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Knowledge-Based Expert System Technology Can Benefit Pavement Maintenance

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Abstract:

The 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 of asphalt concrete pavements in cold areas (ROSE) was developed. The system incorporates 40 numerical variables, such as pavement serviceability, age and pavement surface distresses, and contains about 360 rules.

The system recommendations are given as a desirability of routing and sealing on a scale from 0 to 10. It encodes expertise derived from recent research and development studies and from experience.

The interactive version of ROSE was developed and calibrated using an expert system development shell (EXSYS). This resulted in some 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 highway km. The application enables one to quantify funding requirements for different routing and sealing policies.

Comments:

Key Words: pavement maintenance, expert systems, routing and sealing, preventive maintenance

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1/ INTRODUCTION

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 travelling public. These treatments include, for example, hot-mix patching, installation of pavement edge drains, and milling and resurfacing. The paper describes a knowledge-based computer program which can function like an expert when selecting and recommending one of these treatments; specifically, routing and sealing of cracks in cold areas. This computer program, or expert system, was named ROSE. It is a part of a larger knowledge-based expert system, now under development, for selection and recommendation of all common pavement preservation treatments [1].

Using the routing and sealing treatment 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 the MTC pavement monitoring and evaluation procedures, interacts with its existing pavement management information data bank, and contains the MTC knowledge base, i.e., decision logic when to rout and seal, developed using the latest MTC research results and experience. While the direct applications of ROSE by 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 for other problems.

An overview of expert systems, including their position in the field of Artificial Intelligence, description of architecture, and existing applications can be found in several references [2,3].

Why Use Knowledge-Based Expert System Technology for Pavement Preservation?

The answer to this question should be clear at the end of this paper. However, by way of introduction, some potentially advantageous features of expert systems, as they apply specifically to pavement management, are highlighted in the following:

a) Gathering and Encoding Knowledge

Knowledge associated with the selection of pavement preservation treatments which is readily available (in engineering textbooks, reports and in various guidelines and directives) is not detailed enough to be suitable for direct use. Much of this knowledge is heuristic, unpublished and dispersed among many users. This situation applies particularly to agencies, such as the MTC, administering extensive pavement networks over a large geographical area with a variety of subgrade conditions, load and environmental exposures, and material quality and availability. Gathering and encoding of this knowledge within the expert system structure should be especially valuable for organizations which want to capture and effectively use the expertise of senior pavement design and maintenance engineers today and for many years after their retirement.

b) Systematic and Consistent Knowledge Application

Expert system knowledge rules can encode agency policy and assist in its implementation. For example, if the policy is to use a surface treatment rather than an asphalt concrete overlay if certain conditions are met, an expert system can ensure that the surface treatment alternative is not overlooked.

c) Computerized Application of Knowledge

Many agencies administer highway networks encompassing thousands of pavement kilometres in various stages of repair. For example, the MTC administers about 21 000 centreline kilometres of highways, divided into approximately 2000 pavement management sections. All these sections require, sooner or later, a site-specific preservation treatment. Expert systems can fully utilize all available data for individual pavement sections and can rapidly select practical pavement preservation treatments for all network sections. This can enable one:

i) to analyse funding requirements for different pavement preservation treatments and strategies, as will be illustrated in this paper, and
ii) to optimize the selection and timing of preservation treatments on a network-wide basis by considering all practical treatment alternatives generated by an expert system using detailed, site-specific data [1].

2/ WHAT IS ROUTING AND SEALING AND WHEN TO DO IT

The routing and sealing treatment considered by ROSE is applicable only to asphalt concrete pavements in cold areas. These pavements comprise about 95% of the MTC highway network.

Routing, often done with a carbide-tipped router, opens up the crack to the width of 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]. The objective is to prevent surface water, particularly water containing de-icing salts, from entering and damaging the pavement structure. Because of the continuing improvements in sealants and in routing and sealing technology, it is difficult to estimate the benefits of routing and sealing (R&S) based on past experience. However, it appears that R&S, if timed and executed properly, can prolong pavement life by about 30% (5 years). This estimate is based on continual observation of 7 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 two years, R&S work averaged about $1.5 million in cost. However, the MTC does not have any firm policy for R&S and opinions among MTC personnel regarding its implementation and usefulness may differ.

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 one considers the benefits of the treatment in prolonging pavement life and its cost. While a typical cost of R&S is about $1000 per km, a typical resurfacing cost is about $40,000 per km.

The following R&S guidelines, encoded in ROSE, are based on the latest MTC R&S experience and research. The guidelines have been formulated by the authors. These guidelines are, in our judgement, 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 guidelines were included herein to outline the main features of the problem solved by the system. The conceptual objective of the paper is to demonstrate that, given guidelines of this nature, expert system technology can play a key role in implementing them.

In general, R&S is recommended to 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 the cracking is very extensive, it is usually better to resurface the entire pavement rather than to rout and seal it.

In addition to the amount and width of cracks, R&S decisions also depend on the following factors which are routinely collected or can easily be obtained.

Crack Type -- For example, it is usually most important to rout and seal transverse cracks. These cracks follow a course approximately at right angles to the pavement centreline. Full transverse cracks tend to be regularly spaced along the length of the road, while half transverse and part transverse cracks occur at shorter intermediate distances. 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 Pavement Condition Index (PCI) on a scale from 0 to 100 [5]. Newly-constructed pavements have a PCI of about 95, and rehabilitation is usually done when PCI is between 40 to 60.

Pavement Structure -- For example, it is particularly important to R&S asphalt concrete overlays placed over Portland cement concrete (PCC) pavements. The pavement condition, such as stepping, before overlay placement also affects R&S decisions.

Presence of Pavement Distresses -- such as ravelling, flushing and rutting, reaching certain critical levels. For example, a pavement section with severe ravelling 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.

