Knowledge-Based Expert System Technology Can Benefit Pavement Maintenance

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Timely and judicious selection of pavement maintenance treatments can significantly extend pavement life. To facilitate this task, an expert system for recommending routing and sealing (ROSE) of asphalt concrete pavements in cold areas was developed. The system incorporates data transmitted by 41 variables, such as pavement serviceability, age, and types of pavement surface distress, and encodes expertise derived from recent research and development studies and from experience. It contains about 360 rules. The system recommendations are given as a desirability of routing and sealing on a scale from 0 to 10. The interactive version of ROSE was developed and calibrated using an expert system development shell. This resulted in significant savings in programming, testing, and calibration. An automatic version of ROSE was implemented in FORTRAN and successfully applied to about 900 pavement sections, representing about 7200 km of highway. This application makes it possible to quantify funding requirements for different routing and sealing policies.

There are many maintenance and rehabilitation treatments that a pavement engineer can use to preserve or improve the way in which asphalt concrete pavements serve the traveling public. Described in this paper is a knowledge-based computer program that can function like an expert when selecting and recommending routing and sealing (R&S) of cracks in cold areas. This computer program, or knowledge-based expert system, was named ROSE. It is a part of a larger knowledge-based expert system for the selection and recommendation of all common pavement preservation treatments *(1)*.

Using R&S as an example, the principal objective of this paper is to show how knowledge-based expert system technology can be used to improve the selection and planning of pavement maintenance and rehabilitation actions.

ROSE was designed specifically for the Ontario Ministry of Transportation and Communications (MTC). It is based on MTC pavement monitoring and evaluation procedures, interacts with the existing pavement management information data bank, and contains the MTC knowledge base (i.e., decision logic for when to rout and seal). Although the direct application of ROSE in other jurisdictions may be difficult or even inadvisable, it is hoped that the methodology and programming approach described herein will have general applicability in other jurisdictions and to other problems.

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An overview of expert systems, including their position in the field of artificial intelligence and description of their architecture and existing applications, can be found elsewhere *(2, 3)*.

ROSE was developed to satisfy the following specific objectives:

- Capture and encode expertise. Readily available knowledge associated with the selection of the routing and sealing treatment, as well as with the selection of other pavement preservation treatments, is not detailed enough to be suitable for direct use. Much of this knowledge is heuristic, unpublished, and dispersed among many users. Gathering and encoding this knowledge within an expert system structure should be especially valuable for organizations that want to capture and effectively use the expertise of senior pavement design and maintenance engineers today and for many years after their retirement. Encoding and computerizing knowledge also forces engineers to carefully organize knowledge by formulating detailed R&S guidelines.
- Provide means for consistent application of R&S guidelines.
- Provide a decision support system for preparation of preservation plans for individual pavement sections.
- Support network-level pavement management decisions. The MTC, and many other agencies, has developed a pavement management data bank that contains section-specific, detailed technical data for hundreds of pavement sections that make up the highway network. This wealth of data should be used to improve management decisions involving the total network.

ROUTING AND SEALING

The objective of R&S is to prevent surface water, particularly water containing deicing salts, from entering and damaging the pavement structure. Routing, usually done with a carbide-tipped circular cutter, opens up a crack to a width of from 20 to 40 mm and a depth of about 10 mm. This opening, cleaned and dried by hot compressed air, is required to accommodate enough sealant (hot-poured rubberized or polymerized asphalt cement) to provide an effective seal even after the pavement contracts at low temperatures *(4)*. Because of continuing improvements in sealants and in routing and sealing technology, it is difficult to estimate the benefits of R&S on the basis of past experience. However, it appears that R&S, if timed and executed properly, can prolong pavement life by about 30 percent

(5 years). This estimate is based on continual observation of seven pavement test sections routed and sealed in 1981, on Highway 17 east of Ottawa, and on long-term observation of many other sealed and unsealed sections.

The MTC has been intermittently routing and sealing asphalt concrete pavements for many years. During the last 2 years, for example, R&S work averaged about $1.5 million in cost. However, the MTC does not have any firm policy for R&S, and opinions differ among MTC personnel regarding its implementation and usefulness.

The economic significance of the R&S treatment should not be judged by its past funding or even required funding. The true economic significance emerges if the benefits of the treatment in prolonging pavement life and its cost are considered. Although a typical cost of R&S for a two-lane highway is about $1,000/km, a typical resurfacing cost is about $40,000/km.

To fully realize the significant benefits of this treatment, *(a)* the pavement sections must be selected judiciously for cost-effectiveness and *(b)* R&S applications must be timely and well executed. ROSE was designed to help pavement engineers with the first part of the task—selecting sections that would most benefit from R&S.

DEVELOPMENT OF ROUTING AND SEALING GUIDELINES

The first step in the development of ROSE was formulation of detailed R&S guidelines. The objective was to capture the best available experience and expertise, not just a general consensus among different practitioners, to be encoded in the system. The developed guidelines are thought to be the best available, but they are not yet official MTC R&S guidelines. Such guidelines may be issued after the results of long-term monitoring of an extensive 1986 experimental R&S program are known. The following brief description is included to outline the main features of the problem solved by the system. The conceptual objective is to demonstrate that, given any guidelines of this nature, expert system technology can play a key role in their implementation.

The guidelines were developed in two stages that correspond to two levels of detail: a macro level and a micro level.

