Development of an Expert System for Pavement Rehabilitation Decision Making

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ABSTRACT

In recent years, continued deterioration of the nation's highway infrastructure has led to increased emphasis on pavement rehabilitation, with national annual expenditures of billions of dollars. The nature of the analysis and design process suggests that a new technological approach, knowledge-based or expert system, could play an important role in addressing pavement rehabilitation problems and needs. An overview of expert system characteristics is provided; the pavement rehabilitation analysis and design process is discussed; and a prototype, microcomputer-based, surface condition expert system (SCEPTRE 1.1) for flexible pavement rehabilitation is described. Based on user inputs and a knowledge-base constructed from several human experts, the system can deduce a set of feasible project-level rehabilitation strategies for subsequent detailed analysis and design. The system can also readily explain its reasoning and conclusions, and is easily modified. It can therefore make its body of specialized knowledge accessible to a much broader range of potential engineering users.

In recent years, highway pavements in the United States have been wearing out faster than they can be repaired. This has led to increased emphasis on pavement resurfacing, restoration, and rehabilitation work, or simply pavement rehabilitation strategies, in order to restore highways to their original safe, usable condition without expansion of the original capacity. Large sums of money are currently invested in such programs, but in the future even greater emphasis is likely to be placed on maintaining and rehabilitating existing infrastructure (of which highway systems are a major part) rather than embarking on major capital investment in new facilities. In the state of Washington alone, about $100 million is spent annually on pavement resurfacing (seal coats, overlays, rehabilitation) for a state highway system approximately 7,000 miles long. In comparison, the combined length of the nation's 50-state highway systems is approximately 790,000 miles (1). Estimates of the national annual expenditures by similar state and federal agency programs run into billions of dollars.

Successful pavement rehabilitation strategies are developed by a relatively small number of pavement engineering specialists, using their knowledge, judgment, experience, and usually a limited amount of data--often uncertain in nature--from which inferences are derived and design and investment decisions made. Such experts are only to be found in some federal and state agencies, universities, and private firms. Because the analysis and design of project-specific rehabilitation strategies relies so heavily on expert pavement engineers, and the tasks involved are both complex and ill-defined, conventional computer tools are of limited use. Nevertheless, a pressing need exists to formalize this expertise and make it available to a larger number of engineers to ensure that the most cost-effective designs are constructed statewide. However, this situation is compounded by predictions that one-third of the most experienced engineers in state departments of transportation (DOTs) and county highway agencies will retire during the coming decade (2). It is a premise of the research described in this paper that expert systems can play a significant role in addressing these problems.

Expert systems are basically interactive, problem-solving computer programs that emulate the knowledge of a human expert in a specific professional domain. To date, no attempt has been made to systematically formalize the knowledge, experience, and thought process used by pavement engineering experts. Moreover, only recently has it become technically feasible to automate such a knowledge base in a computer program that could perform as an expert consultant and even as an instructor for other engineers. Such a program would be oriented particularly to engineers at the state DOT district level, but also to those at the county and local agency levels. In this paper, an overview of expert system characteristics is provided; the pavement rehabilitation analysis and design process is discussed, including the role of pavement management systems (PMSs); and a prototype, microcomputer-based surface condition expert system that has been developed for flexible pavements is described. This system represents the first phase of a much more extensive expert system under development for project-level analysis and design of pavement rehabilitation strategies for state-maintained highways. Ongoing research in these areas is also described.

RESEARCH OBJECTIVE

The quality of engineering analysis and design is a function of at least the following: quality of the

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data; quality of the analysis tools; and judgment, experience, and training of the engineer. The ultimate objective of this research is to develop an easy-to-use, generalized microcomputer program that (a) embodies the knowledge, experience, and judgment of expert pavement engineers, and (b) provides the local engineering user with an interactive analysis and design tool (that is also an instructional aid) for development of pavement rehabilitation strategies. The program could also, perhaps with some modifications, be utilized as a more general educational tool for development of skills in the pavement rehabilitation area.