In summary, the R&S treatment is an important and, indeed, a key preventive maintenance treatment for asphalt concrete pavements in cold areas. However, to fully realize the significant benefits of this treatment, the pavement sections must be selected judiciously for cost-effectiveness, and R&S applications must be timely and well executed, i.e., with appropriate materials and careful application techniques.

3/ INTEGRATION AND COMPATIBILITY WITH PMS DATA BASE.

The cornerstone of ROSE is the method MTC uses for evaluation and rating of pavement surface distresses [5]. The method evaluates 15 typical pavement surface distresses, listed in Table 1, such as ravelling, distortion and centreline cracking. Each distress is evaluated separately on a severity scale and on a density scale, each scale ranging from 0 to 5. The severity and density of distresses are assigned using the guides in Tables 1 and 2, respectively. The evaluation considers pavement conditions on the entire length of the pavement management section and is usually done every second year. The average section length is about 10 km. This evaluation method requires that the sections be selected to exhibit a uniform pavement performance.

Pavement distress data are stored in a pavement management information data bank on a mainframe computer. The bank also stores many other pavement-related data such as pavement age, Pavement Condition Index, and type, extent and cost of existing pavement maintenance treatments, as well as pavement structural characteristics.

The knowledge-based expert systems must be integrated with the existing pavement management systems. Our pavement evaluation procedure, together with the pavement information data bank, represents a significant investment. This investment is not just in software and databases but, most importantly, in personnel knowledge, acceptance of the system, and training. It was made to enable determination of deficiencies, remedial measures and fiscal needs associated with preserving pavements for the travelling public. ROSE addresses the same issues. In order for ROSE to be a useful decision tool, it must be integrated and made fully compatible with the pavement management processes, including terminology, pavement evaluation, operating practices, and existing hardware and software.

4/ SYSTEM ARCHITECTURE

Traditionally, pavement preservation decisions have been done either (a) at a project level, or (b) at a network level. Project level decisions are based on detailed technical information related to a specific pavement section. Network level decisions are based on summary condition information relative to the entire highway network. Knowledge-based expert systems, such as ROSE, have the potential to utilize detailed site-specific data also for network level decisions [1]. However, there are still considerable operational and programming differences, depending on whether the system is expected to process one pavement section at a time or hundreds of sections at the same time.

In response to this dual requirement, ROSE was developed to operate in two different modes:

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

The overall architecture of the system is shown in Figure 1.

a) Interactive Mode

The interactive mode was developed first. The development was done using an EXSYS expert system development package which runs on IBM PC compatible computers [7]. This type of hardware should be readily available to the intended users.

The selection of EXSYS was based on a detailed evaluation of several IBM PC compatible expert system development shells (EXSYS, APES [8], INSIGHT2+ [9]) and programming languages (PROLOG [10], LISP [11], C [12]), using basic evaluation parameters such as those given in Reference 13. The evaluation was done in 1985 and in early 1986. EXSYS was selected mainly because of its simple, rule-oriented language and powerful editing capabilities. It may be also noted that EXSYS has been used previously for a similar problem [14]. In retrospect, one of the main evaluation parameters which might have been used (and which is particularly important if one wants to use the software for several years) is the commitment of the software developer to continuous support and enhancement of its product. However, evaluation of this parameter is rather elusive. The EXSYS version used was 3.0; but version 3.1 is now available and it contains many improvements such as provision for forward chaining as well as backward chaining.

EXSYS provides a very suitable programming environment for the development, calibration, testing, and running of expert systems solving structured selection problems. The objective of such problems is an "intelligent" or knowledgeable selection from a finite set of possible solutions. In our case, the selection was formulated to be from a set of numbers, 0, 1, 2, 3, ... 10 which were used to indicate the desirability of routing and sealing. Definite rejection of R&S is indicated by 0, while 10 means that R&S is highly desirable. The set of numbers can be also interpreted as a probability weighting that R&S is an appropriate, cost-effective pavement preservation treatment for a given section. A rating of 0 indicates that R&S has no chance of being cost-effective, while 10 indicates that R&S is recommended with total confidence as being a cost-effective treatment.

The programming was done in the form of "if-then" rules which were used to represent knowledge about R&S. For example, IF PCR is 60 or or less, THEN do not R&S. The rules were interpreted by the EXSYS inference engine using backward chaining similar to backtracking as used by PROLOG [15]. The function of the inference engine is to decide how to apply the rules -- which rules to invoke and in which order, when and how to infer information from other rules, and when to ask the user for additional information so that a solution can be reached. EXSYS has a user-friendly interface which can be used to emulate the interaction a user might have with an expert to solve a problem. The prototype development and rule formulation and coding was greatly assisted by the EXSYS editing program and the inference mechanism.

EXSYS is not an "ideal" rule-based expert system development shell. An ideal system would enable the user (say knowledge engineer) to enter the if-then rules in an arbitrary order without worrying about each rule's context. As it is, however, the knowledge engineer using EXSYS is still basically a programmer. He or she must formulate and organize knowledge rules in order to control the user interface and to create and control (albeit in an implicit way) the structure and strategies for using domain knowledge. For example, if the system developer wants to ensure that the system quarries the user for data in the same sequence an expert is likely to do (i.e., from general to detail, for all required attributes of one object before moving to the next), he or she must arrange the rules in a specific way.

It must be stressed emphatically that the above limitations apply not only to EXSYS, but to all expert development shells that we have evaluated. Indeed, according to Thompson [16], they apply to a certain extent to all currently available rule-based expert system development software.

b) Automatic Mode

The interactive version of ROSE, programmed in EXSYS, is incompatible with the existing mainframe-based pavement management information data bank. To achieve direct access to the data bank, the EXSYS rules were translated into FORTRAN [17] using again the "if-then" format employed by EXSYS. The recoding enabled high-speed processing of sections, direct access to the data bank, and a subsequent statistical analysis of R&S recommendations, obtained for hundreds of sections, using SAS programs [18]. The purpose and sequence of programming steps is shown in Figure 1.