Macrolevel Guidelines

The macrolevel guidelines describe an overall philosophy of R&S and were formulated by studying available literature *(4)* and the performance of existing R&S experimental pavement sections, by interviewing and working closely with one MTC research engineer, and by consulting two other MTC experts. During the interviews, the experts were individually asked whether or not they would recommend R&S for a variety of different pavement sections, with what degree of confidence, and for what reasons. Although some interviews were done in the field, the majority of the interviews was done indoors using pavement deterioration data on existing sections. The macrolevel guidelines made possible construction of a prototype of ROSE.

In general, it is recommended that R&S be used as a preventive pavement maintenance treatment. That is, R&S should be done before the initially formed single pavement cracks deteriorate (ravel; branch out into multiple cracks; or, in the case of transverse cracks, become stepped). On the other hand, it is not always practical to R&S hairline cracks. Also, if there are only a few cracks suitable for R&S, the operation may not be economically viable. Conversely, if cracking is quite extensive, it is usually better to resurface the entire pavement than to rout and seal it.

R&S decisions depend on the following factors in addition to the amount and width of cracks.

- Crack type. It is usually important to rout and seal transverse cracks that follow a course approximately at right angles to the pavement centerline. Transverse cracks directly affect riding quality of the pavement and there is some evidence that R&S may prevent or retard their stepping. As a preventive maintenance treatment, pavement edge cracks may not be routed and sealed and alligator cracks should never be.
- Pavement serviceability. Pavements with low (deteriorated) pavement serviceability should not be routed and sealed. Pavement serviceability was measured using the Pavement Condition Index (PCI) on a scale from 0 to 10 (5).
- Pavement structure. It is particularly important to R&S asphalt concrete overlays placed over portland cement concrete (PCC) pavements. Pavement condition, such as stepping, before overlay placement also affects R&S decisions.
- Presence of pavement distress. Pavement distress, such as raveling, flushing, and rutting, that reaches certain critical levels affects routing and sealing decisions. For example, a pavement section with severe raveling on most of its length should not be routed and sealed.
- Existence of pavement maintenance treatments. The presence of some maintenance treatments, such as spray patching or manual patching, usually makes R&S inadvisable.

Microlevel Guidelines

Microlevel guidelines were developed during the calibration and testing phase with only limited input from experts. The guidelines deal in detail with the influence of all variables and factors affecting R&S decisions. For example, a macrolevel guideline may state that the presence of manual patching reduces chances for cost-effective R&S. The corresponding microlevel guideline quantifies this statement by taking into account all (five) possible density levels used to describe the frequency of manual patching (few, intermittent, frequent, extensive, and throughout).

INTEGRATION AND COMPATIBILITY WITH PMS DATA BASE

Knowledge-based expert systems must be integrated with existing pavement management systems. The pavement evaluation procedure, together with the pavement information data bank, represents a significant investment. This investment is not just in software and data bases but, more important, in personnel knowledge, acceptance of the system, and training. For ROSE to be a useful decision-making tool, it must be integrated and made fully compatible with pavement management processes, including terminology, pavement evaluation

TABLE 1 GUIDE FOR DESCRIBING SEVERITY OF PAVEMENT DISTRESS *(5)*

DISTRESS TYPE / DISTRESS SEVERITY	1 Ravelling and Coarse Aggregate Loss	2 Flushing	3 Rippling and Shoving	4 Wheel Track Rutting	5 Distortion	Single & Multiple Cracks: 6. Longitudinal Wheel Track 8. Centreline 14. Meander and Midlane 15. Random	Single & Multiple Cracks: 12. Transverse (half, full and multiple)	Alligator Cracking: 7. Longitudinal Wheel Track 9. Centreline 13. Transverse	10-11 Pavement Edge Cracking
1 Very Slight	Barely Noticeable	Very faint colouring	Barely noticeable	Barely noticeable (< 6 mm)	Noticeable swaying motion	Crack width < 2 mm Hairline	Crack width < 2 mm Full and partial cracks	Alligator pattern forming Depression < 12 mm	Single longitudinal or single wave-formation
2 Slight	Noticeable	Colouring visible	Noticeable	6 to 12 mm	Good control of car still present	2 to 12 mm width Single cracks	2 to 12 mm width Single full-width cracks	Alligator pattern established with corners fracturing Depression > 12 mm	Multiple parallel longitudinal or wave-formation less than 0.5 m from pavement edge
3 Moderate	Pock-marks well-spaced, open texture	Distinctive appearance with free asphalt	Rough ride Washboard appearance	12 to 19 mm Multiple cracks may be starting	Fair control of car	12 to 19 mm width Multiple cracks starting	12 to 19 mm width Single full cracks with slight cupping or lipping or multiple cracks starting	Alligator pattern established with spalling of blocks Depression > 19 mm	Progressive multiple cracks extend over 0.5 m but less than 1 m from edge. Crack begins to braid.
4 Severe	Pock marks closely-spaced, disintegration, small pot holes	Free asphalt on surface, has wet look	Very rough ride Pronounced washboard appearance	19 to 25 mm May include multiple longi-tudinal cracks	Poor control of car	19 to 25 mm width Multiple cracks, spalling begins to develop	19 to 25 mm width Single full cracks with moderate cupping or lipping, or multiple cracks	Blocks begin to lift, patching required. Depression > 25 mm	Progressive multiple cracks extend over 1.0 m but less than 1.5 m from edge. Begins to alligator.
5 Very Severe	Disintegrated with large pot holes	Wet look with tire noise like wet pavement surface	May cause loss of control of vehicle	Rutting>25mm May include multiple longi-tudinal cracks	Continuous distortion, may be dangerous at speeds > 60 km/h	Width > 25 mm Multiple cracks with spalling developed. May begin to alligator.	Width > 25 mm Severe cupping or lipping, multiple cracks with spalling. May begin to alligator.	Complete disintegration of affected area, pot holes from missing block. Depression > 50 mm	Progressive multiple cracks extend over 1.5 m from edge. Outermost area near edge is alligatored.

methodology, operating practices, and existing computer hardware and software.

