, (expressed in English), is:

IF: there is a distortion distress with moderate severity which is local or general.

THEN: consider using cold mix patching treatment

OR consider using hot mix patching treatment

PRESERVER begins by asking the user for information concerning the section of road and the distress types that have been observed. It then generates a set of feasible treatments for each distress condition. The equivalent annual cost of each treatment is then calculated. The calculations require some input from the user, such as the estimated number of tons of cold mix required, if cold mix patching is considered as an

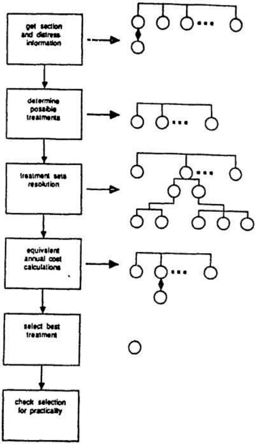


Figure 3.1: Control Structure of PRESERVER [Haas and Shen, 1989]

alternative. The best treatment is selected on the basis of the lowest equivalent annual cost. Running the system has illustrated its ability to handle different combinations of distress conditions and treatments [Haas and Shen, 1989].

3.3 ROSE

ROSE is a knowledge-based computer program intended for recommending routing and sealing (R&S) of asphalt concrete in cold areas. The system recommendation was given as a desirability of routing and sealing on a scale from 0 to 10.

ROSE was designed specifically for Ontario Ministry of Transportation (MTO) and it is not advised to be used in any other jurisdictions [Hajek et al., 1986]. The knowledge was acquired by interviewing one MTO research engineer, and by consulting two other MTO experts. ROSE contains about 360 rules that incorporate 26 numeric variables, including presence of pavement distresses, crack type, pavement serviceability and pavement structure.

ROSE was developed to operate in two different modes as follows:

1 An interactive mode using Exsys, an expert system shell. The system queries the user for required input data and it is designed to process one pavement section at a time.

2 An automatic mode implemented in FORTRAN and designed to interact only with other computer files and programs, which is able to process many sections at the same time.

The interactive and the automatic versions of ROSE use identical knowledge bases, input data and decision logic.

The overall architecture of the two operating modes (the interactive and the automatic) is shown in Figure 3.2.

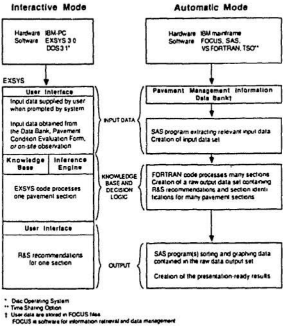


Figure 3.2: Overall Architecture of ROSE [Hajek et al., 1986]

ROSE is an operational prototype. The system has been tested on a number of different pavement maintenance problems. An automatic version of ROSE was successfully applied to about 900 pavement sections representing 7200 km of highway.

3.4 ERASME

In France, an effort was made to use artificial intelligence techniques to facilitate decision making of road maintenance and to make it available to various government agencies. ERASME is an expert system for pavement maintenance developed by Allez, Dauzats, Puggelli and Joubert [Allez et al., 1988]. The prototype included two hundred and ten rules, and fifty decisions. Little published literature was found in English in relation to ERASME; however, the authors indicated in their paper that their system is similar to those developed in North America (SCEPTER, ROSE and PRESERVER) [Allez et al., 1988].

ERASME's objective is to assist the user in selecting pavement maintenance and rehabilitation strategies, given the following parameters:

1 Deflection

2 Pavement structure

3 Nature and date of pavement repairs

4 Surface condition

ERASME performs two different functions: diagnostic and rehabilitative. The first function assists pavement engineers in assessing the pavement condition. The information necessary to establish the diagnosis is gathered from data files or input interactively by the user. The second function seeks successful techniques of rehabilitation, the selection being linked to the initial diagnosis. Several alternatives are generally proposed to the user. Each solution is evaluated in terms of service life, costs and short-term serviceability [Allez et al., 1988]. The knowledge of ERASME was derived from pavement laboratory specialists and pavement management engineers. This collaboration between pavement engineers enhanced the quality of the encoded knowledge. About ten experts were involved in the system development. Some experts have used ERASME's successive prototypes to validate, criticize, and develop the encoded knowledge base [Allez et al., 1988].

3.5 Concrete Pavement Evaluation

The system was developed by Kathleen T. Hall, Michale I. Darter, Samuel H. Carpenter and James M. Connor in the Department of Civil Engineering at the University of Illinois at Urbana-Champaign [Hall et al., 1987]. This demonstration prototype system has been developed to assist state highway engineers in evaluating concrete highway pavements. The system uses information collected by the engineer to determine what mechanisms have caused the distresses present in the pavement, so that the rehabilitation techniques that would be most effective in repairing the distresses and preventing their recurrence can be identified. The system has been developed for use on an IBM-compatible personal computer using the rule-based Insight 2+ expert system shell.

Two knowledgeable and experienced pavement engineers, encompassed all aspects of concrete pavement expertise, were involved in the development of this evaluation procedure. The scope of the system was limited to jointed, reinforced, concrete pavement (JRCP), although adaptation of the procedures for jointed plain and continuously reinforced concrete pavement is also reportedly underway.

The experts identified 12 problem areas that they felt must be considered in an evaluation of a JRCP:

1 Structural capacity

2 Drainage

3 Foundation stability

4 Roughness

5 Concrete durability

6 Skid resistance

7 Transverse joint condition

8 Longitudinal and transverse joint construction

9 Load transfer

10 Slab support

11 Joint sealant reservoir design

12 Shoulder condition

The factors that were identified as important were summarized in a project survey for JRCP. The project survey consisted of two parts: inventory data and monitoring data. These include:

- Climate
- Thickness design
- Layer materials
- Joint design and constriction
- Shoulder design and construction
- Traffic
- Ride quality
- Cracking and corner breaks
- Transverse and longitudinal joint condition
- Settlements and heaves
- Drainage conditions
- Pumping and faulting
- Concrete surface condition
- Joint sealant condition
- Concrete durability

- Previous repair
- Shoulder condition

All of the recommended conclusions state as a minimum whether or not a deficiency is indicated by the data and, if so, what factors were significant in reaching this decision. The following conclusion from the drainage decision tree is an example:
A drainage deficiency is indicated by a wet climate, absence or poor functioning of longitudinal subdrains and a fine-grained soil base.

3.6 Comparison Between the Existing Systems

Comparative analysis of the existing expert systems in maintenance and rehabilitation for flexible and rigid pavements is presented in Table 3.1. Four of the five existing systems were developed for flexible pavements, PRESERVER, SCEPTRE, ERASME and ROSE. Concrete Pavement Evaluation, was developed to evaluate the condition of rigid pavements. Four of the five systems run on microcomputer and use expert system shell for their development. SCEPTRE and ROSE used Exsys, ERASME used a French shell and Concrete Pavement Evaluation used the Insight 2+ shell. PRESERVER runs only on a mainframe using the specially developed expert system programming environment OPS5. PRESERVER is the only system that needs prior experience in OPS5. All the systems but PRESERVER utilize backward chaining to reach a conclusion because there are few conclusions and many conditions. The inference engine in PRESERVER uses forward chaining to reach a conclusion because OPS5 is limited by its default forward chaining control system. All systems considered specific pavement distresses which are considered to be the most damaging in their areas of application. SCEPTRE recommends rehabilitation strategies for alligator cracking, longitudinal cracking, transverse cracking and rutting. PRESERVER recommends the single most effective maintenance treatment for alligator cracking, progressive edge cracking and distortion. ROSE recommendations are given as the desirability of routing and sealing for all cracks

Table 3.1:
Comparison Between Expert Systems

Criteria of the Expert Systems	PRESERVER *For Flexible Pavement*	SCEPTRE *For Flexible Pavement*	ROSE *For Flexible Pavement*	ERASME For Flexible Pavement	Concrete Pavement Evaluation *For Concrete Pavement*
Development Tool	OPS5	EXSYS	EXSYS	French shell	Insight 2+ expert system shell
Hardware	Mainframe	IBM - PC	IBM - PC	IBM - PC	IBM - PC
Number of Rules	Not available	140	360	Not available	Not available
Inference Engine	Forward chaining	Backward chaining	Not available	Not available	Not available
Computer Expertise Required	Requires prior experience with OPS5	No prior programming knowledge is necessary	No prior programming knowledge is necessary	No prior programming knowledge is necessary	No prior programming knowledge is necessary
Pavement Distresses Considered/Problem Areas	Alligator cracking, progressive edge cracking and distortion	*Alligator cracking,* longitudinal cracking, transverse cracking and rutting	*All cracks but* alligator cracking	*Not available*	Structural capacity, *Drainage, Roughness,* Foundation Stability, Concrete durability, Skid resistance, Transverse joint and Shoulder Condition, Slab support, Load transfer, Longitudinal and transverse construction.
Maintenance Strategies	Not available	Ten rehabilitation strategies	One maintenance Routing and Sealing	Diagnostic and rehabilitation	If Rehabilitation is needed and Evaluation conclusion
Numbers of Independent Variables	- Distress type - Section size - Severity and density - Cost	- Type of surface distress - Amount of surface distress - Severity of surface *distress* - Existing pavement performance - Traffic levels - Climate	- Crack type - Pavement serviceability - Pavement structure - Presence of *pavement distress* - Existing of pavement maintenance treatments	- Deflection - Pavement structure - Nature and data of pavement repair - Surface condition	- Inventory data (seven factors) - Monitoring data (eleven factors)
Main Source of Knowledge	Pavement Maintenance Guidelines	Two pavement experts	One research Engineer and two consulting *Engineers from* Ontario Ministry of Transportation	Pavement engineer and pavement management engineers	Two pavement experts
Stage of Development	Field prototype	Field prototype	Field application	Demonstration prototype	Demonstration prototype
Powerful Feature	Select the most single cost effective treatment	Consultations through external program	Automatic Mode	First prototype in France	Concrete Pavement Evaluation

except alligator cracking. Concrete Pavement Evaluation output is limited in whether or not a deficiency is presented in the concrete pavement sections.

SCEPTRE, ROSE, ERASME and Concrete Pavement Evaluation, incorporate experts advice acquired by interviewing experts from the field as source of its knowledge. PRESERVER used pavement maintenance guidelines, developed for Ontario Ministry of Transportation, as the source of its knowledge.

None of the existing systems reached a commercial system level. They are either demonstration prototypes or field prototypes. SCEPTRE, ROSE and PRESERVER are field prototypes because they have been tested on a number of test cases. ERASME and Concrete Pavement Evaluation are a demonstration prototypes because they have not been substantially tested.

3.7 Limitations of the Existing Systems for Flexible Pavement

Each of the existing system was developed to be applied to a particular area under specific climatic conditions and specific distress and maintenance types. None of the existing systems for flexible pavement is applicable to Newfoundland climate or maintenance activities. The following listing provides a summary of the existing systems limitations which include limitations in their data bases and the development environments:

1 The existing systems dealt with particular local conditions which limit their use to those areas. Local conditions include weather, prevailing distress and maintenance type. For example, SCEPTRE was developed for a marine environment and high solar radiation climate to serve State of the Washington. Also, ROSE developers stated that the system was designed specifically for Ontario Ministry of Transportation and direct application of ROSE in other jurisdiction is not advisable [Hajek et al., 1986].

2 None of the existing systems considered Riding Comfort Index (RCI) as a factor affecting the selection of pavement maintenance strategy. RCI significantly affects the decision of selecting appropriate maintenance strategies because it relates to the urgency of a particular maintenance activities [Nair and Hudson, 1986].

3 Most of the existing systems recommend the appropriate maintenance based on a subjective basis. They do not include any cost comparison (total and unit cost of equipment, laborers and materials) for the recommended maintenance strategies. PRESERVER only selects the single most effective maintenance treatment. ROSE calculates the cost for only routing and sealing.

4 There are nine different maintenance strategies that are currently used in Newfoundland. None of the existing systems include these nine maintenance strategies in their data base. For example, SCEPTRE considers ten basic rehabilitation strategies. ROSE recommendations were given as a desirability for routing and sealing.

5 A major problem encountered by the user of the existing systems is his/her inability to identify and classify the type of the existing distresses. Incorporating pictures of "real life" distress with the verbal description would be a definitive asset to the user.

6 There are two basic microcomputers technologies available. IBM and its compatibles and Apple Macintosh. It is estimated that Apple computers has 30% market share [MACWORLD, 1990]. All the existing systems developed either for IBM microcomputers and their compatibles or for mainframes. As a result, 30% of microcomputer users have no access to any system.

It should be noted that the above limitations were observed by reviewing published literature. Other limitations may exist including input/output and accuracy of the data base.

The above mentioned limitations suggest the need to develop a new system more appropriate to Newfoundland conditions.

3.8 Review of Pavement Distress and Maintenance

Existing expert systems for flexible and rigid pavement maintenance were covered in sections 3.1 to 3.7. Another two areas of concern become apparent when one reads through the literature. These two, pavement distress and pavement maintenance strategies, are defined next in more detail.

3.8.1 Distress

Distress is defined as the condition of a pavement structure that reduces serviceability or leads to a reduction in serviceability [Thomas et al., 1978]. Serviceability has been defined by Carey and Irick as "the ability of a pavement to serve the highway user" [Carey and Irick, 1960]. Extensive research has been conducted to identify and classify pavement distresses. At present, the Ontario Ministry of Transportation defines fifteen types of distress and classifies them into three different groups [Chong et al., 1982]:

1 Surface defects

2 Surface deformation

3 Cracking

Each of these groups is further classified into subgroups which will be explained below. A summary of the different distresses is shown in Figure 3.3.

3.8.1.1 Surface defects

Surface defects are caused by a loss of any part of the asphalt concrete layers; these reduce pavement performance substantially and increase the need for maintenance. There are three subgroups of surface defects:

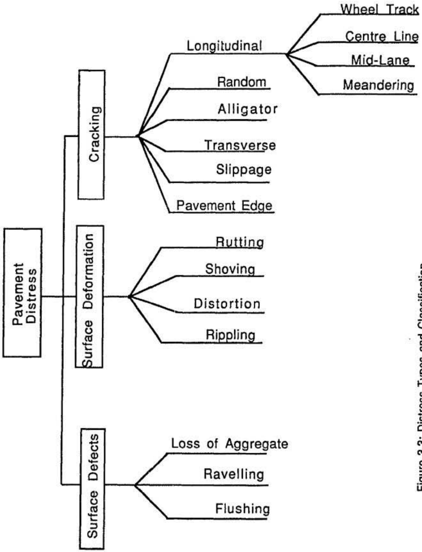


Figure 3.3: Distress Types and Classification

1 Loss of aggregates (Stripping):

This type of distress consists of coarse aggregate loss from the surface, due to lack of bond between the aggregate and the asphalt cement. The loss of aggregate is considered as one of the major asphalt pavement problems in Canada. It typically occurs in areas that are under the combined influence of water and extensive load.