The bulk of the program development work was made up of data verification and transfer, file access, system integration and planning. The translation from EXSYS to FORTRAN alone was relatively easy because:

a/ The FORTRAN program was used only for recoding rules while main input and output functions were done by SAS programs.

b/ the rules in EXSYS code have been already formulated and arranged to obtain a correct solution.

c/ The FORTRAN version used supports an "if-then-else" syntax which closely matches the rule format employed by EXSYS.

5/ DECISION LOGIC

The major challenge in the development of knowledge-based rules for ROSE was to take into account the influence of 15 surface distresses (given in Table 1) in a systematic, quantifiable manner. For illustration, let's consider the first variable of Table 1, ravelling and coarse aggregate loss, and the following knowledge-based statement:

"If a pavement section exhibits severe ravelling (characterized, according to Table 1, by small potholes) throughout the section (occurring on 80 to 100% of the section according to Table 2), then R&S should not be done".

In other words, no matter what the pavement condition is in terms of the type and extent of sealable cracks, age, thickness or other variables, the presence of this type of ravelling dictates that R&S should be recommended with the desirability equal to 0 or close to it. However, what should the recommendation be if, all other conditions being equal, the severe ravelling occurs on only few locations within the pavement section or ravelling is just moderate and occurs intermittently? Actually, each of the 15 distresses listed in Table 1 can occur at five levels of severity and five levels of density for a total of 375 (15 x 25) combinations.

In addition to the 15 distress variables, each having a severity and a density value, the R&S desirability is also influenced by another 10 numerical variables for which data are routinely collected and stored in the data bank. Our task was to utilize the values of these (40) numerical variables and convert them (using heuristic rules based on the previously outlined R&S guidelines) into one variable: desirability of R&S. Moreover, to analyse fiscal consequences of R&S decisions, it was also necessary to calculate the amount of R&S for any given section. The calculation was based on heuristic estimates (made by the authors) as to how many metres of R&S, if any, a given distress condition may require. The inevitable result is a data-intensive solution procedure containing about 360 rules. Due to space limitations, the following description of the solution procedure and decision logic was abbreviated to include only the main features.

A general decision model is given 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 its 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 3. (All values in Table 3 are based on engineering judgement.) If the condition of transverse cracking is judged to be the deciding factor (BASE > 5), the left-hand side of the decision tree of Figure 2 is used, and a preliminary conclusion regarding the R&S desirability (MODIFIED BASE in Figure 2) is made by considering two additional factors:

a/ Influence of all the remaining (14) distresses. In order to provide a graduated relationship between the state of the 14 distresses and the R&S desirability, Cracking Distress Modifiers (CDM) given in Table 3 were established. If more than one remaining distress was present, a final value of CDM is obtained by multiplying CDM values for individual distresses (CDMs are multiplicands).

b/ Influence of PCI, age, existing maintenance treatments, section length and thickness of asphalt concrete. The influence of these variables was captured using Crack Condition Modifiers (CCM) given in Table 4. 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 an heuristic rule that old pavements with good performance in the past without R&S are not prime candidates for R&S in the future. The CCMs for section length model field experience that long pavement sections often exhibit somewhat non-uniform pavement performance which increases opportunities for effective R&S. An analogous approach was used to incorporate the influence of existing maintenance treatments and the influence of the total pavement thickness (sum of asphalt concrete thickness and PCC thickness, if any). CCMs were estimated using engineering judgement: operationally, CCMs are also multiplicands.

Next, the R&S desirability was adjusted (to yield FINAL BASE in Figure 2) by considering the total amount of other cracks (not including transverse cracks) suitable for R&S, ΣEXTENT, obtained by adding the values of the variable EXTENT (Table 3) estimated for individual distresses. For example, if an exceedingly large amount of other 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 in metres per km.

Finally, the influence of pavement structure on R&S recommendations was modelled using PM factors (Table 4). 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 to be a deciding factor for R&S (BASE < 5), it was assumed that this condition exists because there are either "too many" or "too few" transverse cracks. If there were "too few" transverse cracks (right-hand side of the decision tree, Figure 2), the total amount of other cracks suitable for R&S (ΣEXTENT as defined before) was also considered. Engineering judgement was used to assign a preliminary R&S desirability (EXTENT BASE), considering the combined amounts of transverse and other sealable cracks. The preliminary R&S desirability was again adjusted by considering:

a/ the presence of the remaining 14 distresses (using CCMs of Table 3);
b/ the influence of PCI, age and other variables (CDMs, Table 4); and
c/ the influence of pavement base (PMs).

Lastly, in the case where "too many" transverse cracks were deemed to exist to justify R&S (for example, severe half, full and multiple transverse cracking occurring throughout the pavement section, as defined in Tables 1 and 2), the situation was duly noted as a basic section characteristic and a R&S desirability, however small, was also established.

6/ APPLICATION

Pavement deterioration is a dynamic process and its progression during the next 1 or 2 years is difficult to predict. Any success of such short-term prediction in Ontario depends mainly on success in predicting weather, particularly during the winter and spring break-up periods. Moreover, prediction is required in terms of all 15 pavement distress variables. These variables are interdependent through time [19] and, consequently, the occurrence of many of these variables is highly statistically correlated [20].

In order to avoid the need for pavement performance prediction under these circumstances, ROSE's input is the present pavement condition, while it outputs R&S recommendations which are considered to be valid for up to one year. This should be acceptable in practice since R&S treatments are not usually planned more than one year in advance and any changes in pavement performance during this period are often too small to measure.