The research described in this paper is oriented toward developing a tool for state-maintained highway systems. A parallel effort is under way for rural counties and local agencies. The development of these programs represents an exploratory but high-potential basic research effort in the area of knowledge-based expert systems from the field of artificial intelligence. Such systems are discussed in the following section.

OVERVIEW OF EXPERT SYSTEMS

Description

In recent years, expert systems have emerged from decades of research into artificial intelligence, which addresses problems traditionally believed to require human intelligence (e.g., natural language processing, speech recognition, computer vision, and robotics) in order to find a solution. Expert systems are designed to emulate the performance of an expert, or group of experts, in a particular problem domain. Such systems are primarily applicable to situations requiring specialized knowledge, skill, experience, or judgment for determination of a solution or development of a solution strategy. In such cases, the problem is usually said to be ill-structured in the sense that a numerical algorithmic solution is not available or is impractical. Because so many of the problems that transportation professionals face are of this kind (e.g., designing an optimal transit route network or making decisions about how to rehabilitate a deteriorated section of highway), it can be said that, in general, the potential appears high for knowledge-based expert systems to become useful tools for the practicing transportation planner and engineer. Such systems can be envisaged as functioning as expert consultants, capable of explaining their reasoning and why they arrive at certain conclusions. Thus, one could eventually expect to learn from an expert system in the same way that one currently learns from an actual dialogue with an expert consultant.

In a number of disciplines, operational expert systems have already been developed. Examples include the following: MYCIN, for medical consultation and diagnosis (3); DIPMETER, for oil-well logging (4); PROSPECTOR, for mineral exploration (5); and Rl, for computer system configuration (6). In civil engineering, systems developed to date include SACON, for structural analysis (7); SPERIL, for assessing earthquake damage to buildings (8); HYDRO, for watershed management (9); and HI-RISE, for preliminary design of high-rise buildings (10).

In the transportation field, little work on expert systems had been reported until recently. However, a number of systems are now in various stages of development. These include CHINA, for highway noise barrier design (11); DIRECTOR, for urban transportation education (12); TRALI, for traffic signal setting (13); and SCEPTRE, for pavement rehabilitation, which is discussed in more detail later in this paper. Further discussion of high-potential applications of expert systems in the transportation field can be found in Yeh et al. (12).

However, not all problems are suitable candidates for expert system formulation. Evaluation criteria include the following:

- Algorithmic solutions are impractical because of complex physical, social, political, or judgmental components, which generally resist precise description and deterministic analysis.
- Recognized experts exist in the field.
- An expert is often not physically available, or the knowledge transfer is too difficult or costly or may take too long.
- An expert's solution time is finite, typically taking a few minutes to a few hours.
- Tasks are largely cognitive.
- Faulty or incomplete data may be encountered during the problem-solving activity.
- Factual elements of the domain knowledge are routinely taught to beginners, who can eventually become experts.
- The potential pay-offs are high.

It is argued that the majority of these criteria indicate that pavement rehabilitation analysis and design has strong potential for expert system application.

Differences from Conventional Programs

Expert systems are fundamentally different from conventional computer programs. One principal difference is that an explicit problem-solving algorithm is not needed because a separate knowledge processor determines when, where, and how to apply every individual knowledge element. This is advantageous for many practical problems in which the knowledge is difficult to represent in a numerical form and a sequence of steps that will produce a solution is unknown. In addition, expert systems can readily accommodate nonnumeric, qualitative, or symbolic data; they provide an explanation capability for their conclusions, and utilize a reasonably natural dialogue user interface. Many expert systems can also handle incomplete or uncertain data by making inferences from their own knowledge base; this knowledge base can be updated more easily than the knowledge in a conventional program can because it is separated from the rest of the program.

Figure 1 shows the basic architecture of an expert system. The two main components are the knowledge base and the inference engine, or control process. The knowledge base is the power of an expert system in the sense that it contains all the empirical and factual information for the problem domain. The inference engine searches through the knowledge base or the context to find a conclusion for each subgoal and, thus, the entire problem. The result of the user interface can be that the user is queried for information needed to reach a conclusion. The context is the work space or short-term memory of the system. It stores currently relevant facts and knowledge, successively placed there by the inference engine. Finally, a user-friendly interface contains an explanation module to explain the system's problem-solving strategy to the user, and often contains a knowledge acquisition module to help experts articulate their knowledge in a form acceptable to the system's architecture.