The cornerstone of ROSE is the method MTC uses for evaluating and rating pavement surface distress *(5)*. Fifteen types of typical pavement surface distress, given in Table 1, are evaluated. Each type of distress is evaluated separately on a severity scale and on a density scale ranging from 0 to 5. The severity and density of distress are assigned using the guides in Tables 1 and 2, respectively, considering the entire length of the section. The average section length is about 10 km.

Pavement distress data are stored in a pavement management data bank on a mainframe computer. The bank is also designed to store all other pavement-related data that influence R&S decisions, such as pavement age; PCI; and type, extent, and cost of existing pavement maintenance treatments as well as pavement structural characteristics.

SYSTEM ARCHITECTURE

Traditionally, pavement preservation decisions have been made either at a project level or at a network level. Project-level decisions are based on detailed technical information about a specific pavement section. Network-level decisions are based on summary condition information about the entire highway network. Knowledge-based expert systems have the potential to use detailed site-specific data for network-level decisions by operating in two modes *(1)*:

- An interactive mode that queries the user for required input data and is intended to process one pavement section at a time and
- An automatic mode that is designed to interact only with other computer files and programs and is able to process many sections at the same time.

The overall architecture of the two operating modes for ROSE is shown in Figure 1.

Interactive Mode

The interactive mode was developed first using an EXSYS expert system development package *(6)* that runs on IBM-compatible microcomputers. This type of hardware is readily available to the intended users.

Selection of EXSYS was based on a detailed evaluation of several expert system development shells and programming

TABLE 2 GUIDE FOR DESCRIBING DENSITY OF PAVEMENT DISTRESS *(5)*

Class or Code	Description	For all Distresses Except Transverse Cracking [a]	For Transverse Cracking Only
1	Few	< 10%	Cracks (full and/or half cracks) are more than about: 40 m apart
2	Intermittent	10 - 20%	No set pattern. Cracks (full and/or half) are about: 30 to 40 m apart
3	Frequent	20 - 50%	A set pattern. Cracks (full and/or half) are about: 20 to 30 m apart
4	Extensive	50 - 80%	Rather regular pattern. Cracks (full and/or half) are about: 10 to 20 m apart
5	Throughout	80 - 100%	Regular pattern. Cracks (full and/or half) are less than about: 10 m apart

[a] *Based on percent of surface area within the section affected by distress.*

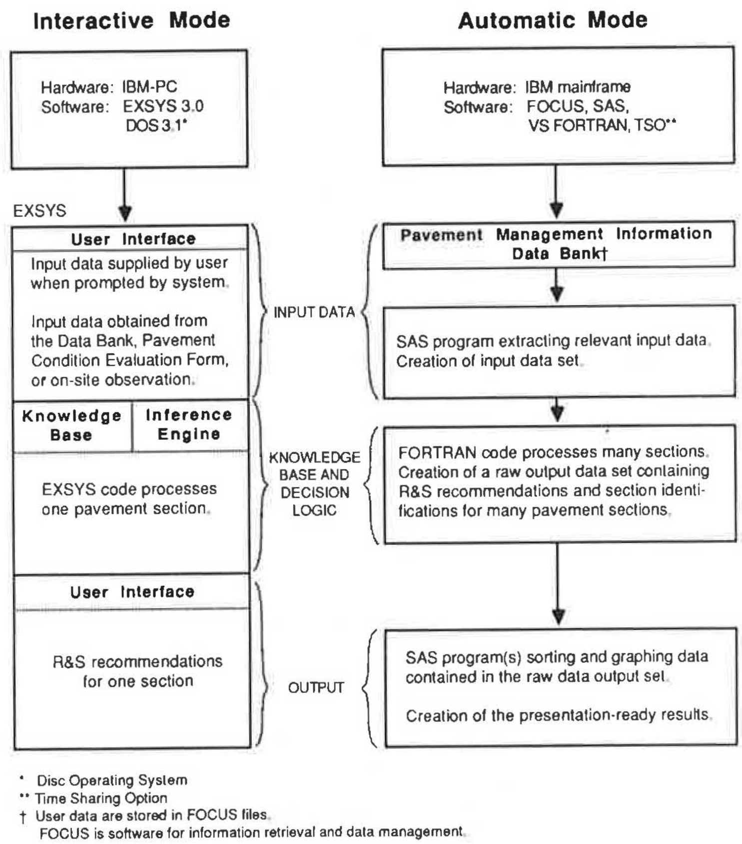

FIGURE 1 Overall architecture of ROSE.

languages *(1)*. EXSYS was selected mainly because of its simple, rule-oriented language and powerful editing capabilities. It has a user-friendly interface that can be used to emulate the interaction a user might have with an expert to solve a problem. It may be also noted that EXSYS has been used previously for a similar problem *(7)*.