In addition to assigning R&S desirabilities, ROSE also estimates, for each section:

a/ the total amount of cracks recommended for R&S in terms of metres per kilometre of 2-lane highway; and

b/ the cost of R&S per section.

Further, ROSE classifies each section as one of the following three categories:

i) sections with too few sealable cracks to warrant R&S next year but which may require R&S in the future,

ii) sections which may require R&S within one year,

iii) sections with too many cracks already to benefit from R&S.

ROSE was designed to fully utilize 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 by:

a/ using more aggregate, global descriptions of pavement surface distresses obtained, for example, by factor analysis techniques [20];

b/ asking the user to input more global data. For example, by asking questions such as "What is the approximate amount of sealable cracks in m per km?" instead of inputing detailed data and expecting ROSE to calculate the amount.

Both the interactive and 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 4). 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%.

ROSE was calibrated, tested and verified on more than 100 pavement sections located in different parts of Ontario, until the authors were satisfied with system reliability and accuracy. 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 regarding the reliability and accuracy of ROSE is the correctness of input distress data obtained from the data bank. This should be overcome with time.

7/ RESULTS

ROSE can be used as a decision-making or a decision support system. In its interactive mode, 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 since the expert, if he or she so chooses, can benefit from evaluating the pavement in situ.

In this case, the expert can carry out an up-to-date evaluation of pavement performance specifically for the purpose of recommending R&S. The routinely collected pavement performance data are intended to satisfy overall pavement management objectives [21] and not just the selection of one particular treatment. Thus, despite the separate evaluation of the 15 surface distresses, some secondary performance characteristics which may have some influence on R&S recommendations (e.g., tendency of the asphalt surface to spall when cracked) are not routinely available. Also, since the distress severity variables are basically categorical (not continuous), a site visit can establish the existence of severity subcategories (e.g., between "slight" and "moderate") and provide additional, more detailed data. On the other hand, while ROSE recommends R&S desirability on the 10-point scale, the expert is likely to express his or her recommendations using only 3 or 4 categories (e.g., priority for R&S is none, low, medium or high). In the interactive mode, analysis of one pavement section on IBM AT computer, including supplying data for up to 40 variables, takes about 4 or 5 minutes.

In the interactive mode, ROSE operates as any other well-designed interactive program. In addition, it contains several enhancements. For example:

a/ The user, when prompted by ROSE for input data, can ask "Why?". ROSE answers why the data is needed. This is done by displaying, on-screen, the first applicable rule for which the data is needed.

b/ The editing program enables the user to easily review and change any part of the EXSYS code. It is also linked to the RUN command so that any changes to the code or input data can be quickly evaluated.

An example of a R&S problem, solved by ROSE in the interactive mode, is given in Table 5.

ROSE's performance in the automatic mode really shines. 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 very patient and consistent expert and the results are available, more or less, instantaneously. Output listing provides, for each section, a section identification, its R&S desirability, the amount of cracks to be routed and sealed, and other parameters. An example output listing, processed by a SAS program (SORT BY region, RSD, DISTRICT), is shown in Table 6. The listing identifies 10 pavement sections in Southwestern Region which would most benefit from R&S. The sections on the list should be considered prime candidates for programming of R&S jobs.

The desirability of R&S treatments was evaluated by ROSE (in automatic mode) for two MTC regions, Southwestern Region and Northern Region (Figure 3). These regions represent different, yet typical, Ontario environments. The evaluation was done, using the most recent pavement performance data, for all pavement management sections stored in the pavement management information data bank. In all, 488 sections were evaluated in Southwestern Region and 396 sections in Northern Region. The highway networks of the two regions are roughly equal in size and, together, comprise about 7200 centreline kilometres (about 45% of the total provincial highway network).

Desirabilities with which the sections were recommended for R&S, and the corresponding costs for these recommendations, are shown in Figures 4 and 5, respectively. For example, about 5.5% of all sections (27 sections) in Southwestern Region were recommended for R&S next year with the desirability of 8, while only 1.5% of the sections (6 sections) in Northern Region were recommended at this level. It should be noted that some sections recommended for R&S may have been sealed once before but require additional sealing (CCMs in Table 4 for the presence of existing R&S are equal or close to 1). Assuming that the cost of R&S is $1 per metre, the cost of R&S for the 26 sections in Southwestern Region, having an R&S probability equal to 8, was estimated to be $300,000 (Figure 5); the corresponding costs for the 6 sections in Northern Region was $150,000 (the sections in Northern Region are longer than in Southwestern Region).

ROSE can be also used to evaluate the funding consequences of different R&S strategies. For example, according to Figure 6, the R&S cost for all sealable cracks in Southwestern Region was estimated to be $2.6 million (assuming unit cost of $1 per metre), 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. The R&S cost for sections for which R&S is not yet recommended, but may become so in the future, was estimated to be $0.8 million.

8/ DISCUSSION

The automatic mode of ROSE is coded in FORTRAN, a common procedural computer language. Therefore, one might ask "Why is ROSE called a knowledge-based expert system?" and, "What has ROSE in common with expert system technology or with artificial intelligence technology?"

To answer the first question, it is realized that the term "expert", as applied to ROSE, does not have a traditional engineering meaning. Engineers usually refer to experts as those professionals who can provide solutions when an unexpected situation arises and textbook engineering solutions fail. The existing expert systems do not deal with unexpected problems. However, it has become customary to call computer programs involving many heuristic factors and rules "expert systems", or knowledge-based expert systems.