2 Ravelling:

'Ravelling' is described as loss of pavement materials from surface downward. It can occur over the entire surface, but the wheel tracks are generally the worst area [Chong et al., 1982].

3 Flushing:

'Flushing' is the term used to describe asphalt migrating to the pavement surface especially during hot weather. Flushing is caused by faulty mix design, improper construction practices, and in some cases, consistency of the binder used in relation to temperature and traffic condition [Chong et al., 1982].

3.8.1.2 Surface deformation

Surface deformation forms on the longitudinal and transverse directions and is caused mainly by heavy traffic loads [Chong and Phang, 1988]. In the last decade, an extensive amount of pavement research has focused on surface deformation. The research concluded that the formation of rut is a serious form of pavement structural distress which affects both ride quality and safety.

1 Rutting:

'Rutting' is used to describe longitudinal depressions in the wheel tracks caused by repeated load applications. Pavement uplift may occur along the sides of the rut; however, in many instances, ruts are noticeable only after rainfall, when the wheelpaths are filled with water. Permanent deformation in the form of rutting is more significant for highway pavements because of increased amount of heavy axle load and increased tire pressures. It was found that poor mix stability resulting from the use of mostly rounded aggregates and insufficient amount of space between the aggregates known as VMA (Voids in Mineral Aggregate) is one of the main causes of rutting [Tam and Lynch, 1986].

2 Rippling:

'Rippling' describes a regular transverse fluctuation in the surface of the pavement which consists of closely spaced alternative valleys and crests, caused by traffic actions. Rippling develops during periods when there are temperature differentials between the surface and the bottom of the pavement [Chong et al., 1982].

3 Shoving:

'Shoving' describes a condition in which the asphalt surfacing is very uneven because it has been moved away from the wheel tracks by the traffic. It has a pattern similar to a wave in the longitudinal direction [Chong et al., 1989].

3.8.1.3 Cracking

Cracking occurs when stresses or strains due to any combination of material, environmental, and loading characteristics exceed threshold limits. The most serious problems of asphalt pavements today is transverse cracking and alligator cracking.

1 Transverse:

Cracks which follows a course approximately at right angles to the pavement centre line [Chong et al., 1982]. The use of asphalt cement with high temperature susceptibility produces severe transverse cracking. The use of asphalt cement with low temperature susceptibility will reduce the frequency of transverse cracking [Ruth et al., 1987].

2 Alligator:

Cracks which form a network of multisided (polygon) blocks resembling the skin of an alligator, and may occur anywhere on the pavement surface. Alligator cracking is a consequence of the inability of a part of the structure to support the repeated loads. This is usually due to a "softening" of the material. Softening is normally associated with an increase in moisture content. Alligator failures which are deep-seated in the subbase or base, are progressive. They tend to spread rapidly, and traffic causes blocks of surfacing to be displaced and broken up. The only successful remedial treatment is to remove all softened material in the affected area and replace it with granular material. Alligator cracks which are in the upper layers, normally appear in the very early spring. They do not generally progress after warmer weather [Chong et al., 1982].

3 Longitudinal cracks:

Longitudinal cracks follow a course approximately parallel to the direction of travel. They are situated at or near centre of the wheel tracks, centre line, mid-lane, and wander from edge to edge of the pavement as meandering crack. They are caused usually by overloaded vehicles, poor construction processes, and environmental action (freezing and thawing) [Chong et al., 1982].

4 Pavement edge:

These type of cracks are longitudinal, and occur a foot or so from the edge of the pavement. They usually develop when there is a lack of shoulder support. They may also be caused by settlement of the material underlying the cracked area, due to poor drainage, frost heave or shrinkage from drying out of the surrounding earth. Cracks begin parallel to the pavement edge [Sargious, 1987].

5 Random (Mapping):

'Random cracks' are interconnected cracks which form a series of large blocks, run randomly along pavement surface, and appear to be a combination of transverse and longitudinal cracks which form a map [Sargious, 1987]. Random cracks are usually caused by the swelling or shrinkage, frost action and aging of asphaltic concrete [Chong et al., 1982].

6 Slippage:

These are cresent-shaped cracks pointing in the direction of the thrust of wheels on the pavement surface. Usually they are caused by the lack of a good bond between the surface layer and the course beneath [Phang and Chong, 1982].

This thesis focuses on the types of distress that are of primary concern in Newfoundland and that must be cons'dered to improve road facility in the province. The types of distress which fall into that category are rutting, alligator cracking and transverse cracking. These types of distress were chosen after conducting several interviews with pavement maintenance engineers in Department of Works Services and Transportation and reading local studies, for example "The Cause of Rutting in Newfoundland" [McCarthy, 1985].

3.8.2 Pavement Maintenance Strategies

To maintain the pavement within a tolerable level of serviceability, maintenance action is taken to correct deficiencies which are potentially hazardous, and to repair defects which may seriously affect the serviceability of the pavement. Maintenance of most asphalt pavements involves repairing localized problem areas. This type of maintenance is needed to prolong the pavement life and prevent rapid damage caused by water penetration and other factors. The proper maintenance of any highway system depends on the correct selection of a maintenance strategy which is appropriate for the climate and other conditions of the area [Thomas et al., 1978 and Phang and Chong, 1982].

Severity and density are two important factors that should be closely measured. Severity is classed as being slight, moderate or severe; density from few to extensive for each kind of distress.

Determining the best maintenance strategy starts by identifying the type, severity, and density of distress. The decision to use a particular type of maintenance is generally made by one or more provincial, federal, or local transportation officials. These officials can be identified here as the decision makers. The problem they face is to determine what pavement maintenance would yield the most cost-effective result for a defined pavement condition. The decision maker's first task is to identify the various maintenance treatments that are available. The nine preventative and corrective strategies listed below will be considered in this research:

1 Do nothing

2 Crack seal (Seal coating)

3 Rout and seal

4 Pothole patching

5 Cold mix patching

6 Hot mix patching

7 Hot mix recycled patching

8 Surface replacement

9 Reconstruction

Each of these maintenance types is described below:

3.8.2.1 Crack seal (Seal coating)

When cracks occur in asphalt pavements, they must be sealed to prevent water infiltration and loss of load-carrying capacity. A number of materials are available for sealing cracks. These materials include cutback asphalt, emulsified asphalt or rubberized asphalt and joint sealing materials. On occasion, large cracks are sealed with sand-asphalt mixtures. If there are few cracks, it may be routed and sealed or left unsealed. If there are many cracks, it is usually too expensive to rout and seal them. In such cases the entire area may be sealed with a surface treatment, or overlay. Liquid asphalt should not be painted on the surface over the crack. This does not seal the cracks properly, and can cause a skid problem. This excess asphalt may also cause problems when overlaying the existing pavement, and may cause slippage of the overlay when it is rolled [Chong and Phang,1988]. There are two types of seal coating: chip seal and sand seal. They differ primarily in the aggregate coating used in the seal coating operation. Chip sealing consists of coating full-width roadway sections with a hot bituminous material and covering it with different sizes of stone. The cover aggregate in sand seal is sand rather than stone. Using sand seal in sealing cracks in roads in fair or good condition will substantially prolong roads life. Sand seal was effective when applied to a pavement surface with flushed asphalt. The chip seal was better suited to dried-out pavements [Kieran et al., 1986].

3.8.2.2 Rout and seal

The rout and seal treatment is designed to seal asphalt concrete pavement cracks to prevent water from entering and damaging the pavement structure. This is important particularly for pavement in cold areas, which are subjected to the combinations of low temperature and to the removal of snow in the winter with salt. Routing is used to open up cracks to accommodate enough sealant to provide an effective seal, even after the pavement crack opens due to contraction at low temperature during the winter months. Dirt is then blown out with compressed air. The crack is dried with hot compressed air, and sealed with liquid bituminous sealant. Sealing water-proofs the crack by bonding to the pavement surface, and extending without fracture over the opened crack during the critical winter period [Chong and Phang, 1988]. The rout and seal procedure will only be successful if all moisture and dirt are removed from the crack and the adjacent area prior to application of the sealant.

3.8.2.3 Pothole patching

Spot patching with premix is performed to provide the motoring public with safe, smooth riding surface and to prevent rapid and progressive deterioration. Patching with premix is a top priority activity in Newfoundland [Road Maintenance Standard, 1989]. Bituminous premix should be used for spot patching to correct ruts.

3.8.2.4 Cold mix patching

Cold mix patching involves placing and spreading premixed asphaltic material over surface defects, and compact it. Cold mix patching material was considered by all the personnel who were interviewed, to be the poorest type of patching material because of its short service life. The reason for short service life using cold patching is that the conditions under which the cold mix is placed make it difficult for the patch to hold. Cold mix is generally used in winter when no hot mix is available, and consequently is applied during poor weather conditions when the road base is liable to be wet. The combination of water and traffic loads can lead to early patch failure [Kieran et al., 1986] and [Brown, 1988].

3.8.2.5 Hot mix patching

Hot mix patching involves placing and spreading of premixed asphaltic material (hot mix) to surface defects, and compacting it. Hot mix patching consistently has the highest estimate of effective service life [Kieran et al., 1986]. The reason is that the material is usually of superior quality, and therefore is easier to place and compact than other types of patching material. Moreover, hot mix is generally available only during summer season because plant production is limited to that season.

3.8.2.6 Hot mix recycled patching

Hot mix recycle patch is considered to be a good performer. The manual procedure is to place and spread recycled asphalt material and compact it. Recycling involves replacing of the pavement surface to a depth of less than one inch by heater-planer, heater-scarifier, and surface milling devices. This operation may involve the use of new materials, including aggregate, modifiers, and or mixtures. Several recycling techniques can be identified based on the device used, and whether or not additional aggregate is used in the process [Telimoye, 1979].

3.8.2.7 Surface replacement

This method involves removing badly damaged surfaces of paved roadway and replacing them with premixed material. Surface replacement is used to correct heavy alligator cracking. This activity is used to correct failures too large for repair by patching. The use of motor grader for economical spreading and a roller for adequate compaction is limited by the size of the area repaired and the quantity of premix used. Failures caused by frost heaves or poor drainage conditions should be corrected if possible, before surface repairs are carried out.

3.8.2.8 Reconstruction and Do nothing

Reconstruction is an action taken both to regain high initial serviceability, and to improve the operational level of service [Blum and Phang, 1981]. This strategy is used when it is necessitated by the severity and density distress conditions and no other maintenance strategy can be applied. Do nothing is the case where severity and density distress conditions are not of concern .

To compare the effects of each strategy, network level benefits have to be calculated. To do this, one needs to know the expected repair life in years for each strategy. In all cases, it is assumed that drainage and mandatory base repair are performed and that the surface friction requirement and structure capacity are satisfied. No routine maintenance repair will be expected to have a long functional life without satisfying these requirements [Kieran et al., 1986].

3.9 Summary

Little work has been reported in the literature with regard to expert system application in pavement maintenance area. A computer search revealed four systems in flexible pavement and one system in rigid pavement. These are: PARADIGM, PRESERVER, ROSE, ERASME and Concrete Pavement Evaluation. PARADIGM (PAvement Rehabilitation Analysis and DesIGn Mentor) consists of four modules, namely SCEPTRE, OVERDRIVE, and two similar systems for utilizing project level information (Network Optimization). SCEPTRE is an advisory tool for evaluating pavement surface condition and recommending rehabilitation strategies. OVERDRIVE is an expert system for the design of flexible asphalt concrete overlay on flexible pavements. Network Optimization describes how the project-level results from the rehabilitation model can be used for network-level pavement management. PRESERVER is a knowledge based system which recommends the single most cost effective maintenance treatment action. PRESERVER was developed using OPS5 representation language on a VAX. ROSE is a knowledge-based computer program intended for selecting and recommending routing and sealing of cracks. ERASME is a tool for assisting pavement maintenance decision making. Concrete Pavement Evaluation is another expert system developed to assist state highway engineers in evaluating concrete highway pavements.

This chapter also summarized the definitions and classifications of pavement distresses. Pavement distresses are classified into three major categories: Surface defects, Surface deformation, and Cracking.

Literature search revealed nine maintenance strategies that are used in Newfoundland. The proper maintenance of any highway system depends on the correct selection of a maintenance strategy which is appropriate for the climate and other conditions of the area.

Chapter 4

Methodology

The methodology for developing the expert system proposed here is divided into three major stages:

Stage 1:	Knowledge Acquisition
Stage 2:	Prototype Development
Stage 3:	System Development

The following sections describe the work involved in each stage.

4.1 Stage 1: Knowledge Acquisition

The process of knowledge acquisition begins by studying the problem at hand and locating the sources of expertise. The purpose of this task was to gather and organize all relevant and available literature, as well as contact and interview highway officials with expertise in pavement maintenance. This information was used to provide an overview of present industry trends for pavement maintenance strategies. The end product of knowledge acquisition was a comprehensive set of rules, governing the decision-making in the pavement maintenance area. Typical steps in collecting and documenting the knowledge base are described.

4.1.1 Literature Search

An extensive literature search from books, journals and technical reports related to pavement maintenance was conducted to collect the knowledge which is characterized as stable and well documented.

A computer search was made to survey the existing ES literature with regards to pavement maintenance and rehabilitation.

4.1.2 Interviews

Interviews were conducted to extract the knowledge from selected experts. The interviews were conducted with two experts from the Newfoundland Department of Works, Services and Transportation. These interviews were conducted in several meetings to assure completeness. The expert was first asked about the factors affecting pavement maintenance decision-making. The expert was then given a copy of Table 4.1, and was asked to determine the appropriate maintenance strategy, along with the expected repair life. A follow-up interview was conducted and the expert was given a copy of the completed knowledge base which incorporated his judgement (Table 4.1). Additional feed0-back comments were recorded and added. During this meeting, an attempt was made to acquire information from the expert about how he would solve the problem, and what basic solution strategies the expert would utilize. These facts and strategies were the foundation of the knowledge base.