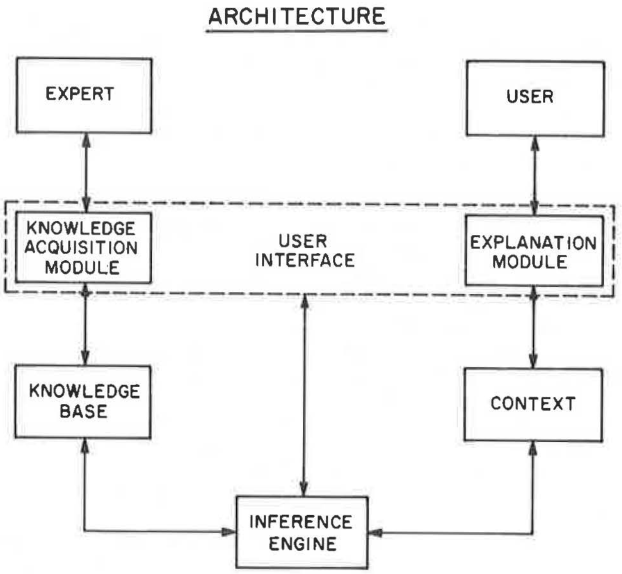


FIGURE 1 Basic architecture of an expert system.

PAVEMENT REHABILITATION

Role of Pavement Management Systems

For many years, state and federal highway agencies have collected pavement condition data with which to make maintenance and rehabilitation decisions. In the past, this was generally done on a project-by-project basis, and the data were used to determine which projects to maintain or rehabilitate and what action was required to correct observed pavement deficiencies. Decisions were made on a year-to-year basis in an environment in which resources (both manpower and money) were usually more plentiful than they are today (1).

More recently (in the past decade), many highway agencies have concluded that they can no longer manage their roadways on the basis of field observations alone. As a result, computerized PMSs have been developed for networks of highways. These systems establish priorities among projects currently in need of maintenance or rehabilitation and the general types of rehabilitation strategies required (often in the form of an annual rehabilitation action plan). The more sophisticated systems also project future pavement performance and the associated need for future rehabilitation strategies to minimize life-cycle costs or maximize net benefits.

An example of the type of pavement performance curve underlying these analyses, for the Washington State Department of Transportation (WSDOT), is shown in Figure 2. Such curves relate the pavement's performance rating to the age of the pavement. The performance rating is a function of a combined ride and surface condition rating. The ride rating is obtained with a Cox Ride Meter, and the surface condition rating reflects a weighted combination of the severity and extent of several types of distress. A pavement in perfect condition has a rating of 100 (15). As indicated in Figure 2, as a pavement ages, its condition gradually deteriorates. WSDOT defines two rehabilitation levels on each performance curve: one in which the pavement should be rehabilitated, and a later one in which the pavement must be rehabilitated. The must level corresponds to a rating of 40, and represents the minimum allowed pavement condition. Beyond this level, temporary fixes may retard the rate of deterioration. When a rehabilitation treatment is applied, the pavement rating increases abruptly and a new performance cycle begins.

A major function of PMSs is programming the rehabilitation process, which results in an objective, optimized mating of rehabilitation needs and available funding. Rehabilitation priority programming also serves as an effective management tool by identifying both those projects that could be implemented at varying funding levels and, conversely, the costs associated with varying levels of service. This flexibility is invaluable when dealing with a state legislature or the general public (16).

Currently only a handful of states actually have operational PMSs, although many are in the process of developing such systems. In addition, applications at the county level are being investigated and appear promising (17), particularly in Washington, which is acknowledged to have one of the most advanced programs in the country (16).