EXSYS provides a suitable programming environment for the development, calibration, testing, and running of expert systems for solving structured selection problems. The objective of such problems is a knowledgeable selection from a finite set of possible solutions. In this case, the problem was formulated as the selection from a set of numbers, 0, 1, 2, 3, . . . 10 that were used to indicate the desirability of routing and sealing. For example, definite rejection of R&S is indicated by 0, 5 may be interpreted as "maybe," and 10 means that R&S is highly desirable and is recommended with total confidence as a cost-effective treatment.

The programming was done with "if-then" rules that were used to represent knowledge about R&S. For example, if PCI is 60 or less, then do not R&S. The rules were interpreted by the EXSYS inference engine using backward chaining *(1)*. Prototype development and rule formulation and coding were greatly assisted by the EXSYS editing program and inference mechanism.

Automatic Mode

The interactive version of ROSE (programmed in EXSYS) is incompatible with the existing mainframe-based pavement management data bank. To achieve direct access to the data bank, the EXSYS rules were translated into FORTRAN using, again, the "if-then" format used by EXSYS. The recoding made possible high-speed processing of sections, direct access to the data bank, and subsequent statistical analysis of R&S recommendations obtained for hundreds of sections using SAS programs *(8)*. The purpose and sequence of programming steps are shown in Figure 1.

The bulk of the program development work was data verification and transfer, file access, system integration, and planning. The translation from EXSYS to FORTRAN alone was relatively easy, mainly because the rules in the EXSYS code had already been formulated and arranged to obtain a correct solution *(1)*.

DECISION LOGIC

The major challenge in the development of knowledge-based rules for ROSE was to take into account the influence of 15 types of surface distress in a systematic, quantifiable manner because each of the 15 types can occur at five levels of severity (Table 1) and five levels of density (Table 2) for a total of 375 (15 × 25) different conditions. Each condition may have a slightly different influence on R&S decisions.

In addition to the 15 distress variables, the desirability of R&S is also influenced by another 11 variables (Table 3) for which data are stored in the data bank. The total number of variables or factors considered by ROSE is 41. Of these, 39 are numerical variables—measured on at least ordinal scales. The task was to use the values of these 41 variables and convert

TABLE 3 QUANTIFICATION OF KNOWLEDGE-BASED PARAMETERS

VARIABLE OR FACTOR		EXTENT OR RANGE				
PCI	Range, PCI	0 - 59	60 - 65	66 - 69	70 - 74	75 and up
	CCM	0	0.2	0.5	0.9	1.0
AGE	Range, yr.	1 - 8	9 -12	13 - 15	16 and up	
	CCM	1.0	0.9	0.8	0.7	
MAINTENANCE TREAT.	Extent, %	< 10	10 - 20	20 - 50	50 - 80	80 -100
Manual Patching	CCM	0.9	0.5	0.1	0	0
Machine Patching	CCM	1.0	0.7	0.3	0	0
Spray Patching	CCM	0.9	0.5	0.1	0	0
Rout and Seal Cracks	CCM	1.1	1.0	0.9	0.8	0.7
Chip Seal	CCM	0.9	0.5	0.1	0	0
SECTION LENGTH	Range, km	0 - 10	10 - 15	>15		
	CCM	1.0	1.05	1.1		
Pavement Structural Characteristics						
TOTAL THICKNESS OF ASPHALT CONCRETE	Range, mm	< 50	50 - 70	70 - 90	90 - 100	>100
	CCM	0	0.5	0.8	0.9	1.0
PCC BASE OR PC TREATED BASE	Range, RSP	0	1	2 - 4	5 - 6	7 - 9
	PM	5	7	8	9	10
OVERLAY OF ASPH. CONC. PAV. WITH STEPPED TRANSVERSE CRACKS	Range, RSP	1	2 - 3	4 - 5	6 - 7	8 - 9
	PM	2	4	6	8	10

Legend: CCM - Cracking Condition Modifier. Multiplication Coefficient for R&S Desirability.
RSD - Routing and Sealing Desirability.
PM - Adjusts R&S Desirability according to pavement structural data.

them (using heuristic rules based on the previously outlined R&S guidelines) into one variable: desirability of R&S.

The conversion was done by developing (and calibrating) micro guidelines (based on the macro guidelines) and expressing them as rules. Moreover, to analyze fiscal consequences of R&S decisions, it was also necessary to estimate the amount of R&S for any given section. The inevitable result is a data-intensive solution procedure containing about 360 rules. The following description of the solution procedure and decision logic is abbreviated and includes only the main features.

A general decision model is shown in Figure 2. The model follows the reasoning an expert is likely to use to solve the problem. ROSE considers first the condition of (half, full, and multiple) transverse cracking in terms of severity and density using the variable BASE (as defined in the figure). Values of this variable, for all possible conditions of transverse cracking, are given in Table 4. (All values in Table 4 are based on engineering judgment.) If the condition of transverse cracking is judged to be the deciding factor (BASE $\geq$ 5), the left side of the decision tree of Figure 2 is used, and a preliminary conclusion regarding the desirability of R&S (MODIFIED BASE in Figure 2) is made by including two additional considerations:

- Influence of all of the remaining (14) types of distress. To provide a graduated relationship between the state of the 14 types of distress and R&S desirability, cracking distress modifiers (CDMs) given in Table 4 were established. If more than one of the remaining 14 types of distress were present, a final value of CDM was obtained by multiplying CDM-values for individual types of distress (CDMs are multiplicands).