The factors provided in Table 4.1 were the result of the literature review on the factors affecting the selection of pavement maintenance strategies [Hajek et al.1986, Ritchie et al 1987 and Haas and Shen 1989]. Factors such as density and severity of distress and their classifications are based on Ontario Pavement Maintenance Guidelines [Chong et al., 1989]. Riding Comfort Index (RCI) is an important factor in deciding the

Table 4.1: Form Used to Acquire Knowledge on Rutting

Climate is Inland (DD is higher than 600 C * days)
Traffic Volume (AADT) is More Than 2000 Veh/Lane

In the Table given below the expected repair life (in years) for any type of maintenance should be expressed in red, and the priority choices for the type of maintenance should be expressed in blue.

			Maintenance type								
Density	Severity	Riding Comfort Index	Do Nothing	Cold mix patch	Hot mix patch	Surface replacement	Hot mix recycled patch	Pothole patching	Reconstruction		Remarks
Few	Slight	≥ 4									
		< 4									
	Moderate	≥ 4									
		< 4									
	Severe	≥ 4									
		< 4									
Extensive	Slight	≥ 4									
		< 4									
	Moderate	≥ 4									
		< 4									
	Severe	≥ 4									
		< 4									

Slight = Rut depth less than 10 mm
Moderate= Rut depth between 10 mm and 20 mm
Severe= Rut depth more than 20 mm
Few = Less than 30% of pavement surface affected; distress over localized area only.
Extensive = More than 30% of pavement surface affected; distress spotted evenly over entire length of pavement section [Chong et al., 1989].

timing of maintenance because RCI affects vehicle operating costs in addition to comfort [Janoff, 1986]. The quality of ride is classified into five levels in a scale from 0 to 10 (i.e., from 0 to 2 means very poor, from 2 to 4 means poor, from 4 to 6 means fair, from 6 to 8 means good and from 8 to 10 means very good) [Janoff, 1986., Nair and Hudson, 1986]. In this study RCI equal to 4 will be considered as the lowest acceptable riding quality (Fair riding quality). This is compatible with AASHTO practice which suggests terminal serviceability, in terms of RCI, between 4 and 5 [AASHTO, 1986].

4.2 Stage 2: Prototype Development

The purpose of this stage was to develop a "working prototype," that is a small demonstration program that could manage part of the problem. This prototype system is a complete expert system but on a smaller scale (i.e., smaller number of rules, usually 20 to 30). This type of program is used to test ideas about problem definition, structure and representation. In the following sections, the tasks involved in developing and building a working prototype expert system are explained.

4.2.1 Select the Development Environment

Three development environment alternatives are currently available for expert system development, namely programming languages, representation languages and expert system shells. The most popular software is the expert system shell or simply "shell." Particular knowledge has to be added to the knowledge base of the shell to formulate an expert system. The objective of this task was to select the proper expert system shell. Most shells are built for use on personal computers. The shell user is not directly involved in developing the control strategy, or the explanation facility because the shell contains a working inference engine.

Two expert system shells were selected, Exsys Professional and Instant Expert Plus [Exsys, 1988 and Human Intellect System, 1988]. There were three major reasons in selecting these shells. The first reason is the flexibility of the systems in terms of modifying and expanding the knowledge base. Flexibility is measured by the ease of adjusting the system for the purpose of increasing the size of the knowledge base, or deleting facts or rules from the knowledge base. The second reason is the "user friendliness" of the systems, because the users of the systems may have little or no experience in programming languages. The third reason is the ability of Instant Expert Plus to associate facts and expressions with figures and pictures.

Exsys is a powerful shell capable of handling up to 3000 rules. Figure 4.1 shows the basic structure of Exsys Professional and its relationship to the domain expert, knowledge engineer and end user. The cycle begins with the interaction between the domain expert and the knowledge engineer. Knowledge was extracted and used to build the knowledge base. The control mechanism of the inference engine uses the input data and searches through the knowledge base to reach a conclusion. The user either accepts the conclusion or rejects it. The cycle ends by accepting the conclusion. In case of rejecting the conclusion, the user must contact with the knowledge engineer to correct the shortcoming fact in the knowledge base to give acceptable conclusions.

Instant Expert Plus, developed by Human Intellect Systems Inc. for Apple Macintosh computers, was another expert system shell chosen for the development of PMAS. Instant Expert Plus was chosen mainly for its ability to associate facts and knowledge with figures. Figure 4.2 shows the structure of Instant Expert Plus and its relationship to the editor, the user inference, the knowledge base and the explanation module. The inference engine works with the rules stored in the knowledge base, to create the reasoning process.

The next section will give a detailed description of the differences between Exsys and Instant Expert Plus.

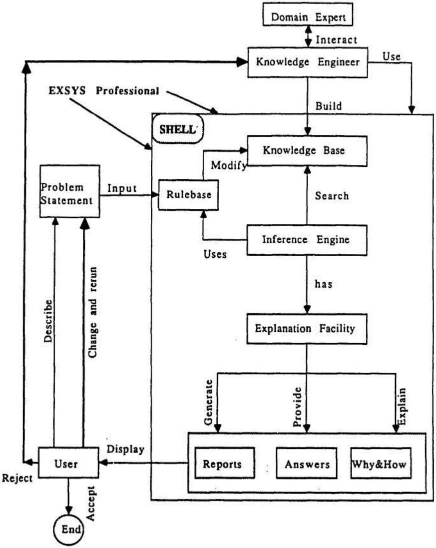


Figure 4.1: Basic Structure of EXSYS Professional [Hanna, 1989]

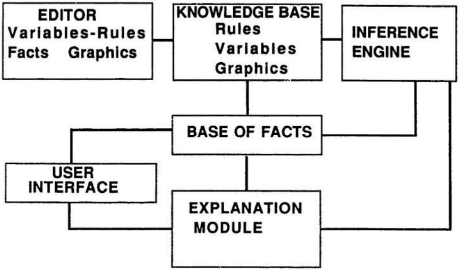


Figure 4.2: The Structure of Instant- Expert Plus [Human Intellect Systems, 1988]

4.2.1.2 Comparison between Exsys and Instant Expert Plus

Table 4.2 demonstrates the differences between Exsys Professional and Instant Expert Plus. The main difference between Exsys and Instant Expert Plus is the graphics capability provided by Instant Expert Plus. This unique feature provides a dynamic interface, particularly for problems that are picture-oriented such as figures, pictures and drawings. This feature is very important for the user because it allows the system to introduce the distress type, severity and extent in a picture form. The control structure in Instant Expert Plus allows three alternative strategies; backward, forward and mixed mode. The control structure in Exsys has only two strategies; backward and forward. The explanation facility in Exsys is more powerful than in Instant Expert Plus, because the user can get a response to 'How' and 'Why' questions. The user can ask 'How' the system arrived of a particular conclusion and the system responds by displaying the chain of the tired rules. The user can also ask 'Why' the system demands the question and the system responds by displaying all the fired rules. Instant Expert Plus can only respond to 'Why' questions. Exsys and Instant Expert Plus have the same capability of interfacing with external programs. Rules input and modification is more powerful in Exsys. Exsys allows 127 conditions in IF part and 54 conclusions in THEN part of any rule. Instant Expert Plus allows only 5 conditions in IF part and 3 conclusions in THEN part of any rule. However, in Instant Expert Plus, there is a special process that combines two rules as one, for the purpose of increasing the number of conditions or conclusions. In Exsys, any change in the IF or THEN parts of the rule will be automatically changed in all the rules that share the same condition or conclusion. In Instant Expert Plus, rules modifications have to be done in every rule. The price of Exsys package is higher than Instant Expert Plus.

Table 4.2:
Comparison Between Exsys Professional and Instant Expert Plus

Criteria	Exsys Professional	Instant Expert Plus
Environment	PC- DOS IBM	Macintosh
Control Strategy	Backward& Forward Chaining	Backward& Forward and Mixed Mode
Explanation Facility	Respond to HOW by displaying the chain of fired rules Respond to WHY by displaying the rules attempt to fire	Respond to WHY by displaying the rules attempt to fire
External Programs	YES	YES with other Mac graphics
Ease of Rules Input	YES	NO
Confidence	Three modes - Yes/ No - 0 to 10 - -100 to 100 Confidence appears in conclusions only	One mode includes - Yes, No, UNKNOWN and 0-10 Confidence appears in questions and conclusions
Graphics	No graphic capabilities	Good graphic capabilities
Ease of Modification	YES	NO
Input Mode	Qualifiers and rules	Rules and graphics
Conclusions (output)	Maintenance Strategies	Maintenance Strategies
Cost	$ 1100 $ 650 (educational price)	$ 600 $ 250 (educational price)

4.2.2 Construct the Knowledge Base

Knowledge base construction is the process of providing the system with knowledge collected from the human experts and the literature. The objective of this task is to encode the knowledge gained from Stage 1 into the computer knowledge base. The result is an appropriately structured knowledge base consisting of selected rules.

The process of constructing the knowledge base involves three basic steps, namely, developing the search tree, constructing the tabular knowledge base and extracting the rules from the tabular knowledge base. Each step is explained in detail next.

4.2.2.1 Develop the Search Tree

This step started with the creation of a list of factors which affect the selection of pavement maintenance strategy. The next step was to incorporate these factors into a decision tree. A decision tree is a grouping of factors and levels that are related to each other and follow a certain path. Each level is further divided into lower levels till the full extent of the tree is reached.

Figure 4.3 shows the factors affecting the selection of pavement maintenance strategies which were explained in section 4.1.2. These factors are surface condition, Riding Comfort Index, traffic volume and climate. These factors were divided into levels. For example surface condition is divided into two levels related to its attributes namely, severity and density. Severity is further divided into three levels which also related to its attributes namely, slight, moderate and severe. Density is divided into few and extensive.

As mentioned earlier, RCI is divided into less than 4 and more than or equal 4. Traffic volume is measured by the Average Annual Daily Traffic (AADT). Traffic volume is classified into low and high. Low traffic is less than, or equal to 2000 vehicles per lane. High traffic is reached when AADT is more than 2000 vehicle per lane. Climate is

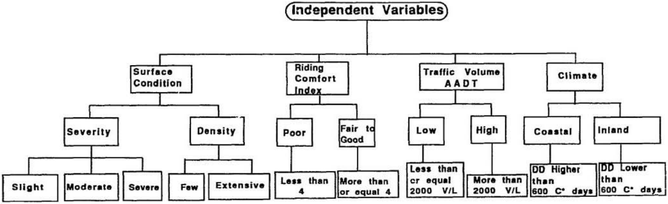


Figure 4.3: Independent Variables Affecting the Maintenance Strategies

classified in coastal and inland which reflect Newfoundland climatic condition.

The structure of the tree for the Pavement Maintenance Advisory System (PMAS) is shown in Figures 4.4, 4.5, 4.6 and 4.7. Figure 4.4 shows the general decision tree for PMAS. The top level shows whether the maintenance is required for a single distress or for a combination of distresses. The second level illustrates whether the repair is advised, or not, based on the evaluation of surface condition for single or combined distress. The lowest level of the tree indicates the urgent maintenance (i.e.,needed this season versus needed next season). Figure 4.5 illustrates the effect of severity and density for a single distress on the repair decision. For example, the outermost left branch of the tree means that, if the severity of rutting is "severe" and the density is "few", then the repair is advised. Figure 4.6 is similar to Figure 4.5 but for combined distresses. Figure 4.7 shows whether a particular repair is required in the current season or it can be postponed. For example, the left outermost branch of Figure 4.7 illustrates that the repair is needed this season if the Riding Comfort Index is less than 4, and if the Annual Average Daily Traffic (AADT) is more than 2000 vehicle/lane. The reason behind that is the road with uncomfortable riding and high traffic volume should get immediate repair to minimize increased vehicle operating costs. This applies to both single and combined distresses.

4.2.2.2 Construct the Tabular Knowledge Base

A tabular knowledge base was created by arranging the types of distresses which were broken down into levels of density and severity in vertical columns, and the maintenance strategies in rows (Table 4.3). Cells under maintenance strategies are to be filled with two values, the order of preference among different pavement maintenance strategies, and the expected repair life in years. The order of pavement maintenance selection is represented by a small number in the upper right corner. The expected

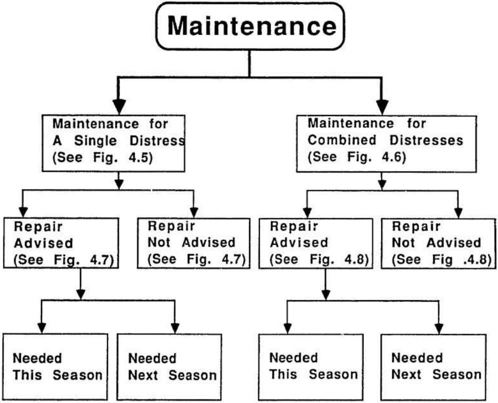


Figure 4.4: General Decision Tree of the Pavement Maintenance Advisory System

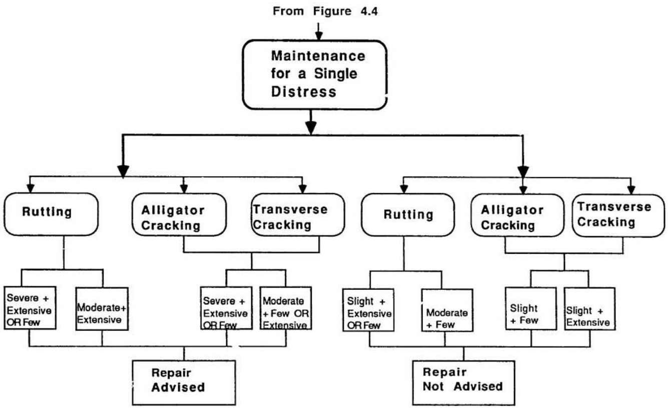


Figure 4.5: Detailed Distress Types, Density and Severity for a Single Distress

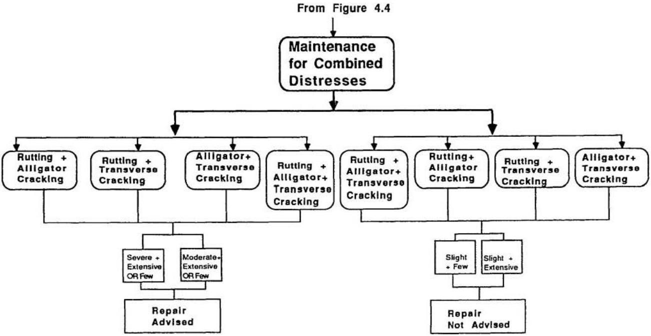


Figure 4.6: Detailed Distress Types, Density and Severity for combined Distresses

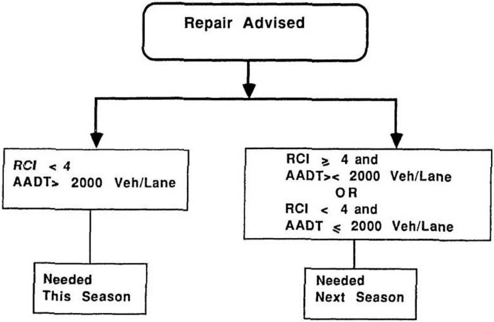


Figure 4.7: Detailed Structure Tree for the Repair Advised for a Single Distress or Combined Distresses

Table 4.3:
Example of the Acquired Knowledge on Rutting

Climate is Inland (DD is higher than 600 C ° days)
Traffic Volume (AADT) is More Than 2000 Veh/Lane

Cells under maintenance type are to be filled with two values, the order of selection among different pavement maintenance strategies and the expected repair life in years. The order of pavement maintenance selection should be represented by a small number in the upper right corner.
The expected repair life for that type of maintenance should be represented by a big number in the middle of the cell.
The capital letter X indicates "Do Nothing."