However, a PMS is not a project-specific design tool, and is not intended to be such. It can help identify the locations of pavement problems in a network and general types of solution strategies, but not at the level of detail necessary for design purposes. Most PMSs do not address a basic need of the district, county, or local agency engineer, who may already know where the problems are but is unable to determine (through lack of training, experience, or time) how those problems arose, how serious the situation is, what procedures to follow, what data to assemble, how to interpret those data, how to

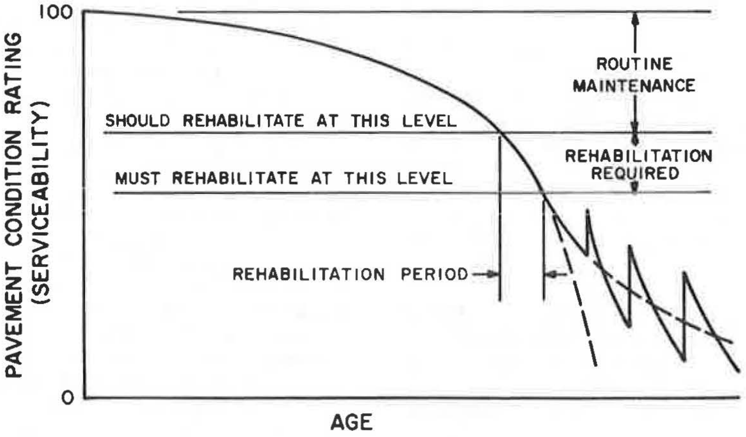


FIGURE 2 Example of WSDOT pavement performance curve.

develop feasible rehabilitation strategies, and how to select an optimal design. The expert system described in this paper represents the first phase (i.e., developing feasible rehabilitation strategies) of more extensive expert systems that will address exactly these analysis and design issues. The respective roles of these expert systems and those of a PMS are therefore different, but complementary.

Surface Condition Evaluation

In theory, the pavement rehabilitation process is composed of at least the following four tasks:

1. Evaluation of pavement surface condition,
2. Analysis and evaluation of structural adequacy,
3. Design of alternative strategies, and
4. Selection of an optimal strategy.

An overall objective of the research described in this paper is to systematically formalize the process by which human pavement experts interpret limited and uncertain data in a specific highway and project context, determine a range of feasible pavement rehabilitation strategies, and develop a recommendation and detailed design for an optimal strategy. After this process is formalized, it can be transformed into an expert system that comprises formal rules necessary for automating the process in a computer program. A first step is therefore to attempt to relate feasible pavement rehabilitation strategies to an evaluation of pavement surface condition. The expert system SCEPTRE 1.1, described in the next section, performs this task.

Although surface condition evaluations provide valuable and necessary information, it is recognized that they do not provide sufficient information for design; such information is obtained from structural adequacy evaluations. However, evaluation of a pavement's surface condition enables a judgment to be made of the adequacy of the existing pavement for current service. It is also used to determine the need for structural evaluation, establish the probable cause of surface distress, and determine the need and establish priorities for maintenance or more extensive rehabilitation. Surface condition evaluations can also indicate the rate of change in pavement conditions and acceptability so that the approximate time for scheduling future work can be predicted (14).

DEVELOPMENT OF SCEPTRE

Description

SCEPTRE 1.1 is the Surface Condition Expert for Pavement Rehabilitation. It evaluates pavement surface distress in order to recommend feasible rehabilitation strategies for detailed analysis and design. SCEPTRE 1.1 is applicable to state-maintained highways and flexible pavements. Rigid pavements will be included in the future. A major effort is also under way to address the needs of bituminous pavements in rural counties.

The major task in building an expert system is to acquire and encode the expertise and knowledge of one or more experts into the knowledge base. The mission of expert system developers (knowledge engineers) is to carry out such a transformation, ensuring that the performance of the resulting system reaches the desired level. The factual and empirical information in the knowledge base can be represented in various ways. The most common is by means of production rules, which take the following format: IF premise THEN action; for example, IF transverse cracking exists AND crack size is at least 1/8 in., THEN fill cracks.