Regarding the second question, ROSE benefits from artificial intelligence techniques in several ways. Without expert system techniques, such as knowledge acquisition and coding, and evidence that computers can generate solutions for problems previously considered not amenable to computerization, we would probably not even attempt to develop ROSE. Furthermore, the development, testing and calibration of a prototype ROSE version was made much easier and efficient by using the inference engine and editing features of the EXSYS expert system development package (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 at all [24].

EXSYS, as well as most of the existing rule-based expert system development software, despite many advantages, 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. This has several implications:

a/ The system developer must possess the combined skills of a domain expert and a programmer. Of course, if the development work is done by a multidisciplinary team, this should not be a problem. Also, the in-house programming support, which is usually readily available in large organizations for conventional programming, may not be available for the selected expert system software.

b/ Because the order of the rules and their context may be important, it is not always easy to change the knowledge base (rules).

c/ The system developer may be the only available person to institute any programming changes in the system. Experience shows that the cost and effort required for life-cycle maintenance of computer systems are often quite high.

There is a definite need for better and more powerful expert system development software.

9/ CONCLUSIONS AND RECOMMENDATIONS

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

2. ROSE, an expert system for recommending routing and sealing of asphalt concrete pavements in cold areas, can quickly and reliably analyse and rank pavement sections in terms of their suitability for routing and sealing.

3. 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 also incorporated into ROSE.

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

5. Knowledge systems development software should be further improved to provide a better programming environment for organizing and applying domain knowledge and to lessen the need for including control strategy in the knowledge base.

6. Significant productivity advantages can be realized using expert system technology in prototype development and testing even though the final expert system may use only traditional programming techniques.

7. Expert systems can fully utilize all available data for the selection of practical pavement preservation treatments. These practical treatment alternatives can then be used as input for programs optimizing allocation of pavement preservation funds [25].

8. Due to their potential for increasing effectiveness through improvement of pavement management information, the development of knowledge-based expert systems should continue. The main advantage of these systems is seen in their ability to utilize detailed, technical site-specific data for network-level decisions.

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Table 1/ Guide for Describing Severity of Pavement Distresses

Severity of Distress	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 longitudinal 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 longitudinal 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.

Note: - Crack width should be determined during the period from May to October.
Do not report routed and sealed cracks, these will be reported as Maintenance Treatment.

Source: Reference 5

Table 2/ Guide for Describing Density of Pavement Distresses

Class or Code	Description	For all Distresses Except Transverse Cracking*	For Transverse Cracking Only
1	< 10%	Few	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

** Based on percent of surface area within the PMS section affected by distress.*

Source: Reference 5.

Table 3/ Quantification of Knowledge-Based Parameters for Pavement Surface Distresses

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.

Table 4/ 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 1)	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 1) 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.

Note: 1) – Applies only to pavements with granular or asphalt concrete bases.

Table 5/ Example of R&S Solution by ROSE

Given:
A two lane, 9 km long, 10-year old pavement section. It has 80 mm thick 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 an approximate cost of R&S it.

Solution by ROSE:

1. Considering transverse cracking, BASE value is 10 (Table 3) and the 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 3).
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 4), 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 x 1 x 0.9 x 0.9 x 0.9 x o.9 x 1 x 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 to be R&S is considered to be somewhat on a low side) resulting in 4.7 (5.2 x 0.9).
8. The amount of cracks to be R&S (AMOUNT) is estimated to be 663 m per km. The estimate is done using equation:
   AMOUNT = 104 x ΣEXTENT - 165, where AMOUNT > 0.
   The above equation was developed using engineering judgement.

Report by ROSE:

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

Conclusions:

1. The section may still benefit from R&S. However, do not R&S before considering first sections with higher R&S desirability than 5.
2. Assuming R&S cost of $1 per m, the total cost is estimated to be $6000.

Table 6/ Listing of All Pavement Management Sections in Southwestern Region with R&S Desirability of 9

----RSD=9----

OBS	RSD	LHRS	OFFSET	LENGTH	DIST	PCR	AGE	BASE	RSCG	AMOUNT	TOTAL
479	9	12170	10.0	16.0	1	90	2	10	20	663	10608.0
480	9	23930	0.6	17.0	1	85	4	8	20	1183	20111.0
481	9	29210	4.0	2.9	1	88	4	10	20	559	1621.1
482	9	47920	0.0	24.0	1	78	5	8	20	923	22152.0
483	9	29168	0.0	14.0	1	80	6	10	20	455	6370.0
484	9	11840	0.0	5.5	2	90	6	8	20	1027	5648.5
485	9	16190	1.3	16.0	3	91	1	10	20	559	8944.0
486	9	24070	1.6	18.0	3	86	5	8	20	923	16614.0
487	9	38400	0.6	23.0	3	75	7	8	20	1079	24817.0
488	9	24510	0.0	25.0	3	75	8	8	20	1547	38675.0

LEGEND:

RSD - Routing and Sealing Desirability

OBS - Section number. Sections are sorted according to RSD. The total number of sections analyzed in Southwestern Region was 488.

