Expert System for Concrete Pavement Evaluation and Rehabilitation

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A prototype knowledge-based system has been developed to assist state highway engineers in project-level evaluation and rehabilitation planning and design for high-type (Interstate) concrete pavements. It uses information provided by the engineer to identify types of deterioration present and determine their causes, to select rehabilitation techniques that will effectively correct the existing deterioration and prevent its recurrence, to combine individual rehabilitation techniques into feasible rehabilitation strategies, and to predict the performance of alternative rehabilitation strategies. Pavement types addressed by the system are jointed reinforced concrete, jointed plain concrete, and continuously reinforced concrete. Predictive models are incorporated into the system to show future pavement performance with and without rehabilitation. These models were developed from national data bases of concrete pavement projects and may be of limited applicability to a specific state's climatic conditions and materials. Interactive computer programs for each of the three pavement types will operate on any IBM-compatible personal computer.

The objective of this research effort was to develop practical and comprehensive systems to assist practicing engineers in evaluating concrete highway pavements, in identifying types of deterioration present and determining their causes, in selecting rehabilitation techniques that will effectively correct existing deterioration and prevent its recurrence, in combining individual rehabilitation techniques into feasible rehabilitation strategies, and in predicting the performance of rehabilitation strategy alternatives.

The system is intended for use by state highway engineers in project-level rehabilitation planning and design for high-type (Interstate) jointed reinforced (JRCP), jointed plain (JPCP), and continuously reinforced (CRCP) concrete pavements. The system does not perform thickness or joint design; the engineer must use existing design procedures to determine these details.

The evaluation/rehabilitation system has been developed in the form of a knowledge-based expert system, which uses information about the pavement provided by the engineer to guide him or her through evaluation of the pavement's present condition and development of one or more feasible rehabilitation strategies. The procedure was developed through extensive interviewing of and interaction with authorities on concrete pavement performance. In addition, predictive models are used to show future pavement performance both with and without rehabilitation.

Evaluation of a pavement and development of feasible rehabilitation alternatives is performed according to the following steps:

1. Project data collection,
2. Extrapolation of project condition over its entire length,
3. Evaluation of present condition,
4. Prediction of condition without rehabilitation,
5. Physical testing as needed,
6. Selection of main rehabilitation approach,
7. Development of detailed rehabilitation strategy,
8. Prediction of rehabilitation strategy performance,
9. Cost analysis of alternatives, and
10. Selection of preferred rehabilitation strategy alternative.

The system has been developed in manual as well as computerized form. An interactive computer program has been developed for each of the three pavement types addressed. The programs operate on any IBM-compatible personal computer. Use of the computer program is highly recommended because of the complexity of the manual procedure.

KNOWLEDGE-BASED APPROACH TO CONCRETE PAVEMENT EVALUATION AND REHABILITATION

Problem Description

Rehabilitation design involves two activities: evaluation of a pavement's present condition, which includes recognition of various types of deterioration and identification of the mechanisms responsible for them; and development of rehabilitation alternatives that will cost-effectively repair the distress and prevent its recurrence (*1*). Distresses are, to use a medical analogy, only symptoms of a problem, and treating the symptoms does not necessarily treat the problem. Quick-fix repairs, which correct the existing distress without arresting the mechanisms that caused it, have a high probability of premature failure and thus are ultimately not cost-effective.

Rehabilitation design requires a good understanding of how pavements perform. However, concrete pavement performance is a complex phenomenon, which is influenced by a large number of factors relating to design, construction, materials, environment, and traffic. These factors interact to influence performance in ways that are not clearly understood. Thus, whereas some aspects of concrete pavement performance can

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be explained by mechanistic models and well-established principles (e.g., calculation of stresses and fatigue damage), many other aspects cannot.

Engineering Problem Solving with Expert Systems

In many areas of engineering, problem solving relies on two different types of knowledge: *deterministic,* which is the body of information that is widely accepted by and available to engineers in the field; and *heuristic,* which is the subjective knowledge possessed by individual engineers, characterized by beliefs, opinions, and rules of thumb (*2*). Difficult engineering problems typically cannot be solved with deterministic knowledge alone, for two major reasons. First, the problem may be so complex that available deterministic knowledge is incomplete. Second, many engineering problems do not have clear-cut right and wrong answers. Finding a "good enough" answer or selecting the best option from among a number of alternatives demands that the engineer apply good judgment. This too requires considerable technical skill on the engineer's part, since these decisions must be based on familiarity with the domain and experience in solving similar problems.

Although deterministic knowledge is preservable in references and textbooks, heuristic knowledge definitely is not. Since it is acquired through individual experience, it is not easily communicated to others and, as experienced engineers retire, it is often lost. The challenge of organizing and preserving heuristic problem-solving knowledge is the basis for development of a relatively new type of engineering tool known as knowledge-based systems. These are computer programs in which heuristic knowledge that has been acquired from humans is utilized to solve problems that are intractable with a purely deterministic approach. A subset of knowledge-based systems are expert systems, which use both the knowledge and the reasoning methods of human experts.