General-purpose programming languages, such as LISP or PROLOG, can be used to build expert systems. However, a much faster route is to use one of several so-called knowledge engineering tool kits (or shells), which comprise an inference engine, empty knowledge base, and context structure. The system developer then simply has to enter the rules into the knowledge base. In the initial prototyping of SCEPTRE reported in this paper, such a shell was utilized, namely EXSYS (18). EXSYS is an expert system development package for IBM personal computers and compatible microcomputers. In the current case, EXSYS was used with a Compaq Portable microcomputer.

The knowledge base for SCEPTRE was derived from the combined expertise of two pavement specialists, with extensive experience of pavement rehabilitation in Washington and Texas.

The following types of surface distress and defects are considered by the system: longitudinal cracking in wheelpath(s), alligator cracking in wheelpath(s), block cracking, transverse cracking and/or longitudinal cracking outside wheelpath(s), and rutting. These are compatible with those used in developing the WSDOT pavement condition ratings discussed earlier. A copy of the actual pavement rating form is shown in Figure 3.

The following is a list of the rehabilitation and maintenance strategies (RAMs), from which a subset is drawn by SCEPTRE to form a feasible set for any particular combination of distress types.

- Do nothing,
- Fog seal,
- Chip seal,
- Double chip seal,
- Make thin asphalt concrete overlay (≤0.10 ft),
- Make medium asphalt concrete overlay (0.10 < thickness < 0.25 ft),
- Make thick asphalt concrete overlay (≥0.25 ft),
- Friction course,
- Fill cracks,
- Reconstruct,
- Hot recycle asphalt concrete,
- Level up, mill, and make medium asphalt concrete overlay (0.10 < thickness < 0.25 ft), and
- Level up, mill, and make thick asphalt overlay (≥0.25 ft).

The knowledge base also contains multiple estimates, both subjective and data based, of the mean survival time (years) and standard deviation of survival time for each RAM in the list just given for various types of distress and other conditions. These estimates, provided by experts, relate to the service life of any rehabilitation strategy until the pavement rating score again reaches the must-rehabilitate level of 40. In the current version of SCEPTRE, this information on service life is used to calculate the probability that a given RAM, under given conditions, will provide acceptable performance for at least as long as a minimum desired service life input by the user. This is believed to be a useful, although approximate, measure of the comparative risk and performance associated with each RAM, and one that can be readily appreciated by potential users. In future versions of SCEPTRE, this information will be complemented by a life-cycle cost analysis for each RAM to provide an indication of the financial impacts of each strategy.

BITUMINOUS PAVEMENTS	RUTTING PAVT. WEAR			
	CORRUGATION, WAVES, SAGS, HUMPS	% Roadway (1) 1-25% (2) 26-75% (3) Over 75%	1/8" - 2" CHANGE / 10 FT.	
			2 - 4" CHANGE / 10 FT.	
			OVER 4" CHANGE / 10 FT.	
	ALLIGATOR CRACKING	(1) Hairline (2) Spalling (3) Spalling & Pumping	1 - 24% WHL. TRK/STA.	
			25-49% WHL. TRK/STA.	
			50-74% WHL. TRK/STA.	
			75-100% WHL. TRK/STA.	
	RAVELING OR FLUSHING	(1) Slight (2) Moderate (3) Severe	LOCALIZED	
			WHEEL PATHS	
			ENTIRE LANE	
			R - RAVELING F - FLUSHING	
	LONGITUDINAL CRACKING	Lineal Ft/Sta (1) 0-99 (2) 100-199 (3) 200 Plus	LESS THAN 1/4"	
			OVER 1/4" WIDE	
			SPALLED	
	TRANSVERSE CRACKING	No. / Station (1) 1-4 (2) 5-9 (3) 10 Plus	LESS THAN 1/4"	
			OVER 1/4" WIDE	
			SPALLED	
	PATCHING	% Area / Sta. (1) 1 - 5% (2) 6 - 25% (3) Over 25%	0.10 - 0.50" THICK	
			0.50 - 1.0" THICK	
			OVER 1.0" THICK	

FIGURE 3 WSDOT pavement rating form.