LHRS, OFFSET } Section identification parameters used by Location Referencing System [22]

LENGTH - Section length in km

DIST - MTC District number

PCR - Pavement Condition Index

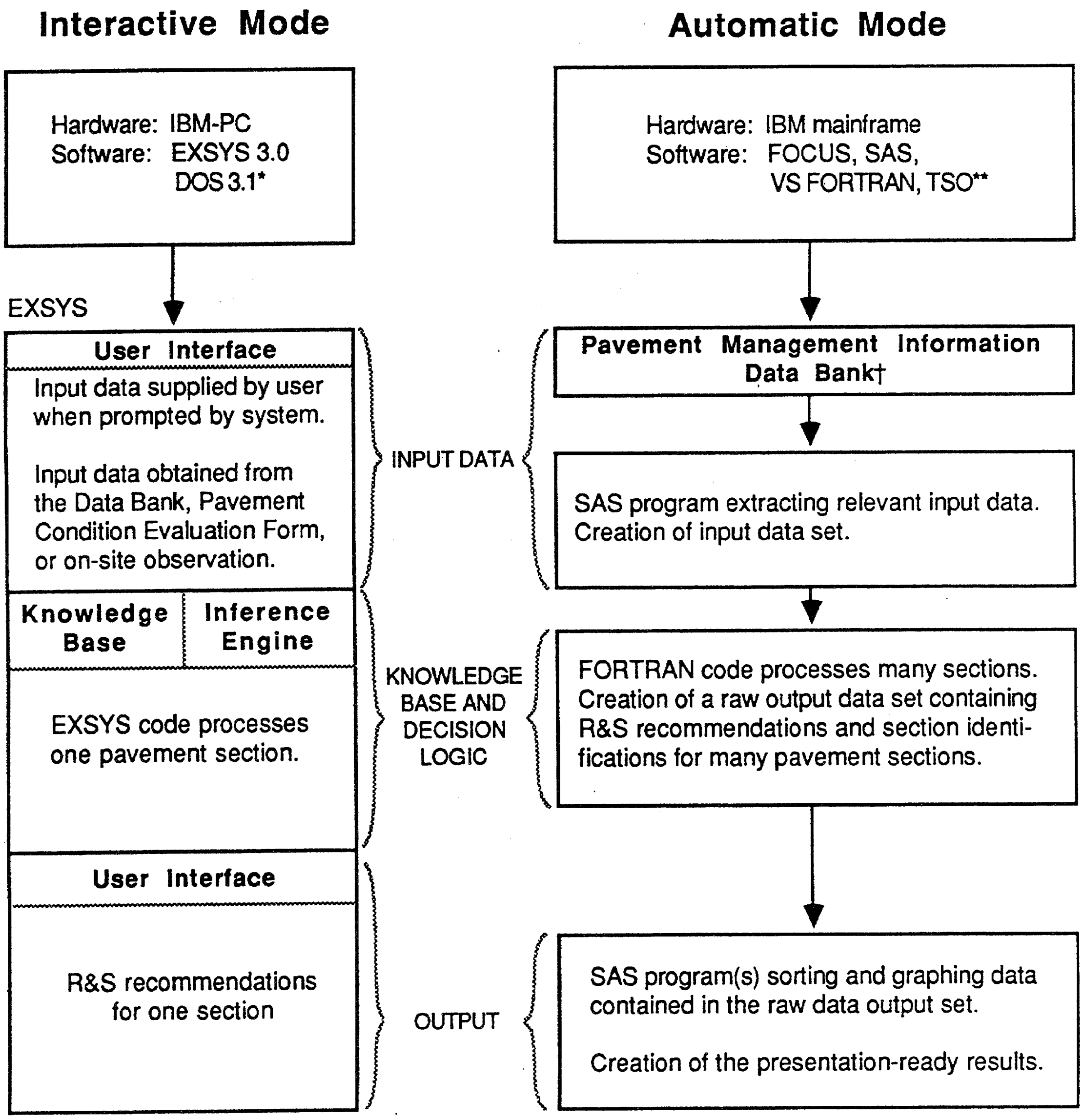
AGE - Pavement age in years

BASE - Defined in Table 3

RSCG - R&S classification category. 20 indicates that the section should be routed and sealed within one year.

AMOUNT - Estimated amount of cracks to be routed and sealed in m per km.

TOTAL - Total estimated amount of cracks to be routed and sealed in m per section



* Disc Operating System
** Time Sharing Option
† User data are stored in FOCUS files.
FOCUS is software for information retrieval and data management [6].