Density	Severity	Riding Comfort Index	Do Nothing	Maintenance type: Cold mix patch	Hot mix patch	Surface replacement	Hot mix recycled patch	Pothole patching	Reconstruction		Remarks
Few	Slight	≥ 4	X								
		< 4	X								
	Moderate	≥ 4	X								
		< 4	X								
	Severe	≥ 4					3^{1}	3^{2}			
		< 4			3^{1}		2^{2}	2^{2}			
Extensive	Slight	≥ 4	X								
		< 4	X								
	Moderate	≥ 4					3^{1}	1^{2}			
		< 4		2^{1}			1^{2}				
	Severe	≥ 4			4^{2}	3^{3}	5^{1}				
		< 4			3^{1}		3^{2}				

Slight = Rut depth less than 10 mm
Moderate= Rut depth between 10 mm and 20 mm
Severe= Rut depth more than 20 mm
Few = Less than 30% of pavement surface affected; distress over localized area only.
Extensive = More than 30% of pavement surface affected; distress spotted evenly over entire length of pavement section [Chong et al.,1989].

repair life for that type of maintenance is shown in bold numbers in the middle of the cell. The capital letter X indicates "Do Nothing".

The tabular knowledge representation format is an efficient way of facilitating the task of knowledge acquisition. Its advantages are:

1 It is easy for the expert to add or delete information from the knowledge base.

2 Any vacant cells can be easily identified and as a result a complete knowledge base can be achieved.

3 Rules can be easily extracted directly from the table.

The main shortcoming of the tabular knowledge base is that experts are limited to the already defined variables on the table, and may not add or change any of the variables. This, however, is not a serious limitation because extensive communication with the experts before the design of the table, assisted in defining the variables which are important in the decision making and establishing their interaction.

4.2.2.3 Elicit Rules from the Tabular Knowledge Base

Rules can be easily extracted from Table 4.3. The IF part was taken directly from the vertical cells. The THEN part was taken from the horizontal cells associated with the appropriate ranking and the expected life. Rules were then loaded directly into Exsys and Instant Expert Plus in the form of IF-THEN rules.

4.3 Stage 3: System Development

In this stage, the prototype is subjected to a series of sequential increases in the number of rules to cover the full size of the system and to enhance the knowledge base. The following iteration steps were used to achieve a well structured complete system.

1 Add more rules into the knowledge base

2 Test and evaluate the system

3 Analyze any problems which appear

4 Restructure and refine the prototype design

5 Go to step 1 until all rules have been added.

This section will be described in detail in the next chapter.

4.4 Summary

The methodology for expert system development is divided into three major stages, namely knowledge acquisition, prototype development and system development. The knowledge acquisition stage describes the process of acquiring pavement maintenance knowledge through literature search and interviews with experts. The second stage involves the development of a prototype system which has the full features of the completely developed system but on a smaller scale. The third stage involves the increase of the size of the prototype system until it reaches the full scope of the complete system. Chapter five will present the actual development of a complete system in detail.

Chapter 5

Developing the Expert System

This chapter describes the process of developing the Pavement Maintenance Advisory System (PMAS). This chapter first describes the knowledge acquisition process through interviews with pavement experts. Subsequently, it explains how the acquired knowledge is transformed into rules compatible with the selected shells.

5.1 Source of Knowledge for Maintenance Selection

Three sources of knowledge are used for developing PMAS, namely formal documents, documented case studies and expert interviews, all of which are discussed.

5.1.1 Formal Documents

Two basic documents were used to establish comprehensive guidelines for pavement maintenance strategies. These are:

1 Pavement Maintenance Guidelines (Ministry of Transportation, Ontario, 1989).

2 Manual for Condition Rating of Flexible Pavements: Distress Manifestations (Ministry of Transportation, Ontario, Chong et al., 1982).

These documents were chosen because they provided guidelines on how to identify pavement distresses, their possible causes and how to evaluate severity and density. These documents also recommended the appropriate maintenance treatments for each type of distress. For example, Figure 5.1 shows how the Pavement Maintenance Guidelines Manual describes the severity and density of wheel track rutting.

5.1.2 Documented Case Studies

Another source of information was found in technical Journals. Three technical Journals were found relevant to this research: Transportation Research Board Records, Asphalt Paving Technology Proceedings and Canadian Technical Asphalt Association Proceedings. They describe successful case studies of certain maintenance strategies. Several rules were obtained by reviewing these journal articles. Some of these rules were explicit, while others could be inferred from the documents description. For example, an article entitled "Improved Preventive Maintenance: Sealing Cracks in Flexible Pavement in Cold Regions" described the successful use of rout and seal in Ontario [Chong and Phang, 1988]. The paper stated explicitly that rout and seal is used as maintenance for transverse cracks. Part of Rule # 61 was extracted from this paper. It stated:

IF:	(1) The type of distress observed is a single distress
and	(2) The type of distress is transverse crack
and	(3) The severity of transverse crack is severe
and	(4) The density of the distress is extensive
and	(5) The climate is inland
THEN:	Rout and Seal

The first two conditions in the IF part were found in the first six lines in the article's abstract. Conditions (3) and (4) were found in two pictures which accompanied the article. Condition (5) was deduced from the description of the case.

Surface Defects

Wheel Track Rutting

Description: Longitudinal depression left in the wheel tracks after repeated load application. It results from compaction under load combined with a shoving sideways of pavement material. Wheel track rutting can appear as single rut or double ruts.

Possible Causes:

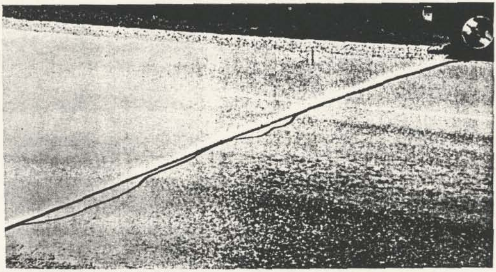
1. Poor construction technique and poor quality control.
2. Poor materials and/or material design.
3. Traffic action.

Severity:

Class	Guidelines (Based on appearance and rut depth measured with a standard 1.2 m gauge width)
Slight	Less than 10 mm.
Moderate	Up to 20 mm.
Severe	Greater than 20 mm.

Density:

Local:	Less than 30% of pavement surface affected; distress spotted over localized areas only.
General:	More than 30% of pavement surface affected; distress spotted evenly over entire length of pavement section.



Severe Double Wheel Track Rutting

Figure 5.1: Pavement Maintenance Guidelines [Chong et al., 1989]

5.1.3 Expert Interaction

A third way in which the available knowledge compiled, was by means of interviewing experts. The rules obtained from experts contained personal knowledge that they had acquired through their experience with particular problems. These subjective opinions incorporate knowledge such as how to handle incomplete or inconsistent data, or how to select the best solution among several possible alternatives, under a particular set of conditions. The degree of success achieved by the system depends on the ability of the experts, whose knowledge is encoded in the knowledge base .

Two experts (Mr. Foster and Sellars) who routinely handle maintenance decision in the Newfoundland and Labrador Department of Works, Services and Transportations, were selected.

5.1.3.1 Interview with an Expert

The interview started by explaining the objectives and the scope of this research. The scope of the interview was limited to three types of pavement distresses, alligator cracking, transverse cracking, rutting and all their possible combinations. Thirteen maintenance alternatives were considered: do nothing, crack seal (sand seal), crack seal (chip seal), rout and seal, cold planning, heater planning, cold mix patching, hot mix patching, hot mix recycled patching, mulch pavement, spray patch, surface replacement, and reconstruction. During the first interview with Mr. Sellars, he described the different types of maintenance used in Newfoundland. He also agreed that the main distress problems faced in Newfoundland are transverse cracking, alligator cracking and rutting. A list of all the maintenance strategies used in this research was shown to him. After reviewing this list, Mr. Sellars stated that four maintenance types are not commonly used in Newfoundland. These four, cold planning, heater planing, mulch pavement and spray patching, were then dropped from the list.

During the second interview, Mr. Foster explained the sources of pavement distresses in Newfoundland and the different maintenance strategies. He provided a copy of the Maintenance Manual used by pavement engineers in the province [Road Maintenance Standard, 1989].

A copy of Table 4.1 combined distresses (Transverse cracking and Rutting) was given to Mr. Foster and he was then asked to table his opinion related to the ranking of maintenance selection.

The following question (Q) and answer (A) sessions show some of the important responses from both experts.

Q: What types of distresses are most prevalent in Newfoundland?

A: Rutting, transverse cracking and alligator cracking.

Q: Does your department use any recycling method?

A: Yes, in the operations department we use hot mix recycled patch very often.

Q: Do you agree that these thirteen types of pavement maintenance are the ones used in Newfoundland (do nothing, crack seal (sand seal), crack seal (chip seal), rout and seal, cold planning, heater planning, cold mix patching, hot mix patching, hot mix recycled patching, mulch pavement, spray patch, surface replacement, and reconstruction)?

A: I agree with most of the list. However, we do not use mulch pavement, spray patch, cold planning and heater planning.

Q: Can you estimate the life expectancy for each of the remaining maintenance types?

A: Hot mix patching is estimated to last for two years, cold mix patching one year, crack seal and rout and seal, five years.

Q: Can you elaborate more on weather conditions?

A: Some of these maintenance strategies are more efficient in coastal weather conditions and others are more efficient in inland weather conditions. For example, crack seal is not efficient in inland weather condition and will lose at least one year from its expected life. On the other hand, some maintenance strategies may not be affected by inland or coastal weather conditions such as hot and cold mix patch.

Q: What are the factors affecting your decision to repair roads?

A: Surface condition, traffic volume, climate and Riding Comfort Index.

Q: Are any particular maintenance activities limited to specific season?

A: Yes; for example cold mix patch is limited to winter time only because of the weather factor.

The above mentioned sources of knowledge provided all of the rules contained in the knowledge base. Table 5.1 presents a summary of the rules and their sources.

5.2 Creating Goals and Subgoals

The end goals of an expert system are the final conclusions which the system reaches. Subgoals are intermediate goals that facilitate the definition of the problem, and reduce the number of rules to be utilized. For example, two main subgoals were created in Exsys and Instant Expert Plus to determine if particular distresses need repair or not. These are: "The Maintenance repair of the Distress is Advised" and "The

Table 5.1:
The Source of Knowledge

Rules #	Source of Knowledge
From 1 to 4, 27, 38	Pavement Maintenance Guidelines" Distresses, Maintenance Alternatives and Performance Standards" (1989, pp. 51).
From 5 to 9, 39, 43, 47, 48 50, 52	Pavement Maintenance Guidelines" Distresses, Maintenance Alternatives and Performance Standards" (1989, pp. 22).
From 10 to 15, 55, 57, 59 61, 63, 65	Pavement Maintenance Guidelines" Distresses, Maintenance Alternatives and Performance Standards" (1989, pp. 18).
From 16 to 21, 23, 24, 26	Pavement Maintenance Guidelines" Distresses, Maintenance Alternatives and Performance Standards" (1989, pp. 19).
22, 25, 28, 30, 32, 33, 34, 36, 42, 44, 46, 58, 67, 68,	Private Communication, Mr. Sellars (Department of Works Services and Transportation, Government of Newfoundland and Labrador)
From 70-106	Private Communication, Mr. Sellars and Mr Foster(Department of Works Services and Transportation, Government of Newfoundland and Labrador)
29, 31, 45, 53	Road Maintenance Standard, Department of Transportation, Province of Newfoundland (1989, pp. 1-3)
From 107-170	Private Communication, Mr. Foster (Department of Works Services and Transportation, Government of Newfoundland and Labrador)
35, 40, 41, 49, 51, 54, 56 60, 62, 64, 66, 69, 70	Pavement Maintenance Guidelines" Distresses, Maintenance Alternatives and Performance Standards" (1989). Private Communications, Mr. Sellars and Mr Foster(Department of Works Services and Transportation, Government of Newfoundland and Labrador)
37	Pavement Maintenance Guidelines" Distresses, Maintenance Alternatives and Performance Standards" (1989). Road Maintenance Standard, Department of Transportation, Province of Newfoundland (1989, pp. 1-3)

Maintenance repair of the Distress is Not Advised". Two secondary subgoals were triggered to determine the urgency to do the maintenance. These are: " Repair is Needed This Season" and " Repair is Needed Next Season." The first subgoal (Repair is Needed This Season) is created when RCI is less than 4 (i.e., the road is in such bad condition that the comfort of travellers is affected). While the subgoal "Repair is Needed Next Season" is used when RCI is equal or more than 4 (i.e., the road is in tolerable condition). It should be noted that subgoals will not appear during a computer run. For example, Rule # 2 shows the conclusion as subgoal.