Selection of Strategies

The selection of feasible RAMs in SCEPTRE is keyed to specific measures of pavement surface distress or defects. A structured approach to deriving project-specific RAMs for each defect type has been used, involving complex decision trees. A similar but much simpler (by comparison) set of procedures was incorporated in the California PMS (16). Such an approach lends itself readily to a rule-based representation of knowledge, as used in SCEPTRE. As an example, for alligator or fatigue cracking in the wheelpath(s), Table 1 gives a list of the levels of information that are utilized in determining RAMs feasible for this distress type; similar procedures are used for other distress types. The list of all feasible RAMs is then refined to include only those appropriate to the distress types for the particular pavement section.

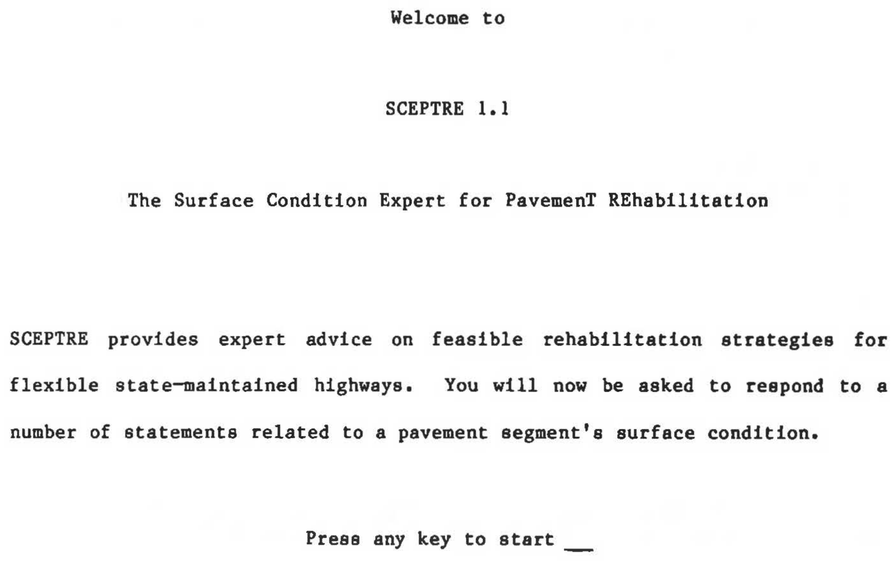
Most of the information SCEPTRE seeks for each project, which is currently input by the user interactively, can be obtained from data files for the WSDOT PMS. A new version of this PMS is currently being developed for counties and local agencies. The authors believe that variations of the surface condition rating surveys used by this PMS, and SCEPTRE, will increasingly be adopted by other states and agencies. SCEPTRE could be modified to accommodate any regional or agency differences.

Figures 4-8 show selected examples of a sample session with SCEPTRE 1.1 (the output has been edited slightly for presentation). Figure 4 shows the log-on welcome-to-SCEPTRE message. Figure 5 shows the starting dialogue for flexible pavements. Figure 6 shows a sample interaction in the case of a segment with alligator cracking in the wheelpath(s). Figure 7 shows part of SCEPTRE's explanation capability. Figure 8 shows an example of the final set of feasible RAMs determined by SCEPTRE for the segment, together with the probability that each RAM will

TABLE 1 SCEPTRE Knowledge-Base Levels for Alligator Cracking in Wheelpath(s)

Level	Description
1. Climate	Region A: marine-dominated climate Region B: high solar radiation, temperature extremes
2. Amount of surface distress	Based on percent length of both wheelpaths distressed: 1. ≤10% 2. 10% < amount < 25% 3. ≥25%
3. Severity of surface distress	1. Hairline cracking 2. Spalling or spalling and pumping
4. Existing pavement performance	Based on predicted or actual life to a rating score of 40[a]: 1. ≤5 years 2. 5 < performance < 10 yr 3. ≥10 yr
5. Traffic levels	1. ADT < 800 veh/lane 2. 800 ≤ ADT ≤ 4,000 veh/lane 3. ADT > 4,000 veh/lane
6. RAMs	See list in text