Figure 1/ Overall Architecture of ROSE

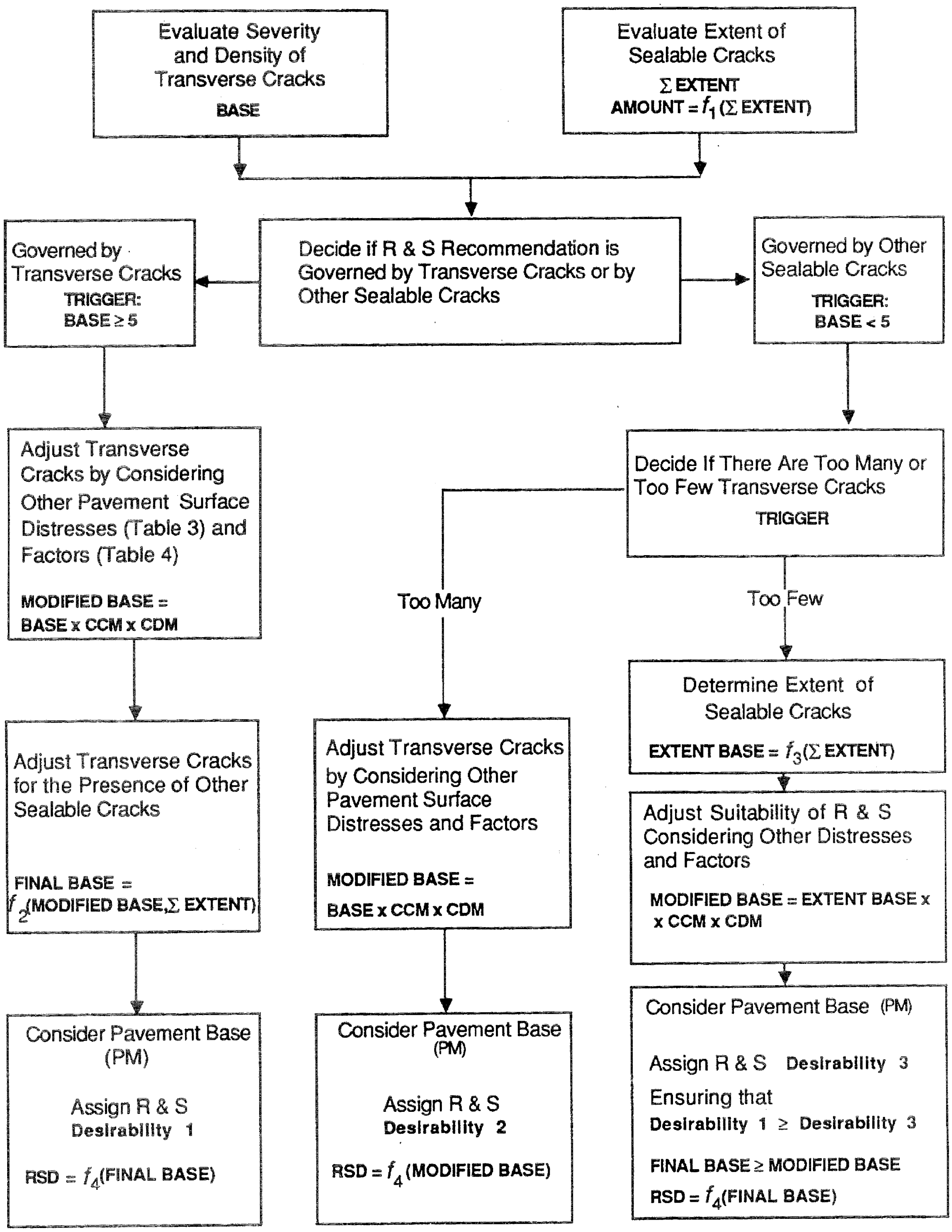
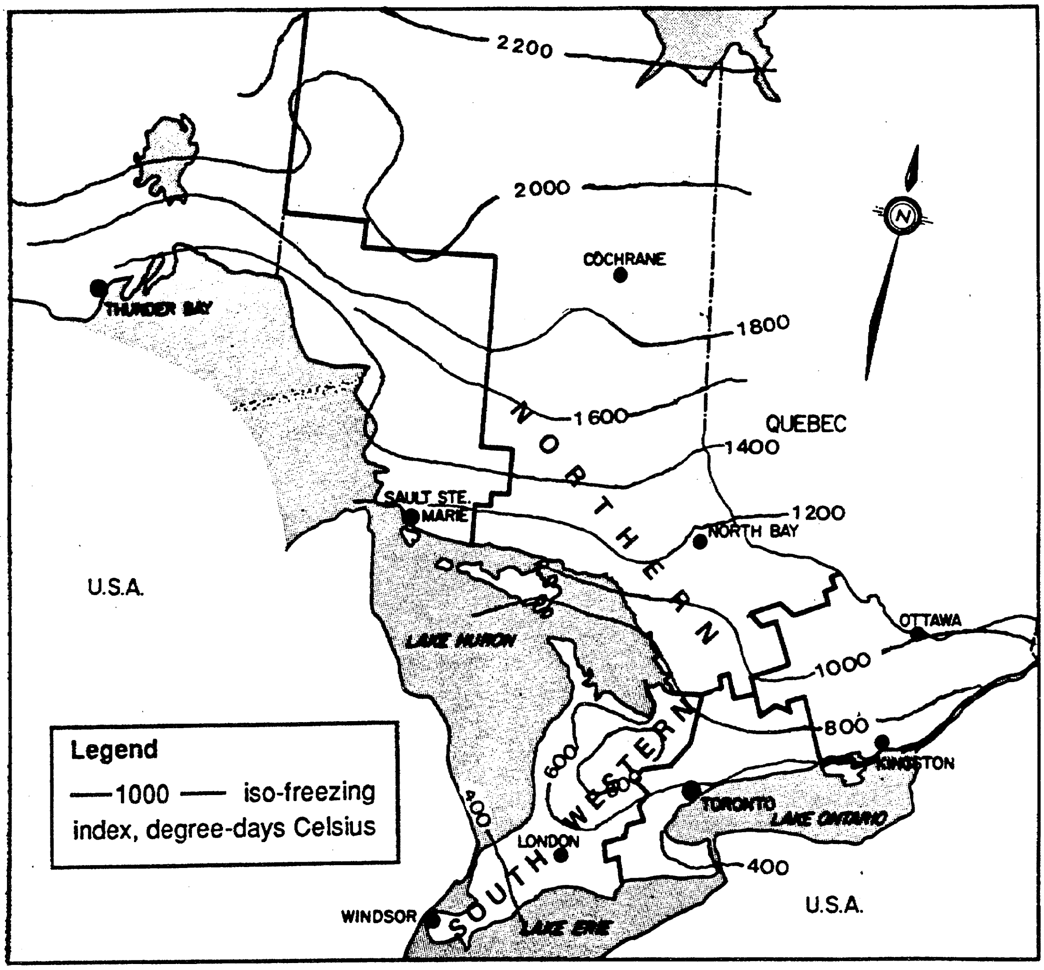


Figure 2/ General Decision Model for R & S Expert System (ROSE)