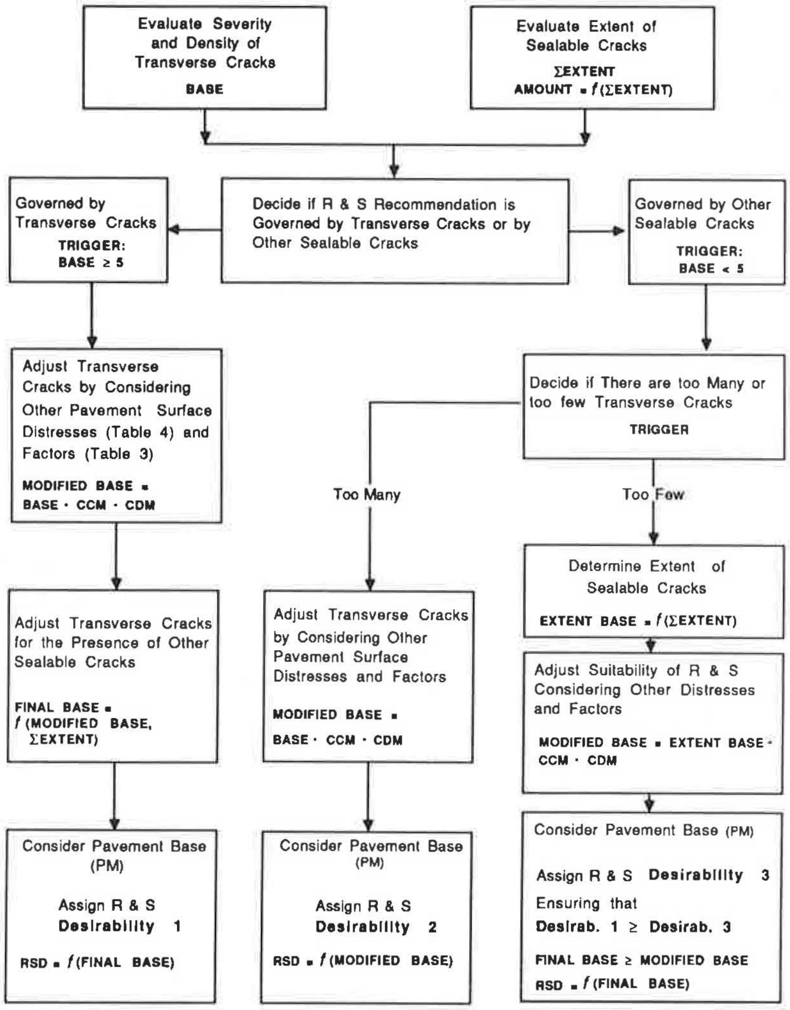

FIGURE 2 General decision model for ROSE.

- Influence of PCI, age, existing maintenance treatments, section length, and thickness of asphalt concrete. The influence of these variables was captured using cracking condition modifiers (CCMs) given in Table 3. For example, if pavement serviceability, measured in terms of the PCI, was below 60, R&S was not recommended (CCM = 0). If the PCI was in the range of 60 to 65, CCM = 0.2. CCMs for pavement age were used to capture a heuristic rule that old pavements with good performance in the past without R&S are not prime candidates for R&S in the future. An analogous approach was used to incorporate the influence of the remaining variables. CCMs were estimated using engineering judgment; operationally, CCMs are also multiplicands.

Next, the desirability of R&S was adjusted (to yield FINAL BASE in Figure 2) by considering the total amount of cracks suitable for R&S (ΣEXTENT) obtained by adding the values of the variable EXTENT (Table 4) estimated for individual types of distress. For example, if an exceedingly large amount of cracks suitable for R&S was detected, the desirability of R&S was reduced. The variable ΣEXTENT was also used to estimate the amount of R&S.

Finally, the influence of pavement structure on R&S recommendations was modeled using PM factors (Table 3). For example, if a pavement section with an asphalt concrete layer was placed over an existing asphalt concrete pavement with distinctly stepped transverse cracks (rather than over an unstepped pavement or over a granular base), its R&S desirability, which was up to this point in the range of, say 8 to 9, was increased to 10.

Returning to the top of Figure 2, if the condition of (half, full, and multiple) transverse cracking was not considered a deciding factor for R&S (BASE < 5), it was assumed that this condition existed because there were either too many or too few transverse cracks. If there were too few transverse cracks (right side of Figure 2), the total amount of cracks suitable for R&S (ΣEXTENT) was considered to assign a preliminary R&S desirability (EXTENT BASE). The preliminary R&S desirability was again adjusted by considering

- The presence of the remaining 14 types of distress (using CDMs of Table 4);
- The influence of PCI, age, and other variables (CCMs, Table 3);
- The influence of pavement base (PMs, Table 3); and
- R&S desirability based only on the condition of transverse cracks.