[a] Pavement life is the time since original construction or the last resurfacing to a pavement condition rating of 40 (based on a scale of 0 to 100).



```
                              Welcome to

                              SCEPTRE 1.1

            The Surface Condition Expert for PavemenT REhabilitation


SCEPTRE provides expert advice on feasible rehabilitation strategies for
flexible state-maintained highways.  You will now be asked to respond to a
number of statements related to a pavement segment's surface condition.


                           Press any key to start __
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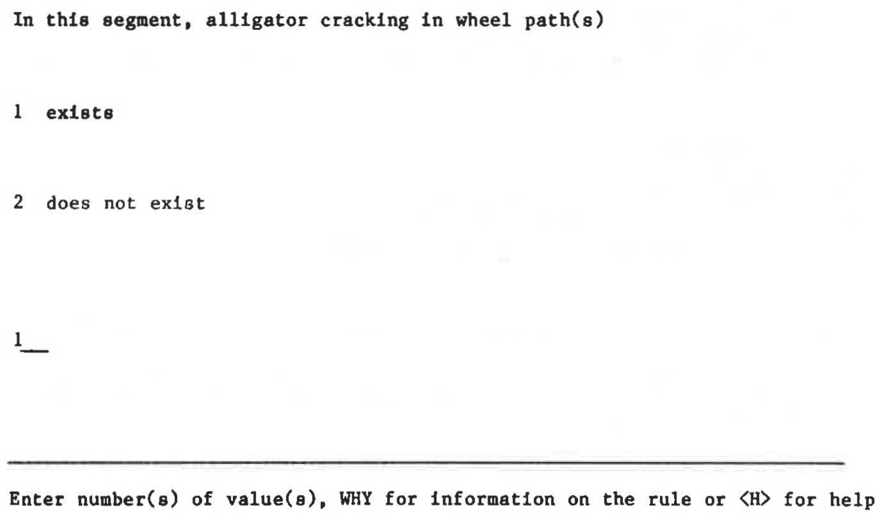
FIGURE 4 Welcome-to-SCEPTRE message.



```
 In this segment, alligator cracking in wheel path(s)

 1  exists

 2  does not exist


 1__

 ________________________________________________________________

 Enter number(s) of value(s), WHY for information on the rule or <H> for help
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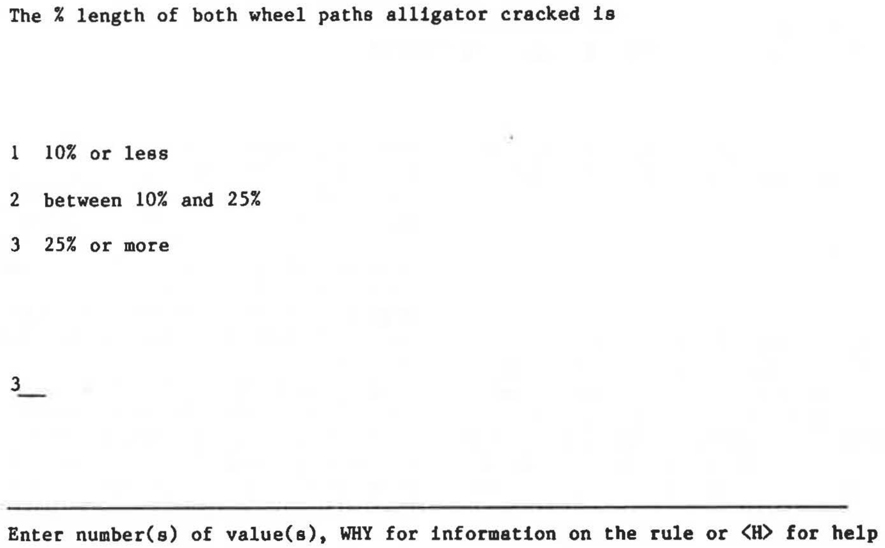
FIGURE 5 Starting dialogue for flexible pavements.



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The % length of both wheel paths alligator cracked is


1  10% or less
2  between 10% and 25%
3  25% or more


3__

________________________________________________________________
Enter number(s) of value(s), WHY for information on the rule or <H> for help
```

FIGURE 6 Sample interaction in the case of segment with alligator cracking in the wheelpath(s).