IF : The type of distress observed is single distress

and The type of distress observed is rutting

and The density of the distress is few OR extensive

and The severity of the rutting is severe

THEN : The Maintenance of the rutting is Advised

5.3 Extracting Rules from the Tabular Knowledge Base

Figure 5.2 shows how the rules were extracted from the tabular knowledge base that was shown in Table 4.3. For example, the IF part of the rule is taken from those cells highlighted by dotted lines on the left part of the table, the THEN part of the rule is taken from those cells located under the maintenance type. The big number indicates the expected repair life in years. The small number in the upper right corner indicates the priority of selection. Rule number 37, for example, is directly extracted from Figure 5.2.

Confidence factors are used to rank preference of selection among different maintenance strategies. Exsys Professional utilizes three modes of goal selection. The first is a Yes/No mode which merely assigns a value of yes or no to a choice. The second mode assigns a value between 0 and 10 to a choice. A value of 0 designates absolutely no,

Rutting

Density	Severity	Riding Comfort Index	Maintenance type: Do Nothing	Cold mix patch	Hot mix patch	Surface replacement	Hot mix recycled patch	Pothole patching	Reconstruction		Remarks
Few	Slight	≥ 4	X								
		< 4	X								
	Moderate	≥ 4	X								
		< 4	X								
	Severe	≥ 4					3 [1]	3 [2]			
		< 4									

IF: The type of distress observed is rutting
AND: The density is few
AND : The severity of rutting is severe
AND : Riding comfort index is equal or more than 4

THEN Hot mix recycled patch (the expected repair life is 3 years)

OR Pothole patching (the expected repair life is 3 years)

Figure 5.2: Example of How Rules are Extracted from the Tabular Knowledge Base

while a value of 10 designates absolutely yes. Values from 1 to 9 allow degrees of certainty to be expressed. The third mode assigns a value between -100 and + 100 [Exsys, 1988]. PMAS in Instant Expert Plus utilizes only the 0 to 10 mode. PMAS utilizes the 0 to 10 in both Exsys and Expert Instant Plus.

Confidence factors assigned to PMAS are directly extracted from Table 4.2. If the expert chooses a particular maintenance type as his first choice, the choice will be assigned a confidence value of 9. The reason of assigning 9 instead of 10 is because of the limitation of the selected shells. If a value of 10 is assigned to a particular maintenance type, the final conclusion will be locked to one choice and obscure any other maintenance types. Experts second and third selections were assigned confidence of 7 and 5 respectively. It should be noted that assigning values of 7 and 5 were based on the expert's suggestions when he was asked to give a rating on scale from 0 to 10.

5.4 Loading the Rules

Rules extracted from the tabular knowledge base should then modified to be compatible with the selected shells. Sections 5.4.1 and 5.4.2 explain how the acquired knowledge should be entered into Exsys Professional and Instant Expert Plus, respectively.

5.4.1 Loading Rules In Exsys Professional

Rules are loaded into Exsys Professional by creating a series of qualifiers and selecting the components of the qualifiers to build the rules. Qualifiers are text expressions with a specified list of options (components). The component of each qualifier should cover all possible alternatives within the scope of the knowledge base. For example, rule # 20 utilizes the first option from qualifiers # 14, 1, 6 and 4 shown below. The THEN part of the rule is taken from the first option from qualifier # 13.

IF : The type of distress observed is single distress and The maintenance of rutting is advised

and Riding comfort index is less than 4

and The traffic volume (AADT) is less than or equal 2000 veh/lane

THEN : The repair is needed this season

Qualifier # 14

The type of distress observed is

1) single distress

2) combined distresses

Qualifier # 1

The maintenance of rutting is

1) advised

2) not advised

Qualifier # 6

Riding comfort index is

1) less than 4

2) more than or equal 4

Qualifier # 4

The traffic volume (AADT)

1) less than or equal 2000 veh/lane

2) more than 2000 veh/lane

Qualifier # 13

The repair is

1) needed this season

2) needed next season

As mentioned earlier, rules loaded into Exsys are taken directly from the tabular knowledge base. The rules are somewhat modularized due to the separation of subgoals. It should be noted that a pure production system requires no rule ordering; however, following an organized rule pattern for input facilitates revision to the system. Also, there is no particular order in which the system asks questions.

Exsys Professional allows 127 conditions and 54 conclusions in each rule. Each condition or conclusion is entered as a string of statement in the IF or THEN field. The THEN field consists of subgoals or conclusions. Conclusions are the final choices (maintenance strategy) or recommendations related to expected repair life in years. For example, Rule #40 shows a conclusion consists of final choice (hot mix patching) and its associated text expression (the expected repair life is four years).

IF : The distress observed is single distress

and The maintenance of alligator cracking is advised

and The repair is needed this season

and The severity of alligator cracking is moderate

and The density of distress is few

and The climate is coastal

THEN : Hot mix patching

and The expected repair life is four years

5.4.2 Loading Rules and Pictures In Instant Expert Plus

Instant Expert Plus allows five conditions in every rule. Each condition is entered as a single phrase or short sentence on a single line in the IF field. The THEN field consists of three lines, where three separate conclusions can be entered. Where there are more than five conditions needed to reach a conclusion, Instant Expert allows the linking of rules by creating subgoals. Subgoals are used in subsequent IF conditions, in rules to inform the system that such questions should not be asked, but rather deduced from the user responses. Figure 5.3 shows a typical input screen in Instant Expert Plus. At the end of each "IF" statement field there is box labeled "A". If the box is marked with X, then the user will be asked the question indicated on that line. Similarly, at the end of each "THEN" statement there is box labelled "D". If the box is marked with X, then Instant Expert Plus will display the statement to the user during a computer run.

Instant Expert Plus has a unique feature to associate facts with pictures. This feature provides a dynamic interface by allowing the system to:

1 Ask questions by showing pictures instead of using words

2 Capture information that could not be communicated well with words

3 Provide an interesting user interface by allowing the user choosing from pictures to answer questions

To load the distress pictures into Instant Expert Plus, three steps were followed. The first step, was to scan the picture in a scanner and save it in PICT file. The PICT file is a graphical file format used by Macintosh to store images. Any screen saved in PICT format can be displayed by Instant Expert Plus. The second step, was to link each picture with its associated facts by selecting "Create a Graphics/Facts Links" from the Graphics Menu, and link each graphic with its related facts. The third step, was to call the file which has the distress picture and provide some descriptive information related to each picture. The picture is displayed with text expressions that describes its contents. For example, severe rutting picture, contains a description of rutting and its severity (e.g. rutting describes as longitudinal depressions in the wheel tracks caused by

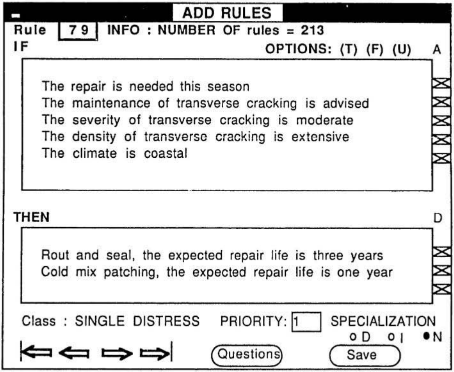


Figure 5.3: Input Screen in Instant Expert Plus

repeated load applications and severe rutting appears when the depth of depression is more than 20 mm).

5.5 Cost Estimate and Comparison

As mentioned earlier, the cost/benefit analysis of pavement maintenance strategy is not considered as part of the decision making in PMAS. However, in an effort to assist the user in selecting the best economic pavement maintenance, PMAS provides a cost comparison for the selected maintenance strategies.

One of the key components of routine maintenance is the identification and estimation of the type and cost of maintenance activities to be performed in the field. There are a variety of maintenance strategies that a highway agency can select. However, there are a large number of candidate maintenance strategies competing for the limited available budget. Consequently, to optimize its available funding, an agency must determine the lowest cost and highest expected repair life for candidate strategies. Cost estimating is an important factor in determining the most appropriate maintenance strategy.

The two most common types of cost estimates are: lump sum and unit cost [Barrie and Paulson, 1984]. Pavement maintenance cost lends itself to unit cost estimate due to the difficulty of quantifying the volume of work required by the system. Using unit cost information yields another measure for comparison between different maintenance strategies. The following paragraphs show an example of how to calculate the unit cost for pothole patching. The cost information used in this example was obtained from Equipment Rental Rate Schedule Report, Road Maintenance Standard and personal communication from Newfoundland Department of Works, Services and Transportation [Equipment Rental Rate Schedule, 1990 and Road Maintenance Standard, 1989].

i Equipment Cost

A fleet consisting of dump truck, hand tamper, hand roller and pavement cutter is needed to produce 4.5 tones of premix per day for pothole patching activity.

1 Dump Truck	@	\$ 25.17/hr x 8 hr/day	= \$ 201.36/day
1 Hand Tamper	@	\$ 23.00/hr x 8 hr/day	= \$ 184.00/day
1 Hand Roller	@	\$ 13.60/hr x 8 hr/day	= \$ 108.80/day
1 Pavement Cutter	@	\$ 6.68/hr x 8 hr/day	= \$ 53.44/day
Total Equipment Cost Per day			= \$ 547.6/day

2 Labor Cost

A crew consisting of one equipment operator II, one Laborer I and one laborer II is needed to produce 4.5 tones of premix per day for pothole patching activity.

1 Equipment Operator II	@	\$ 10.95/hr x 8 hr/day	= \$ 87.60/day
1 Laborer I	@	\$ 10.35/hr x 8 hr/day	= \$ 82.80/day
2 Laborer II (Flag person)	@	\$ 10.49/ hr x 2 x 8 hr/day	= \$ 167.84/day
Total Labor Cost Per Day			= \$ 338.24/day

3 Material Cost

Hot or Cold Bituminous

Premix	@	\$ 70/ton x 4.5 ton	= \$ 315.00/day
Tack Coat	@	\$ 0.6/liter x 30 liters	= \$ 18.00/day
Total Material Cost Per Day			= \$ 333.00/day

The Total Cost of Equipment, labors and Materials = \$ 547.6/day + \$ 338.24/day +333.00/day = \$ 1218.84/day

Unit Cost = Total Cost / Daily Production = \$1218.84/4.5 = \$ 270.9

A similar procedure was followed to calculate the unit cost for other maintenance types. Table 5.2 gives the cost information for all routine maintenance activities

Table 5.2:
The Cost of Equipment, Laborers and Materials

Maintenance Type	Equipment Cost		Laborers Cost		Material Cost		Total Cost	Daily Production	Unit Cost
	Type	Cost/day	Crew Size	Cost/day	Type	Cost			
Pothole Patching	1 Dump Truck 1 Hand Tamper 1 Hand Roller 1 Pavement Cutter	$ 547.6/day	1 Labourer I[a] 1 Labourer II[b] (flag person) 1 Equipment operator II[c]	$338.24/day	Hot or Cold Bituminous Premix + Tack Coat	$333/day for 4.5 tones of premix	$1221.24	4.5 tones of premix	$270.9
Crack Sealing	1 Crew Cab Pickup 1 Flat Bed Truck or 1 Copmressor Truck 1 Compressor 1 Melting Kettle 1 Router	$ 885/day	1 Equipment operator II 1 Labourer I (Routing) 1 Labourer I (Blowing) 2 Labourer II (flag person) 1 Labourer II	$ 505/day	Hot Poured Sealant Material	$ 300/day for 200 liters	$ 1690	200 liters	$ 8.5
Rout and Seal	1 Crew Cab Pickup 1 Compressor Truck 1 Melting Kettle 1 Router 1 Brooms-Sweepers 1 Asphalt Heater	$ 1540/day	2 Equipment operator II 2 Labourer I (Routing) 2 Labourer I (Sealant) 2 Labourer II (flag person)	$ 675/day	Sealant Material	$ 300/day for 200 liters	$ 2515	200 liters	$ 12.6
Hot Mix Recycled Patching	1 Dump Truck 1 Hand Roller 1 Pavement Cutter 1 Recycler	$ 695/day	1 Equipment operator II 2 Equipment operator I[d] 2 Labour[illegible] (flag person)	$ 421/day	Propane +Reclamed Asphalt	$ 80/day for 3 tones reclamed asphalt	$ 1196	3 tones reclaimed asphalt	$ 389.7
Hot Mix Patching	1 Dump Truck 1 Hand Tamper or Hand Tamp 1 Crew Cab Pickup	$ 493/day	1 Equipment operator II 2 Equipment operator I 2 Labourer II (flag person)	$ 421/day	Hot Bituminous Premix	$ $225/day for 4.5 tones of premix	$ 1139	4.5 tones of premix	$ 253
Cold Mix Patching	1 Dump Truck 1 Hand Tamper or Hand Tamp 1 Crew Cab Pickup	$ 493/day	1 Equipment operator II 2 Equipment operator I 2 Labourer II (flag person)	$ 421/day	Cold Bituminous Premix	$ 405/day for 4.5 tones of premix	$ 1319	4.5 tones of premix	$ 293
Surface Replacement	1 Grader 2 Dump Truck 1 Pneumatic 1 Asphalt Cutter 1 Compressor 1 Backhoe	$ 1237/day	2 Equipment operator II 2 Equipment operator III[e] 2 Equipment operator I 2 Labourer II (flag person) 3 Labourer I 1 Labourer II	$ 1237/day	Bituminous Premix + Tack Coat	$ 2890/day for 40 tones of premix	$ 4987	40 tones of premix	$ 124.7

[a] Utilizing pick and shovel, dig ditches, post holes, clean out culverts, screen sand, spread gravel or sand as required, cuts and cleans brush and replaces road signs.
[b] Operates jackhammers in the cutting and mending of pavement, operates compressor, operates sand blasting machine, serves as flag person, serves as dumps person at construction sites.
[c] Watch for evidence of developing mechanical defects, performs normal maintenance on assigned equipment, positions dump truck for loading of materials, drive truck to destination and unload unload material in specifies area.
[d] Operates delivery vans, pick-up trucks or cars in delivering and picking up various types of materials and equipments, cleans and maintains vehicles.
[e] Operates equipment as necessary in gravel pit, along highway, or at work site, grades gravel roads, paves road shoulders.

considered in this thesis. It should be noted that the cost information is based on 1990 price quotations [Equipment Rental Rate Schedule, 1990].