TABLE 4 QUANTIFICATION OF KNOWLEDGE-BASED PARAMETERS FOR PAVEMENT SURFACE DISTRESS

PAVEMENT DISTRESS MANIFESTATION				DISTRESS CONDITION, SEVERITY AND DENSITY																								
				1. VERY SLIGHT					2. SLIGHT					3. MODERATE					4. SEVERE					5. VERY SEVERE				
NAME			PARAMETER	FEW	INT.	FREQ.	EXT.	THR.	FEW	INT.	FREQ.	EXT.	THR.	FEW	INT.	FREQ.	EXT.	THR.	FEW	INT.	FREQ.	EXT.	THR.	FEW	INT.	FREQ.	EXT.	THR.
CRACKING	Transverse	Half, Full and Multiple	BASE/ TRIGGER	0	1	1	2	3	1	3	7	10	8	7	8	6	5	3	4	2	1	1	0	1	0	0	0	0
			EXTENT	0	0.5	1	2	3	1	2	4	6	8	2	4	5	6	8	3	0	0	0	0	0	0	0	0	0
		Alligator	CDM	0.9	0.4	0.1	0	0	0.8	0.3	0	0	0	0.7	0	0	0	0	0.6	0	0	0	0	0.6	0	0	0	0
	Longitudinal Wheel Track	Single and Multiple	CDM	1	1	1	1	1	1	1	1	1	1	1	0.9	0.8	0.7	0.6	0.9	0.6	0.4	0.1	0	0.7	0.3	0.1	0	0
			EXTENT	0	0.5	1	2	3	1	2	4	6	8	2	4	5	5	7	2	0	0	0	0	0	0	0	0	0
		Alligator	CDM	0.9	0.4	0.1	0	0	0.8	0.3	0	0	0	0.7	0	0	0	0	0.6	0	0	0	0	0.6	0	0	0	0
	Centerline	Single and Multiple	CDM	1	1	1	1	1	1	1	1	1	1	1	1	0.9	0.8	0.7	0.9	0.7	0.6	0.3	0	0.7	0.4	0.1	0	0
			EXTENT	0	0.5	1	1	2	0.5	1	2	4	5	1	2	5	7	9	1	0	0	0	0	0	0	0	0	0
		Alligator	CDM	1	0.7	0.4	0.2	0.1	0.9	0.6	0.3	0.2	0.1	0.9	0.4	0.1	0	0	0.8	0.3	0.1	0	0	0.6	0.2	0	0	0
	Longitudinal Meander and Midlane		CDM	1	1	1	1	1	1	1	1	1	1	1	0.9	0.8	0.7	0.6	0.9	0.6	0.4	0.1	0	0.7	0.3	0.1	0	0
			EXTENT	0	0.5	1	1	2	0.5	1	2	4	5	1	2	4.5	5	7	2	0	0	0	0	0	0	0	0	0
	Random		CDM	1	1	1	1	1	1	1	1	1	1	1	0.9	0.8	0.7	0.6	0.9	0.6	0.4	0.1	0	0.7	0.3	0.1	0	0
			EXTENT	0	0.5	1	1	2	0.5	1	2	4	5	1	2	3.5	3	4	1	0	0	0	0	0	0	0	0	0
	Pavement Edge	Single and Multiple	CDM	1	1	1	1	1	1	1	1	1	1	1	1	0.9	0.8	0.7	0.9	0.7	0.6	0.3	0	0.7	0.4	0.1	0	0
			EXTENT	0	0	0.5	1	1.5	0.5	1	2	3	4	1	2	3.5	3	4	1	0	0	0	0	0	0	0	0	0
		Alligator	CDM	1	0.7	0.4	0.2	0.1	0.9	0.6	0.3	0.2	0.1	0.9	0.4	0.1	0	0	0.8	0.3	0.1	0	0	0.6	0.2	0	0	0
Ravelling and C. Agg. Loss			CDM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.6	0.1	0.1	0	0.4	0.2	0.1	0	0
Flushing, Ripping and Shoving, Wheel Track Rutting, and Distortion			CDM	1	1	1	1	1	1	1	1	0.9	0.9	0.9	0.8	0.4	0.1	0	0.9	0.7	0	0	0	0.6	0.2	0	0	0

Legend:
- BASE - Indicates suitability of transverse half, full & multiple cracks for R&S.
- EXTENT - Approximate relative extent of transverse half, full & multiple cracks.
- TRIGGER - Determines if R&S desirability is governed by transverse cracks or by other sealable cracks.
- CDM - Cracking Distress Modifier. Multiplication coefficient for R&S desirability.
- EXTENT - Approximate relative extent of sealable cracks.

Last, in the case in which too many transverse cracks were deemed to exist to justify R&S, the situation was duly noted as a basic section characteristic and an R&S desirability, however small, was also established.

APPLICATION

The input to ROSE is the present pavement condition. The outputs are R&S recommendations that are considered valid for up to 1 year. This should be acceptable in practice because R&S treatments are not usually planned more than 1 year in advance and any changes in pavement performance during this period are often too small to be measured. Also, the experts interviewed during the development of R&S guidelines worked on the assumption that although their R&S recommendations cannot be implemented immediately, they should be before the end of the next construction season.

In addition to assigning R&S desirability, ROSE also estimates for each section the total amount of cracks recommended for R&S in terms of meter per kilometer of two-lane highway. Further, ROSE classifies each section in one of the following three categories:

1. Sections with too few sealable cracks to warrant R&S next year but that may require R&S in the future,
2. Sections that may require R&S within 1 year, and
3. Sections that already have too many cracks to benefit from R&S.