```
The observed or predicted service life of the existing pavement (to a WSDOT
rating score of 40) is



1  5 years or less
2  between 5 and 10 years
3  10 years or more



WHY



RULE NUMBER:  51



IF:
     (1) In this segment, alligator cracking in wheel path(s) exists
and  (2) The regional climate has high solar radiation and temperature
         extremes
and  (3) The % length of both wheel paths alligator cracked is 25% or more
and  (4) The severity of alligator cracking involves spalling and/or pumping
         and rutting
and  (5) The observed or predicted service life of the existing pavement (to
         a WSDOT rating score of 40) is 5 years or less
and  (6) The AADT on this segment is between 800 veh/lane and 4000 veh/lane


THEN:
         Do-nothing
and      Fog seal
and      Thin asphalt concrete overlay
and      Medium asphalt concrete overlay
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FIGURE 7 Sample of SCEPTRE'S explanation capability.

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

YOUR MINIMUM DESIRED RAM SERVICE LIFE FOR THIS SECTION IS 5 YEARS.
IN THE OUTPUT BELOW, P IS THE PERCENT PROBABILITY THAT THE ACTUAL SERVICE
LIFE FOR EACH RAM WILL BE AT LEAST THIS LONG.

THE LIST OF FEASIBLE STRATEGIES FOR THIS PAVEMENT SECTION IS AS FOLLOWS:

DO-NOTHING                        P =  0% (EXPECTED LIFE = 2 YEARS)
FOG SEAL                          P = 25% (EXPECTED LIFE = 3 YEARS)
THIN ASPHALT CONCRETE OVERLAY     P = 37% (EXPECTED LIFE = 4 YEARS)
MEDIUM ASPHALT CONCRETE OVERLAY   P = 75% (EXPECTED LIFE = 7 YEARS)

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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FIGURE 8 Feasible RAMs determined by SCEPTRE.

equal or exceed the minimum desired service life input by the user; the expected life for each RAM is also displayed.

ONGOING RESEARCH

Ongoing research with SCEPTRE is proceeding on several fronts. It is planned that the expert system be implemented by using an originally developed shell, which will allow greater flexibility in representing knowledge and controlling program operation. This would also facilitate distribution of the program to users. A prototype shell, written in LISP, has already been developed, although at this point only for a mainframe computer. A major effort will be devoted to interfacing SCEPTRE with a PMS data base to further automate the operation of the system and to incorporate pavement performance analysis over time and life-cycle costing for feasible RAMs. The knowledge base will also be expanded to include rigid pavements. To facilitate the system's use as an educational tool, the user interface will be improved significantly and the explanation capability enhanced. Because SCEPTRE is to become part of a larger detailed analysis and design expert system, it is planned to link SCEPTRE's output to design and analysis subroutines, particularly for pavement overlay design.

A significant knowledge engineering effort remains in tackling these issues. Consideration may also be given to linking SCEPTRE's output to a network optimization program to determine optimal project-level RAMs and budgets before performing the detailed analysis and design. The authors believe that the feasibility of the expert system approach to pavement rehabilitation has been proven with SCEPTRE 1.1, and that the research outlined in this paper will make the system a powerful and useful tool.

SUMMARY AND CONCLUSIONS

Rehabilitating the nation's highway infrastructure will continue to require both major effort and investment in years to come. However, the nature of the pavement rehabilitation analysis and design process suggests that a new technological approach, knowledge-based or expert system, could play an important role in addressing pavement rehabilitation problems and needs. Expert systems represent an emerging technology and may revolutionize professional activities in some areas. This paper has presented an overview of expert system characteristics, a discussion of the pavement rehabilitation analysis and design process, and a description of a prototype, microcomputer-based, surface condition expert system (SCEPTRE 1.1) for rehabilitation of flexible pavements. This system will become part of a much larger expert system to assist practicing engineers in analyzing and designing optimal and cost-effective rehabilitation strategies on a project-by-project basis. However, even in its current form SCEPTRE can make its body of specialized knowledge accessible to a broad range of potential engineering users.

ACKNOWLEDGMENT

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