During PMAS run, the system will ask the user for input such as the equipment rental cost, the laborers hourly rate and cost of materials for specific type of maintenance strategy. By providing this information, the system will display a final conclusion with one or more recommended maintenance strategies along with the expected repair life, the unit cost and equivalent annual cost for each of the recommended maintenance strategies. The system gives the user a flexibility of choice by giving several alternatives and cost comparison for the recommended maintenance strategies. This feature enables the user to select the best alternative according to the availability of the materials, experienced labor and budget in his/her jurisdiction.

5.6 Developing the Complete Expert System

In expert system development, it is typical to start with a small, but completely workable prototype, and then develop it into the target system by incrementally improving its performance and enlarging its knowledge base. Therefore, the objective of this task was to enhance the knowledge base and performance of the prototype until the completed system was obtained.

To achieve a well structured approach to develop the prototype into a complete system, two steps had to be followed. These steps involved the iterative process of increasing the number of rules to cover the full scope of the knowledge base, and testing the system using simulated scenarios till the expected performance was reached.

5.7 PMAS Features

PMAS is a production system built using expert system shells. The system takes input from the user concerning type, severity, density, RCI, climatic condition, AADT and applicable cost information. The system then outputs the appropriate maintenance selection, along with its expected repair life and the unit cost for each of the recommended strategies. The following sections reveal some of the main features of PMAS operating in Exsys and Instant Expert Plus environments.

5.7.1 Control Mechanism

PMAS utilizes backward chaining mechanisms to arrive at a conclusion. The system presumes a conclusion first, and returns to the known data or facts which would support, or discount the assumed conclusion. Backward chaining is most useful in situations similar to those of PMAS where there are many solutions and relatively few input data [Maher, 1987].

5.7.2 Explanation Facility

The pavement maintenance explanation facility is designed to respond to two types of questions:

1 During the run, if the user questions why the program demands to know particular facts, the program will respond by displaying the rules for which a decision is needed. This function is available in both Exsys and Instant Expert Plus.

2 After the run, if the user desires an explanation of particular conclusion, the system will respond by displaying a series of rules that were fired to arrive at the conclusion. This function applies only in Exsys.

5.7.3 Addition and Removal of Knowledge

In a pure production system as mentioned before, rule ordering is not important. Therefore, addition and deletion of rules is simple. The only concern is the impact of the changes (addition or deletion of rules) on the structure of the subgoals. As a result, PMAS can be easily modified in the future, if new knowledge arises.

5.8 System Validation

The purpose of this step is to validate the implemented expert system with "real world" test cases and to refine the system if necessary. It should be noted that the system at this stage is complete, and no drastic changes are expected because it has already been tested several times during the development stage. A total of nine cases were used to test the system; five test cases were provided by Mr. Sellars and four by Mr. Foster. The system succeeded in seven out of the nine cases. In two cases, the system provided different preference orders than those provided by the experts (see test case # 2). The system was corrected and successfully tested toward extra test cases. The next section will provide two of the actual test cases as examples. Table 5.3 summarizes the input and the output for all nine test cases.

5.8.1 Test Case # 1

A section of TC-1 (Trans-Canada -1) located about 20 kilometers east of Gander (inland climate), was dominant by transverse cracking and RCI was related to be less than 4. The cracking was identified as moderate (crack width was between 13 and 25 mm) and the density as few (less than 30% of pavement surface affected, distress over localized area only). The traffic volume was less than 2000 veh/lane. This part of TC-1 was one lane in each direction. After running the program, the final conclusion was to rout and seal as first selection and cold mix patching as second selection. The system selection was compatible with the actual work performed in this section. It should be noted that the decision to use rout and seal, and cold mix patching for this section, was a decision made by the management personnel and the contractor of the Department of Works, Services and Transportation.

Table 5.3:
Summary of the Test Cases

Test Case #	Distresses	Severity	Density	Riding Comfort Index	Traffic Volume AADT	Climate	PMAS Recommendations	The Performed pavement maintenance
1	Single distress Transverse Cracking	Moderate	Few	More than 4	Less than 2000 veh/lane	Inland	(1) Rout and Seal (2) Cold mix patching	Rout and Seal
2	Single distress Alligator Cracking	Moderate	Few	Less than 4	Less than 2000 veh/lane	Coastal	(1)Hot mix patching	Hot mix patching
3	Single distress Rutting	Severe	Extensive	Less than 4	Less than 2000 veh/lane	Inland	(1) Cold mix patching (2) Pothole patching	Pothole patching
4	Single distress Alligator Cracking	Severe	Extensive	Less than 4	More than 2000 veh/lane	Inland	(1) Reconstruction (2) Surface replacement (3) Hot mix patching	Reconstruction
5	Single distress Transverse Cracking	Slight	Few	More than 4	More than 2000 veh/lane	Coastal	(1) Do nothing	Do nothing
6	Combined distresses Rutting and Alligator Cracking	Severe	Extensive	Less than 4	Less than 2000 veh/lane	Inland	(1) Hot mix patching (2) Reconstruction	Reconstruction
7	Combined distresses Rutting and Transverse Cracking	Severe	Few	More than 4	Less than 2000 veh/lane	Coastal	(1) Crack seal (2) Hot mix patching	Crack seal
8	Combined distresses Transverse and Alligator Cracking	Moderate	Few	More than 4	Less than 2000 veh/lane	Inland	(1) Hot mix patching	Hot mix patching
9	Combined distresses Rutting, Transverse Cracking and Alligator Cracking	Severe	Extensive	Less than 4	More than 2000 veh/lane	Inland	(1) Reconstruction (2) Hot mix patching	Reconstruction

5.8.2 Test Case # 2

A section of TC-1 (Trans-Canada -1) located near Deer Lake, Newfoundland (inland climate), was found with combined distresses, rutting and alligator cracking, and RCI less than 4. The cracking was identified as severe and the density as extensive. The traffic volume was less than 2000 veh./lane. This part of TC-1 was one lane in each direction. After running the system, the final conclusions provided were (1) Hot mix patching with confidence (9/10) and (2) Reconstruction with confidence (7/10). The results provided by the system selection were different from Mr. Foster's ranking. In his opinion, the order should have been as follows: (1) Reconstruction with confidence (9/10), (2) Hot mix patching with confidence (7/10). As a result, the system has changed the reconstruction to be first selection. This was done by correcting the rule which has that conclusion, and changing reconstruction from the second position to be first by changing the confidence factor from 7/10 to be 9/10. The same steps were followed to change the first option, hot mix patching, to be the second selection. This was corrected by changing the confidence from 9/10 to be 7/10.

5.9 Comparison Between PMAS and Other Systems

A comprehensive review of expert systems in flexible pavement maintenance, and rehabilitation which was found in literature was presented in Chapter three. A comparison of PMAS with these systems is presented in Table 5.4. Each element of comparison is further discussed.

Three of the four systems run on microcomputers (IBM) and used Exsys, an expert system shell, for their development. PRESERVER runs only on a mainframe using the specially developed expert system programming environment OPS5. PMAS was developed to run on two microcomputer environments, IBM-PC and Macintosh.

The number of rules in PMAS is 170 in Exsys and 225 in Instant Expert Plus. The reason Instant Expert Plus has more rules for the same knowledge base is because of

Table 5.4:
Comparison Between PMAS and Other Systems

Criteria of the Expert Systems for Flexible Pavement Maintenance	PMAS	PRESERVER	ROSE	SCEPTRE
Development Tool	- EXSYS Professional - Instant Expert Plus	OPS5	EXSYS	EXSYS
Hardware	- IBM - PC - Macintosh	Mainframe	IBM - PC	IBM - PC
Number of Rules	- 170 (EXSYS) - 225 (Instant Expert)	Not available	360	140
Inference Engine	Backward chaining	Forward chaining	Not available	Backward chaining
Computer Expertise Required	No prior programming knowledge is necessary	Requires prior experience with OPS5	No prior programming knowledge is necessary	No prior programming knowledge is necessary
Pavement Distresses Considered	Alligator cracking, transverse cracking and rutting	Alligator cracking, progressive edge cracking and distortion	All cracks but alligator cracking	Alligator cracking, longitudinal cracking, transverse cracking and rutting
Maintenance Strategies	Ten alternative maintenance strategies	Not available	One maintenance Routing and Sealing	Ten rehabilitation strategies
Numbers of Independent Variables	- Type of surface distress - Density of surface distress - Severity of surface distress - Traffic volume - Riding comfort index - Climate - Cost comparison	- Distress type - Section size - Severity and density - Cost	- Crack type - Pavement serviceability - Pavement structure - Presence of pavement distress - Existing of pavement maintenance treatments	- Type of surface distress - Amount of surface distress - Severity of surface distress - Existing pavement performance - Traffic levels - Climate
Main Source of Knowledge	Pavement Maintenance Guidelines and Two experts	Pavement Maintenance Guidelines	One research Engineer and two consulting Engineers from Ontario Ministry of Transportation	Two pavement experts
Stage of Development	Field prototype	Field prototype	Field application	Field prototype
Powerful Feature	Graphics and cost comparison	Select the most single cost effective treatment	Automatic Mode	Consultations through external program

its inability to accept more than five conditions (IF part) in each rule. Rules with many IF conditions must be broken into separate rules. SCEPTRE contains 140 rules and ROSE contains 360 rules in Exsys.

Pavement maintenance and rehabilitation systems are characterized by a limited number of conclusions (i.e. maintenance and rehabilitation strategies), which warrant the use of backward chaining in their inference engine. As a result, all the systems use backward chaining except PRESERVER, which was developed on OPS5 which uses forward chaining as its default mechanism [Haas and Shen, 1989].

The selected shells for PMAS, ROSE and SCEPTRE require no prior programming experience. The only exception is PRESERVER, which requires a special programming experience to use the system.

PMAS evaluates three types of distresses; alligator cracking, transverse cracking and rutting. SCEPTRE also considers these distresses as well as longitudinal cracking. ROSE evaluates all cracks except alligator cracking. It should be noted that each system considers the type of cracks which are prevalent in the area where the system was applied.

PMAS selects the appropriate maintenance strategies among nine different alternatives used in Newfoundland and Labrador. SCEPTRE basically uses project level pavement surface distress data and other user inputs, to select a feasible rehabilitation strategy among ten different alternatives. ROSE was developed for Ontario environment and deals only with rout and seal for repairing cracking in cold regions. PRESERVER recommends the single most effective maintenance treatment for pavement.

SCEPTRE considers six variables, ROSE considers five variables and PRESERVER considers four variables while PMAS considers seven independent variables. PMAS is unique in considering RCI as one of its independent variables and outputing a cost comparison between the selected maintenance strategies.

SCEPTRE, ROSE and PRESERVER are field prototypes, and as such display good performance and have been extensively tested. None of these systems is commercially available [Ritchie et al., 1986]. PMAS is a research prototype and has not been substantially tested.

PMAS has several features that distinguish its performance from other existing systems. First, the Macintosh version of PMAS interactively questions the user using distress pictures along with various distress forms. This unique feature allows the user to better understand various distress forms and expressions such as 'few' and 'extensive' by presenting photographs of "real world" road conditions along with its text expression. Second, PMAS was developed using two different computer technologies. PMAS is the only maintenance expert system that runs on Apple Macintosh. Third, PMAS provides unit cost comparisons with each recommended maintenance strategy. This allows the user to evaluate other maintenance options in case particular materials and equipment are not available. Finally, PMAS is developed to consider Newfoundland local conditions, prevailing distresses and pavement maintenance practices.

5.10 Summary

This chapter has provided an explanation of PMAS development starting from the preparation of the knowledge base to the development of the complete expert system. Three sources of knowledge were used for building the PMAS knowledge base; formal documents, documented case studies and expert interviews. Pavement Maintenance Advisory System is a rule-based system built, using Exsys Professional and Instant Expert Plus expert system shells. Instant Expert Plus was chosen mainly for its ability to associate facts and expressions with graphics. PMAS utilizes a backward chaining mechanism to arrive at a conclusion. Facts in PMAS are presented in the form of IF/THEN statements and consist of 170 rules in Exsys Professional and 225 rules in Instant Expert Plus. The system provides the user with a list of candidate maintenance types followed by the expected effective life and equivalent annual cost for each type. The system was tested successfully and validated by the experts during real case studies.

Chapter 6

Summary and Conclusions

6.1 Problem Domain

Pavement distresses are a serious problem of Canada's infrastructure because they reduce the ability of highways to serve the public and increase the life cycle cost of the highways. In 1989, the total cost of highway repairs was $1.56 billion which represented 25.4% of the total cost of highway construction. Most highway agencies have started to place far more emphasis on maintaining and preserving existing highways, than on building new ones. Determining the best maintenance strategy starts by identifying the type of surface distress, and then finding out which preventative and corrective strategies are most appropriate. This research was conducted to accomplish various objectives. First, the body of knowledge concerning flexible pavement maintenance strategies was collected and second, a computer program was developed which would simulate as closely as possible, the way in which a human expert selects appropriate pavement maintenance strategies.

6.2 Suitability of the Problem Domain for Expert Systems

Expert systems are primarily applicable to situations which require specialized knowledge, skill, experience and judgement for determining a solution, or developing a solution strategy [Maher, 1987]. In pavement maintenance decisions, numerical algorithmic solutions are not available: multi objective decision making is involved, and deciding on the optimum maintenance strategy is largely a subjective problem. Yet optimum maintenance strategies, which maximize benefits while minimizing costs have not been quantified [SHRP, 1986]. Hence, the problem does not lend itself to a traditional economic analysis in which benefits and costs can be explicitly considered. As a result, knowledge-based expert systems have the potential of becoming useful tools in pavement maintenance strategy selection.

6.3 Literature Search

Little work has been reported in the literature with regard to expert system application in the pavement maintenance area. A computer search revealed four systems in flexible pavement and one system in rigid pavement. These are: PARADIGM, PRESERVER, ROSE, ERASME and Concrete Pavement Evaluation.

PARADIGM (PAvement Rehabilitation Analysis and DesIGn Mentor) consists of four modules, namely SCEPTRE, OVERDRIVE, and two similar systems for utilizing project level information (Network Optimization). SCEPTRE is an advisory tool for evaluating pavement surface condition and recommending rehabilitation strategies. OVERDRIVE is an expert system for the design of flexible asphalt concrete overlay on flexible pavements. Network Optimization describes how the project-level results from the rehabilitation model can be used for network-level pavement management.

PRESERVER is a knowledge based system which recommends the single most cost effective maintenance treatment action. PRESERVER was developed using OPS5 representation language on a VAX.