Source: Reference 23

Figure 3/ Location of Southwestern and Northern Regions

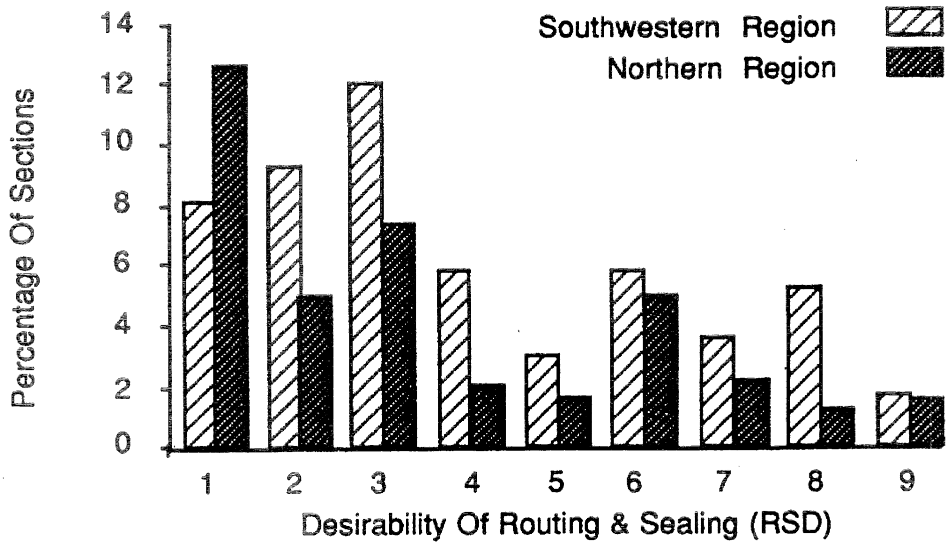


Figure 4/ Routing And Sealing Recommendations For All Sections In Southwestern And Northern Regions

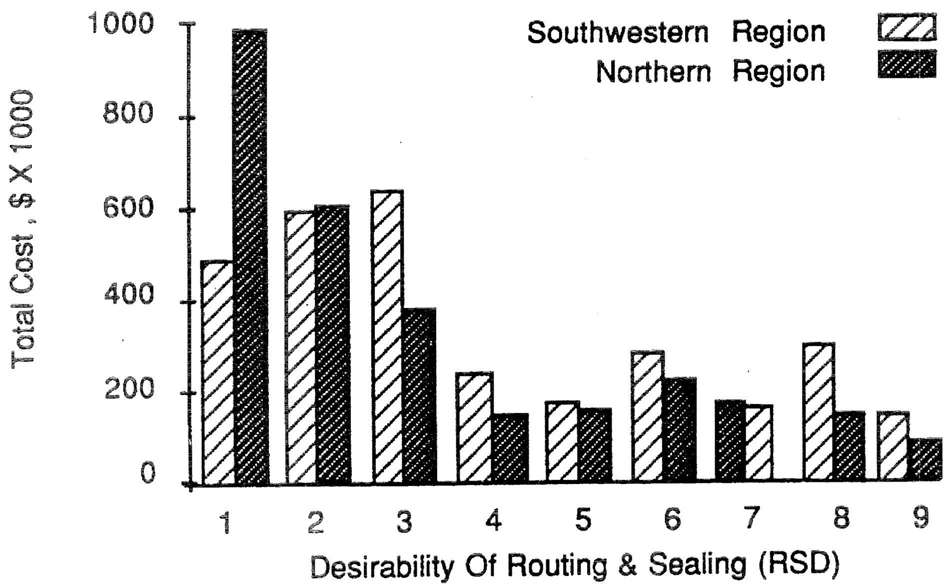


Figure 5/ Cost Of Routing And Sealing Recommendations

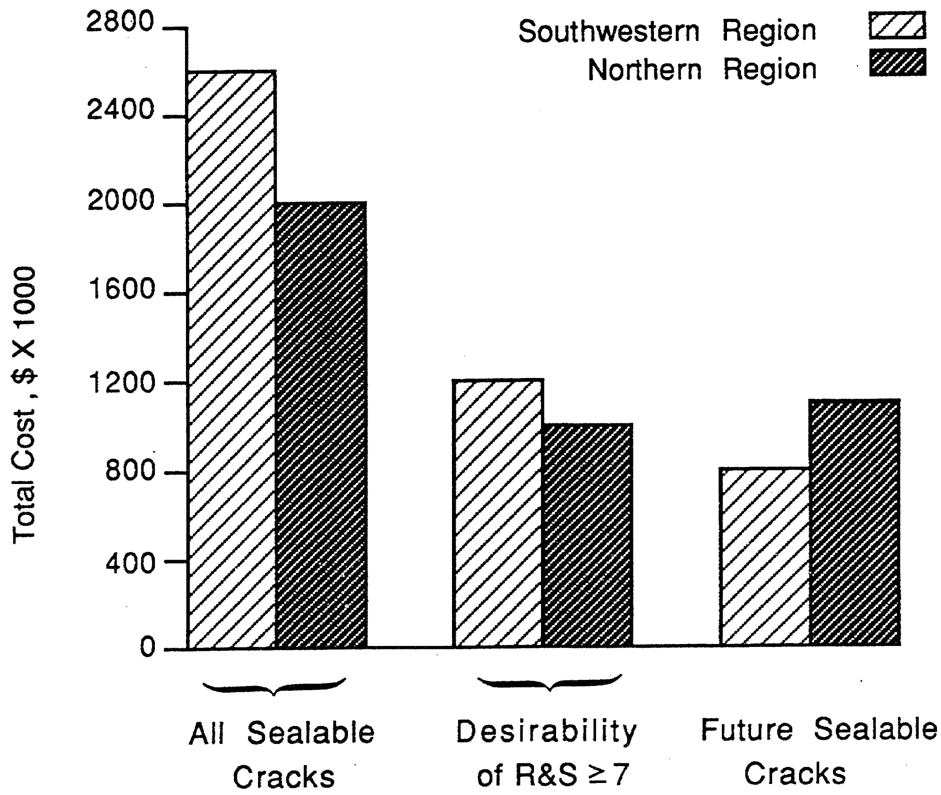


Figure 6/ Consequences Of Different Routing And Sealing Policies