ROSE was designed to fully use all available surface distress data, and other data stored in the data bank, without any unnecessary assumptions or simplifications. It would be possible to significantly reduce the number of rules (360) by asking the user to input more global data. For example, by asking questions such as "what is the approximate amount of sealable cracks in meters per kilometer?" instead of inputting detailed data and expecting ROSE to calculate the amount.

Both the interactive and the automatic versions of ROSE use identical knowledge base, input data, and decision logic. The exceptions are input data and relations concerning pavement structural characteristics (last part of Table 3). The data bank does not yet contain detailed pavement structural data for all pavement management sections. For this reason, the automatic version assumes that asphalt concrete thickness is about 100 mm or more and that it was placed over a granular base or asphalt concrete base without distinctly stepped transverse cracks. These assumptions are usually met, and in many MTC districts the degree of compliance is about 95 percent.

ROSE was calibrated and tested on about 100 pavement sections, located in different parts of Ontario, until a satisfactory level of system reliability and accuracy was achieved. The calibration was done by using ROSE in the interactive mode and taking advantage of the editing features and the inference engine supplied by EXSYS.

Field verification of the results indicates that the main limitation on the reliability and accuracy of ROSE is the correctness of input distress data obtained from the data bank. This should be overcome with time when it is realized how the use of distress data has been expanded by ROSE.

RESULTS

Interactive Mode

In interactive mode, ROSE can be used as a decision-making or a decision-support system. It performs at the level of a pavement maintenance professional who is roughly in agreement with the R&S methodology embedded in the system and applies this methodology consistently. This assumes that the input data used are the routinely available data taken from the data bank or directly from a field evaluation form *(5)*. However, ROSE does not outperform an expert because the expert, if he or she so chooses, can benefit from evaluating the pavement in situ and obtaining specific, up-to-date pavement deterioration data for the sole purpose of recommending R&S.

Analysis of one pavement section on an IBM XT microcomputer, including supplying data for up to 40 variables, takes about 4 min. ROSE operates as any other well-designed interactive program. In addition, it contains several enhancements. For example,

- The user, when prompted by ROSE for input data, can ask "Why?" ROSE answers why the data are needed. This is done by displaying, on-screen, the first applicable rule for which the data are needed.
- The change and rerun option and the editing program enable the user to easily review and change any input data, or part of the EXSYS code, and rerun the program.

An example of an R&S problem, solved by ROSE in the interactive mode, is shown in Figure 3.

Automatic Mode

ROSE's performance in the automatic mode is excellent. Assuming that an expert cannot visit hundreds of sections and uses the same information as that available to ROSE, ROSE's accuracy is similar to that of a patient and consistent expert and the results are available more or less instantaneously.

The desirability of R&S treatments was evaluated by ROSE for two MTC regions, Southwestern Region and Northern Region, using the most recent pavement deterioration data. In all, 488 sections were evaluated in the Southwestern Region and 396 sections in the Northern Region. The highway networks of the two regions are roughly equal in size and, together, comprise about 7200 centerline kilometers (about 40 percent of the total provincial highway network). An example output listing is given in Table 5. The listing identifies 10 pavement sections in the Southwestern Region that would most benefit from R&S. The sections on the list should be considered prime candidates for R&S in 1987. The distribution of the desirabilities with which the sections were recommended for R&S in the two regions is shown in Figure 4.

ROSE can also be used to evaluate the funding consequences of different R&S strategies. For example, assuming that the cost of R&S is $1 per meter, the R&S cost for all sealable cracks in the Southwestern Region was estimated to be $2.6 million (Figure 5), and the cost for the sections recommended for R&S next year with a desirability of 7 or more was estimated to be $1.2 million.

Given:

A two-lane, 9-km-long, 10-year-old pavement section. It has an 80-mm-thick original asphalt concrete layer placed over a granular base. Its PCI is equal to 70, and the section has only three surface distresses (unusual but simple):

a) Transverse cracking (half, full, and multiple), which is rated as slight and occurring extensively.
b) Centerline cracking (single and multiple) rated as slight and frequent.
c) Wheel track rutting considered to be slight and extensive.

In addition, there are also few manual patches.

Task:

Estimate R&S desirability for this section and the approximate cost of R&S.

Solution by ROSE:

1. Considering transverse cracking, BASE value is 10 (Table 4) and R&S desirability is governed by transverse cracking (Figure 2). EXTENT/TRIGGER is 6.
2. Considering centerline cracking, CDM is 1, and EXTENT is 2 (Table 4).
3. Considering wheel track rutting, CDM is 0.9. (There is no EXTENT because rutting is not a sealable distress.)
4. PCI has the corresponding CCM equal to 0.9 (Table 3), CCM for age is 0.9, CCM for a few manual patches is 0.9, CCM for length is equal to 1, and CCM for total thickness of asphalt concrete is 0.8.
5. MODIFIED BASE = $10 \times 1 \times 0.9 \times 0.9 \times 0.9 \times 0.9 \times 1 \times 0.8 = 5.2$ (based on equation in Figure 2).
6. ΣEXTENT = $6 + 2 = 8$.
7. MODIFIED BASE is adjusted by a multiplication coefficient of 0.9 (the amount of cracks for R&S is considered to be somewhat on the low side) resulting in 4.7 (5.2×0.9).
8. The amount of cracks for R&S (AMOUNT) is estimated to be 663 m/km. The estimate is done using the heuristic equation

   AMOUNT = $104 \times \Sigma$EXTENT $- 165$, where AMOUNT > 0.