ROSE is a knowledge-based computer program intended for selecting and recommending routing and sealing of cracks.

ERASME is a tool for assisting pavement maintenance decision making in France. ERASME performs two different functions: diagnostic and rehabilitative.

Concrete Pavement Evaluation is another expert system developed to assist state highway engineers in evaluating concrete highway pavements.

Each of the existing systems was developed for application in a particular jurisdiction under specific climatic conditions and specific distress and maintenance type. None of the existing systems considered Riding Comfort Index (RCI) as a factor affecting the selection of pavement maintenance strategy. Most of the existing systems recommend the appropriate maintenance based on a subjective basis. They do not include any cost comparison (total and unit cost of equipment, laborers and materials) for the recommended maintenance strategies. Therefore, a need to develop an expert system program to facilitate the decision making in the province was essential.

6.4 Knowledge-Based Expert System Development Issues

Two issues related to knowledge-based expert system development have been studied as part of this research: the process of acquiring, compiling and organizing knowledge related to pavement maintenance and distress, and the process of developing Pavement Maintenance Advisory System (PMAS). PMAS is a computer program developed to assist highway engineer in selecting the appropriate maintenance strategy.

Knowledge was acquired for the PMAS from both technical literature and direct interaction with experts. Interviews were conducted with experts from Department of Works, Services and Transportation. From these interviews, a multi level search tree was conceived to capture and to structure the knowledge of the experts.

Two environments have been selected for this study; Exsys Professional and Instant Expert Plus. The major strengths of Exsys, which runs on IBM and Compatibles, are its flexibility, ease of use, and its sophisticated user interface features. The major drawback of Exsys is its lack of graphic capabilities. Instant Expert Plus, a Macintosh-based tool provides excellent graphics capabilities. The major drawback of Instant

Expert Plus is its lack of explanation facilities. Expert system shells have proven to be efficient expert system development tools.

6.5 Status of Current System

PMAS is a knowledge-based expert system designed for selecting the appropriate maintenance strategies in cold/coastal regions. The system takes input from the user concerning type of distress, surface condition (severity and density), traffic volume, Riding Comfort Index, climate condition and outputs maintenance strategies with expected repair life in years for the recommended maintenance type. PMAS utilizes backward chaining to derive inferences in Exsys and mixed mode in Instant Expert Plus. It has the ability to answer questions about its reasoning both during, and after a run session. Confidence factors have been employed to provide the user with a degree of certainty of the relative importance of each type of maintenance strategy.

The system is also capable of providing cost estimates and comparison between different maintenance types. The system asks the user for input regarding equipment rental cost, materials cost and labor hourly rates. The system provides the user with the appropriate maintenance strategy, along with unit cost and equivalent annual cost for each selected maintenance type. The unit cost information per production unit was obtained from Road Maintenance Standard [Road Maintenance Standard, 1989]. The expected repair life data was developed through personal interviews with two experts from Department of Works, Services and Transportation. The system was successfully tested and validated in Newfoundland.

6.6 System Strengths and Limitations

The next sections, 6.6.1 and 6.6.2, discuss the various strengths and limitations of the Pavement Maintenance Advisory System.

6.6.1 Strengths

1 Knowledge contained in PMAS was acquired from credible sources and thus can be used as a decision support system. The system can also be used to train new personnel with little or no expertise in pavement maintenance.

2 The runs of the system have illustrated that the system is capable of handling single distress as well as different combinations of distress conditions.

3 The system considered RCI as one of the main variables which affects pavement maintenance decision making. RCI significantly affects the decision of selecting appropriate maintenance strategy because it relates to the urgency of a particular maintenance activity [Nair and Hudson, 1986].

4 The system gives the expected repair life in years as well as the total cost of equipment, labor and materials for each type of maintenance. This helps the user to make the final decision based on the available resources and budget.

5 One of the main features of the PMAS in Instant Expert Plus is its capability of associating facts or expressions with pictures. For example, instead of the system asking questions about the severity of distress, it demonstrates severity of distress by showing actual pictorial examples of different levels of severity. PMAS is the only system which runs on Macintosh, and is capable of giving powerful user interface by providing pictures during runs.

6.6.2 Limitations

1 The most important limitation, inherent to any expert system concept, is the process of knowledge acquisition. Experts often have difficulty expressing or formalizing their opinions in a structured fashion.

2 The system is limited to the three types of distress which are the most common problems in Newfoundland: alligator cracking, transverse cracking and rutting [Sellars, 1991., McCarthy, 1985., Tam and Lynch, 1986].

3 The main shortcoming in constructing the knowledge base is that the experts were limited to the already defined variables on the knowledge base tables. This, however, was not a serious limitation because through extensive communication with the experts the variables which are important in the decision making were defined and their interactions with other variables was established.

4 The system was tested only using nine test cases. Further substantial test cases are needed to assure satisfactory performance.

5 The direct application of PMAS in other provinces may be difficult and inadvisable, although the methodology may have general applicability.

6.7 Conclusions

This thesis demonstrates how knowledge based expert systems can be effectively utilized for the selection of pavement maintenance strategies. PMAS is interactive in nature and it asks the user simple questions about general features of the highway section. Questions are asked in a user friendly language and are easy to interpret. The resulting information provides a reasonable set of input data for the comparison of maintenance decisions. PMAS was applied successfully to several test cases in Newfoundland, showing that it is a suitable and versatile tool for selecting the most appropriate and cost effective pavement maintenance strategy. This computer program will provide the user with:

1 The type and ranking of maintenance strategies
2 Knowledge of when work is to be done (the urgency of taking maintenance action)
3 Suitable equipment, crew size and tasks for each selected maintenance strategy
4 The total cost of equipment, laborers and materials
5 The unit and equivalent annual cost for each maintenance strategy
6 The expected repair life for each maintenance strategy.

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Appendix A

GLOSSARY

This glossary presents some definitions of the terminology used in this thesis. Definitions were taken from Building Expert Systems [Frederic, 1983].

ARTIFICIAL INTELLIGENCE

It is a one of the computer science fields, involved in developing intelligent computer programs. This contains programs that can solve problems, interpret visual scenes, and behave in a way that would be considered intelligent if inspected by a human.

DOMAIN EXPERT

A person, who, through years of training and experience, has become highly qualified at problem-solving in a special field.

HEURISTIC

A piece of knowledge capable of suggesting plausible actions to follow, or implausible ones to avoid.

KNOWLEDGE

The fact or condition of knowing something with familiarity gained through experience or association [Webster's dictionary, 1971].

KNOWLEDGE ENGINEER

The person who designs and implements the expert system. This person is usually a computer science engineer, experienced in applied artificial intelligence methods.

NODE

Node is a point (representing aspects such as the system state or an object) in a graph connected to other points in the graph by arcs (usually representing relationship).

RULE

A certain way of explaining a recommendation, expressed as an IF premise THEN conclusion or an IF condition THEN action.

PRODUCTION RULE

An IF-THEN statement or rule used to represent knowledge in terms of human thinking.

USER

A person who uses an expert system, such as a domain expert, knowledge engineer, or any other person.

TREE STRUCTURE

A way of organizing information as a connected graph where each node can branch into other nodes in the structure.

SEARCH

The procedure of seeking through the set of possible outcomes to a problem in order to find a qualified outcome.

GOAL

Goal is the final conclusion.

Appendix B

Example Runs

Instant Expert Plus User's Instructions

Instant Expert Plus is an expert system generator containing all of the tools needed to create complete applications without complicated programming. The description of a tutorial run refers usually to the screen displayed by the system. Printouts of these screens are included at the end of the tutorial. Best results are achieved when the user runs the system along with the tutorial. The only equipment required is a Macintosh Computer. To install the Instant Expert Plus and the PMAS on the hard disk insert the Instant Expert Plus disk into a disk drive, select the Instant Expert Plus icon and associated files from the disk and drag these icons to the hard drive after opening an empty folder to contain all Instant Expert Plus files and PMAS. The user can give the empty folder name Instant Expert Plus. Repeat the last step with the other Instant Expert Plus disk and the PMAS disk. After loading the Instant Expert Plus and PMAS into the hard drive, the user should double-click on the Instant Expert Plus folder to open (Screen 1). Screen 1 shows all the folders including Instant Expert Plus folder. The user should click twice inside the Instant Expert Plus folder to open the program. Instant Expert Plus logo on Screen 2 will appear. The IEPlus icon is the actual Instant Expert Plus Program. This contains all the user needs to build and to run your expert system application. Screen 3 will appear after clicking twice inside IEPlus icon. Screen 3 is the introduction to the system. The user should click once inside the box on Screen 3 and the main menu will be displayed, Screen 4. The main menu contains Apple, File, Edit, Rule, Facts, Graphics and Inferences menus. After opening each one of this menu separately, Screen 5 will be displayed. Apple menu is resident on all Macintosh applications and contains many items (Screen 5). The File menu contains commands that are used to work with the knowledge bases stored on the disks. This menu also controls the creation of knowledge bases and text files, as well as the printing functions (Screen 5). The Edit menu used in Instant Expert Plus is very similar to the Edit menu in the finder and most Macintosh programs (Screen 5). The concepts behind the Edit commands are quite simple. Items that are highlighted can be cut out or copied, and pasted elsewhere. The Rules menu contains all of the commands working with rules and classes (Screen 5). The Facts menu commands control the use, storage and retrieval of facts (Screen 5). Facts are the data offered by the user during a consultation and the data inferred by the expert system as a result of a consultation. The Graphics menu provides the tool to link areas of the graphic to your rules and other Instant Expert Plus functions (Screen 5). The Inferences menu controls which process and/or search strategies are employed (Screen 5). Inferences menu will be described later. The user should choose Open a Base from the File menu to work with PMAS. The PMAS folder is selected by clicking twice to open it. Now that the program and the knowledge base are loaded into memory the knowledge contained in it can be used.

If the user wants to know some information about the base, he/she should select Get Base Info from the File menu. This base contains some information about the author, size, creation time, and scope of a knowledge base Screen 6. After reviewing this information click OK inside Screen 6 to return to the menu.

To run the system, Instant Expert Plus uses four modes of inference and user information. These are DEDUCTION, INTERACTIVE DEDUCTION, VERIFY HYPOTHES, EXPERTISE:

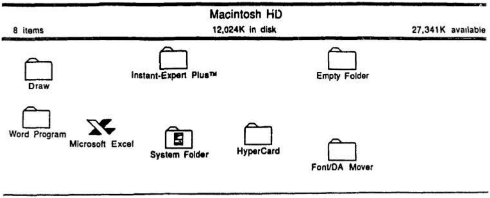
DEDUCTION, This command involves a forward chaining. Instant Expert Plus uses the facts in the current Base of Facts to arrive at a conclusion, without asking the user any questions. During consultation, the user opens the Base of Facts and adds facts to this base from the Add Facts by Dictionary section. This section stores all expert knowledge line by line for every IF condition entered. The user goes through this information and only clicks on the relevant ones. If the user clicks on the extreme left on the line he records the fact as false in the base of facts; if he clicks on the extreme right he records the fact as unknown; if he clicks in the middle of the sentence the facts are recorded as true. Having selected the facts, the user goes to the Inference menu and selects DEDUCTION. The inference engine picks the given facts and searches for all rules to give the conclusions and display them. This consultation mode is useful for users who have all relevant facts about the problem but are not sure of the conclusions to be derived. Moreover, the user does not need to run the whole system when he needs information on only a small part of the problem.

INTERACTIVE DEDUCTION, This command is similar to the Deduction mode except that further information will automatically be requested from the user if the facts required for the testing of a selected rule are not in the Base of Facts. Consulting in the interactive deduction mode is helpful for users who have inadequate information about the problem, and need more information to arrive at a conclusion.

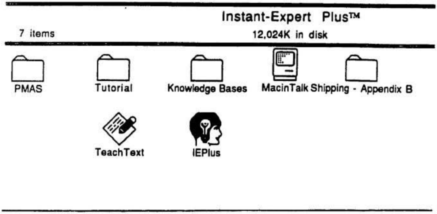
VERIFY A HYPOTHESIS, This command evokes the backward chaining mode where the user can discover if a given hypothesis is true. The user opens the inference menu and selects Verify hypothesis. The user is offered a list of conclusions to select the active hypothesis. The user selects a hypothesis for the system and the system asks the user questions to confirm it. The user opens the Inference menu and selects VERIFY A HYPOTHESIS. The system displays all conclusions entered in the then field . If the user clicks on the conclusion that the recommended maintenance type is hot mix patching, the effective repair life will be shown as two years. The inference engine locates all questions that will lead to that conclusion and poses them to the user. If the user answers in a way that will conflict with the confirmation of the hypothesis, the system will display that the hypothesis could not be verified.

EXPERTISE, This command invokes a mixed mode of chaining where both forward and backward chining are used. Consultation at the Expertise mode is useful for all groups of users, including beginners. The system assumes the user has no knowledge about the solution to the problem and therefore starts asking questions from the fundamental stage. As the user answers the questions posed, the results or conclusions are displayed to him. The selection of goals and the answering of questions continues until all relevant rules have been tested.

When the user clicks "Deduction" from the Inference menu, Screen 7 will appear. The user should choose one of the two classes (single distress or combined distresses) and click OK. Starting from this point until the end of this run, screens containing different questions will appear. Screen 8 is an example of how the questions appear. The user will note that there is a"Why" in each of the screens. Clicking "Why" will give the user the reason why the system is asking that particular question. "Quit" will end the session. After the user answers all the question asks, the final report with the recommended maintenance decision will be presented.