Report by ROSE:

1. Desirability of R&S: 5 (rounded from 4.7).
2. Amount of sealable cracks: 663 m/km.

Conclusions:

1. The section may still benefit from R&S. However, do not R&S before considering first sections with R&S desirability higher than 5.
2. Assuming R&S cost of $1 per meter, the total cost is estimated to be $6,000.

FIGURE 3 Example of R&S solution by ROSE.

TABLE 5 LISTING OF ALL PAVEMENT MANAGEMENT SECTIONS IN SOUTHWESTERN REGION WITH R&S DESIRABILITY OF 9

OBS	RSD	LHRS	Offset	Length	DIST	PCI	Age	BASE	RSCG	Amount	Total
479	9	12170	10.0	16.0	1	90	2	10	20	663	10,608.0
480	9	23930	0.6	17.0	1	85	4	8	20	1,183	20,111.0
481	9	29210	4.0	2.9	1	88	4	10	20	559	1,621.1
482	9	47920	0.0	24.0	1	78	5	8	20	923	22,152.0
483	9	29168	0.0	14.0	1	80	6	10	20	455	6,370.0
484	9	11840	0.0	5.5	2	90	6	8	20	1,027	5,648.5
485	9	16190	1.3	16.0	3	91	1	10	20	559	8,944.0
486	9	24070	1.6	18.0	3	86	5	8	20	923	16,614.0
487	9	38400	0.6	23.0	3	75	7	8	20	1,079	24,817.0
488	9	24510	0.0	25.0	3	75	8	8	20	1,547	38,675.0

NOTE: RSD = routing and sealing desirability; OBS = section number (sections are sorted according to RSD; the total number of sections analyzed was 488); LHRS and Offset = section identification parameters used by location referencing system; Length = section length in km; DIST = MTC district number; PCI = pavement condition index; Age = pavement age in years; BASE = defined in Table 4; RSCG = R&S classification category (20 indicates that the section should be routed and sealed within 1 year); Amount = estimated amount of cracks to be routed and sealed in m per km for a two-lane highway; and Total = total estimated amount of cracks to be routed and sealed in m per section.

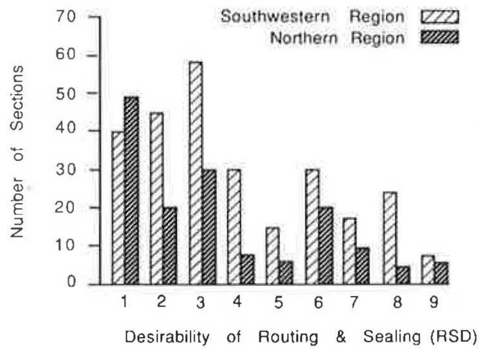

FIGURE 4 Routing and sealing recommendations for all sections in Southwestern and Northern regions.

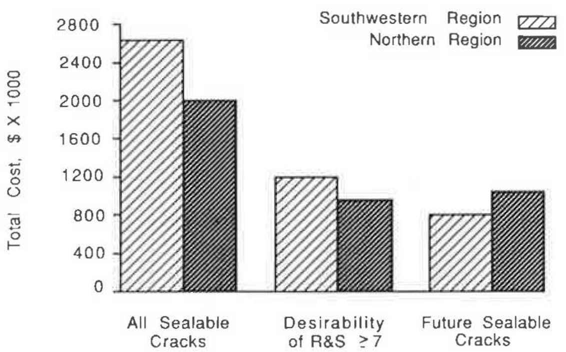

FIGURE 5 Consequences of different routing and sealing policies.

CONCLUSIONS AND RECOMMENDATIONS

Expert system technology can improve the design, planning, and programming of pavement preservation treatments. This can be achieved by efficient and consistent application of the encoded knowledge and experience of many pavement engineers. At a project level, knowledge-based expert systems can recommend routine preservation treatments enabling experts to concentrate on more difficult tasks. At a network level, these systems can quantify the consequences of pavement preservation policy decisions for planning and programming.

The development, testing, and calibration of a prototype version of ROSE were made much easier and more efficient by using the inference engine and editing features of the EXSYS expert system development shell (and, of course, the interactive mode of ROSE runs under EXSYS and uses its user interface). It is thus possible to realize significant productivity advantages in developing prototype expert systems, or other computer programs, using artificial intelligence techniques (for example, mechanical interpretation of the knowledge base by an inference engine), even though the finished expert systems or computer programs may not employ any artificial intelligence techniques *(9)*.

ROSE, a knowledge-based expert system for recommending routing and sealing of asphalt concrete pavements in cold areas, can quickly and reliably analyze and rank pavement sections in terms of their suitability for routing and sealing. The routing and sealing recommendations given by ROSE and their correctness are governed by the preliminary routing and sealing guidelines. Any future changes in the guidelines should be incorporated in ROSE.

Because of huge investments in existing pavement management systems, knowledge-based expert system technology must be integrated and made fully compatible with the existing pavement management processes.

EXSYS, in common with most existing rule-based expert system software, has many advantages, but it does not yet represent an "ideal" programming environment. For example, it requires use of domain rules to create contextual assertions that control the application of other rules.

Because of their potential for increasing effectiveness through improvement of pavement management information, the development of knowledge-based expert systems should continue.

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