Macintosh HD
8 items
12,024K in disk
27,341K available
Draw
Instant-Expert Plus™
Empty Folder
Word Program
Microsoft Excel
System Folder
HyperCard
Font/DA Mover

Screen 1


Instant-Expert Plus™
7 items
12,024K in disk
PMAS
Tutorial
Knowledge Bases
MacinTalk
Shipping - Appendix B
TeachText
IEPlus

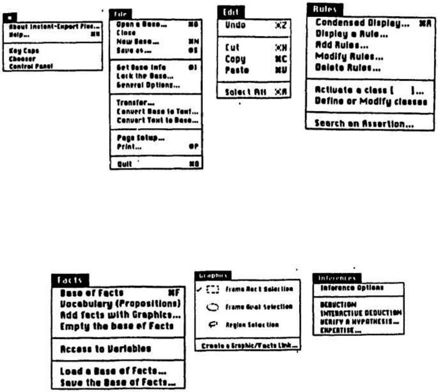
Screen 2

Instant-Expert Plus™

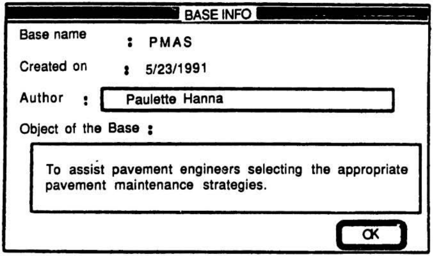
Screen 3

File Edit Rules Facts Graphics Inferences

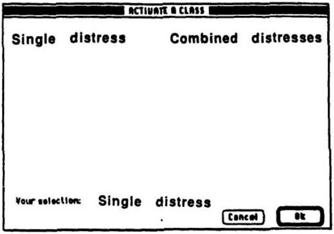
Screen 4


About Instant-Expert Plus...
Help...
Key Caps
Chooser
Control Panel
File
Open a Base...
Close
New Base...
Save as...
Set Base Info
Lock the Base...
General Options...
Transfer...
Convert Base to Text...
Convert Text to Base...
Page Setup...
Print...
Quit
Edit
Undo
Cut
Copy
Paste
Select All
Rules
Condensed Display...
Display a Rule...
Add Rules...
Modify Rules...
Delete Rules...
Activate a class [ ]...
Define or Modify classes
Search an Assertion...
Facts
Base of Facts
Vocabulary (Propositions)
Add facts with Graphics...
Empty the base of Facts
Access to Variables
Load a Base of Facts...
Save the Base of Facts...
Graphics
Frame Rect Selection
Frame Oval Selection
Region Selection
Create a Graphic/Facts Link...
Inferences
Inference Options
DEDUCTION
INTERACTIVE DEDUCTION
VERIFY A HYPOTHESIS...
EXPERTISE...

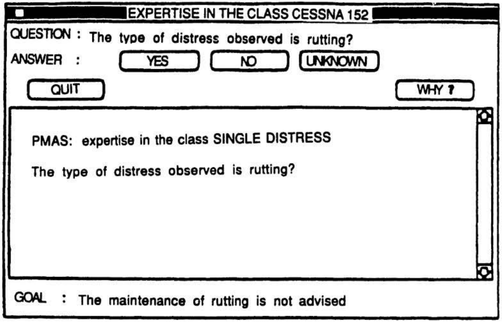
Screen 5


BASE INFO
Base name : PMAS
Created on : 5/23/1991
Author : Paulette Hanna
Object of the Base :
To assist pavement engineers selecting the appropriate pavement maintenance strategies.
OK

Screen 6


ACTIVATE A CLASS
Single distress
Combined distresses
Your selection:
Single distress
Cancel
Ok

Screen 7


EXPERTISE IN THE CLASS CESSNA 152
QUESTION : The type of distress observed is rutting?
ANSWER :
YES
NO
UNKNOWN
QUIT
WHY ?
PMAS: expertise in the class SINGLE DISTRESS
The type of distress observed is rutting?
GOAL : The maintenance of rutting is not advised

Screen 8

The menu at the bottom of Screen 6 appears with every question. Typing WHY instead of a number prompts the system to display the series of the rules which it is used to reach a conclusion. This will be investigated later. Typing QUIT allows the user to save all of his input data to this point, turn off the system, and return to it later. Typing <H>, provides the user with further guidance.

The proper response to the question displayed in Screen 6 is 1, Single distress. Thus 1 and ENTER will display Screen 7; the user should continue answering the question until Screen 12 is displayed. Screen 12 to 14 will provide an example of the type of information that is produced when WHY is typed. Screen 13 shows the rule which is to reach a conclusion. Typing ENTER will cause the Screen to advance (Screen 14).

It should be noted in Screen 13 that the menu at the bottom has changed. If the user types a line number in the IF condition the system will display all rules used to verify or refute that condition. <K> will cause a listing of all known data input so far to be displayed. <C> will provide the user's choices. <R> will provide the textual reference from which the rule was obtained. <ENTER> will display the next consecutive rule, <J> will cause the system to jump to a rule of the user's choosing.

At this point, the user should merely type ENTER and proceed. Compilation of the scenario will bring the user to Screen 15. Screen 15 will ask the user to input the equipment cost for hot mix patching. The user should put 500 and press enter. Screen 16 and 17 will ask the user for the labor and materials cost for hot mix patching. Typing 450 in Screen 16 and 250 in Screen 17 and press enter after each input will cause Screen 18 to advance. Screen 18 will briefly introduce the results of the analysis which will follow. Screen 19 will display the results of the analysis and should be read carefully.

A new menu will be revealed at the bottom of Screen 19. <H> will explain what each choice will do. At this point, the the user should type <C>, which will allow him to change any input data and rerun the system. After the user types <C> and ENTER, the Screen 20 will appear.

Screen 20 will indicate that line 3 is to be changed. Line 3 is a statement which says that Riding Comfort Index is equal to or more than 4. Screen 21 will bring the same question. By choosing Riding Comfort Index less than 4, will display Screen 22. Writing R (RUN) Screen 23 will display. Screen 23 will ask the user for the cost of equipment for hot mix recycled patching. Writing 700 will display another input for the cost of the labor for hot mix recycled patching (Screen 24). Writing 450 will display Screen 25. Screen 25 will ask the user for the cost of materials for hot mix recycled patching. Writing 100 will display Screen 26. Screen 26 is introduction to the final conclusion. The user must press ENTER to get to the final conclusion (Screen 27).

As may be quickly noted, the results have changed from Hot Mix Patching 9 to Hot Mix Recycled Patching 9 OR Hot Mix Patching 7. Screen 27 shows the Total Cost for equipment, labor and materials for hot mix recycled patching and hot mix patching. Screen 27 also display the Unit Cost and Equivalent Annual Cost for each decision.

eeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeee

Exsys

Professional

eeeeeeeeeeeeeeeeeeeeeeeee

@ RUNTIME @

eeeeeeeeeeeeeeeeeeeeeeeee

eeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeee

Expert System File Name: **PMAS**

Screen 1

Do you wish instruction on running the program? (Y/N):

Screen 2

Do you wish to have the rules displayed as they are used? (Y/N)

(Default = N):

Screen 3

&&&&&&&&&&&&&&&&&&&&&&&&&&&&&

&   &

& **Pavement Maintenance Advisory System** &

&   &

&&&&&&&&&&&&&&&&&&&&&&&&&&&&

By : Paulette Hemaya

Press any key to start:

Screen 4

The Knowledge base, Pavement Maintenance Advisory System, was developed to assist engineers and to help them choose the appropriate type of maintenance. This expert system will ask several questions about pavement distress. Each question will appear, followed by the appropriate selections that are valid responses for that particular question. You should select the number of value you desire and then press the <ENTER> key.

Press any key to start:

Screen 5

The type of distress observed is

1 Single distress

2 Combined distress

1

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S) WHY to display rule being used

QUIT to save data <H> for help <Ctrl-U> to undo

Screen 6

The type of distress observed is

1 rutting

2 alligator cracking

3 transverse cracking

2

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S) WHY to display rule being used

QUIT to save data <H> for help <Ctrl-U> to undo

Screen 7

The density of the distress is

1 few (less than 30% of pavement surface affected, distress over localized area only).

2 extensive (more than 30% of pavement surface affected, distress spotted over entire length of pavement section)

2

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S) WHY to display rule being used

QUIT to save data <H> for help <Ctrl-U> to undo

Screen 8

The severity of alligator crack is

1 slight (crack width less than 13mm)

2 moderate (crack width between 13mm and 25mm)

3 severe (crack width more than 25mm)

2

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S)   WHY to display rule being used

QUIT to save data   <H> for help   <Ctrl-U> to undo

Screen 9

Riding comfort index is

1 less than 4

2 equal to or more than 4

2

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S) WHY to display rule being used

QUIT to save data <H> for help <Ctrl-U> to undo

Screen 10

The traffic volume is

1 less than 2000 veh/lane

2 more than 2000 veh/lane

2

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S) WHY to display rule being used

QUIT to save data <H> for help <Ctrl-U> to undo

Screen 11

The climate is

1 *coastal (DD is lower than 600 C * days)*

2 inland (DD is higher than 600 C * days)

WHY

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S) WHY to display rule being used

QUIT to save data <H> for help <Ctrl-U> to undo

Screen 12

Rule Number:50

IF:

(1) The type of distress observed is single distress

and (2) The maintenance of alligator crack is advised

and (3) The repair is needed next season

and (4) The severity of alligator crack is moderate (crack width between 13mm and 25mm)

and (5) The density of the distress is extensive (more than 30% of pavement surface affected, distress spotted over entire length of pavement section)

and (6) The climate is coastal (DD is lower than 600 C * days)

THEN:

Hot mix patching- confidence=9/10

and The expected repair life for hot mix patching is three years

and [TC] IS GIVEN THE VALUE [CE]+[CL]+[CM]

and [UC] IS GIVEN THE VALUE [TC]/4.5

and [EAC] IS GIVEN THE VALUE [UC]/3

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

IF line # for derivation, <K>known data, <C>-choices or- prev or next rule, <J>-jump, <H>-help or <ENTER> to continue:

Screen 13

The climate is

1 coastal (DD is lower than 600 C * days)

2 inland (DD is higher than 600 C * days)

1

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S)   WHY to display rule being used

QUIT to save data   <H> for help   <Ctrl-U> to undo

Screen 14

Please input the equipment cost per day for hot mix patching for 1 Dump truck, 1 Roller or hand tamp and 1 Crew cab pickup. The recommended cost for that per day is $ 493/day.

500

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Input a value for variable   WHY for rule used

Quit to save data   <ctrl> to undo

Screen 15

Please input the labor cost per day for hot mix patching for 1 equipment operator II, 2 equipment operator I and 2 laborer II (flag person). The recommended cost for that per day is
$ 421/day.

450

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Input a value for variable   WHY for rule used

Quit to save data   <ctrl> to undo

Screen 16

Please input the materials cost per day for hot mix patching . The materials are hot bituminous premix and tack coat. The daily production is 4.5 Ton of premix. The recommended cost for that per day is $ 225/day.

250

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Input a value for variable WHY for rule used

Quit to save data <ctrl> to undo

Screen 17

The recommendation that will be given is on a numeric scale of 0 to 10. A value of 0 would be a very poor selection and a value of 10 would be a very good maintenance selection. The value in between 0 and 10 represent the degree of confidence (or certainty) to select.

Press any key to display results:

Screen 18

Press any key to display results:

Value based on 0-10 system		VALUE
1	Hot mix patching	9
2	*The expected repair life for hot mix patching is three* years	
3	Total Cost of equipment, laborer and materials per day for hot mix patching = $1200	
4	Unit Cost for hot mix patching = $ 266.66	
5	Equivalent Annual Cost for hot mix patching= $88.88	

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

All choice <A> only if value>1 <G> Print <P> Change and return<C>

Rules used <line#> Quite/save <Q> Help <H> Done <D>: C

Screen 19

1 The traffic volume (AADT) is more than 2000 veh/lane

2 The climate is coastal

3 Riding comfort index is equal to or more than 4

4 The density of the distress is extensive (more than 30% of pavement surface affected , distress spotted over entire length of pavement section)

5 The severity of alligator crack is moderate (crack width between 13mm and 25mm)

6 The type of distress observed is alligator cracking

7 The type of distress observed is single distress

8 Variable [CE] =500

9 Variable [CL] =450

10 Variable [CM] =250

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number of line to change, <O> for original data, <R> to run the data,<H> for help or any other key to redisplay data: S

Screen 20

Riding comfort index is

1 *less than 4*

2 equal to or more than 4

1

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number (S) of the value (S) WHY to display rule being used

QUIT to save data <H> for help <Ctrl-U> to undo

Screen 21

1 The traffic volume (AADT) is more than 2000 veh/lane

2 The climate is coastal

3 Riding comfort index is less than 4

4 The density of the distress is extensive (more than 30% of pavement surface affected , distress spotted over entire length of pavement section)

5 The severity of alligator crack is moderate (crack width between 13mm and 25mm)

6 The type of distress observed is alligator cracking

7 The type of distress observed is single distress

8 Variable [CE] =500

9 Variable [CL] =450

10 Variable [CM] =250

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Enter the number of line to change, <O> for original data, <R> to run the data,<H> for help or any other key to redisplay data: R

Screen 22

Please input the equipment cost per day for hot mix recycled patching for 1 Dump truck, 1 Hand Roller, 1 Pavement cutter and 1 Recycler. The recommended cost for that per day is $ 695/day.

700

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Input a value for variable WHY for rule used

Quit to save data <ctrl> to undo

Screen 23

Please input the labor cost per day for hot mix recycled patching for 1 equipment operator II, 2 equipment operator I *and 2 laborer II (flag person). The recommended cost for that* per day is $ 421/day.

450

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Input a value for variable   WHY for rule used

Quit to save data   <ctrl> to undo

Screen 24

Please input the materials cost per day for hot mix recycled patching. The materials are propane and reclaimed asphalt. The daily production is 3 Ton of reclaimed asphalt. The recommended cost for that per day is $ 80/day.

100

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

Input a value for variable WHY for rule used

Quit to save data <ctrl> to undo

Screen 25

The recommendation that will be given is on a numeric scale of 0 to 10. A value of 0 would be a very poor selection and a value of 10 would be a very good maintenance selection. The value in between 0 and 10 represent the degree of confidence (or certainty) to select.

Press any key to display results:

Screen 26

Press any key to display results:

Value based on 0-10 system		VALUE	PREV
1	Hot mix recycled patching	9	NONE
2	Hot mix patching	7	9

3 The expected repair life for hot mix recycled patching is four years.

4 The expected repair life for hot mix patching is two years.

5 *The total cost of equipment, labor and materials per day* for hot mix recycled patching = $ 1250

6 The unit cost for hot mix recycled patching = $ 416.66

5 The equivalent annual cost for hot mix recycled *patching*= $ 104.166

3 The total cost of equipment, labor and materials per day for hot mix patching = $ 1200

4 The unit cost for hot mix patching = $ 266.66

5 The equivalent annual cost for hot mix patching= $133.33

aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

All choice <A> only if value>1 <G> Print <P> Change and return<C>

Rules used <line#> Quite/save <Q> Help <H> Done <D>:

Screen 27