Pavement Evaluation and Rehabilitation with Expert Systems

Pavement evaluation is a *diagnostic* activity, similar to medical diagnosis, in which conclusions about the pavement's condition are drawn from an examination of relevant factual data. Several approaches exist for performing diagnostic activities with knowledge-based expert systems. The approach selected was to develop a decision tree for each major problem area of concrete pavement performance (e.g., roughness, structural adequacy). Decision trees permit factual information as well as reasoning processes to be conceptually expressed and graphically illustrated in a form that is easy to understand, examine, and revise. The paths of the decision trees lead to one or more sentences of text explaining the deficiencies that exist and the factors considered in identifying them. These conclusions are represented by a three-letter code for the major problem area and the number of the specific conclusion reached. The decision tree for structural adequacy of JPCP is shown in Figure 1 as an example.

A pavement evaluation system that can only identify current rehabilitation needs has limited usefulness as a pavement management tool. What about a pavement that does not need rehabilitation now, but will within the next five years? What about a relatively new pavement that does not exhibit much visible distress, but which is inadequately designed or constructed to withstand the traffic loadings and environmental influences that will act upon it over its design life? Deter-

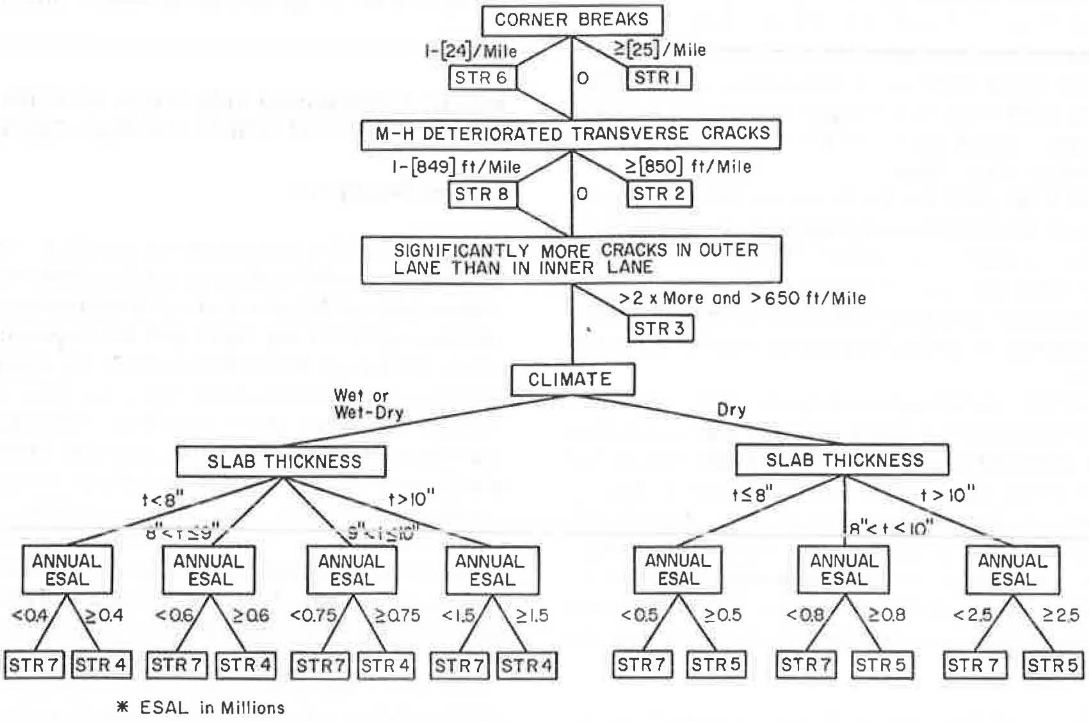

FIGURE 1 Structural deficiency decision tree for JPCP.

ministic knowledge can be applied here, in the form of existing models for predicting concrete pavement performance. A number of predictive models for key concrete pavement distress types are used to project the future condition of the pavement without rehabilitation. The system uses these predicted values to reevaluate the pavement each year for the next 20 years into the future, and identify the years in which deficiencies in the various problem areas will occur. By combining deterministic and heuristic knowledge, the system produces a more comprehensive and useful evaluation than would be possible using either type of knowledge alone.

Unlike evaluation, rehabilitation strategy development is a *design* activity, in which the engineer generates a strategy that satisfies the repair and/or improvement needs identified by the evaluation. Whereas evaluation generally considers a limited set of potential problems, rehabilitation design involves a huge number of combinations of many individual rehabilitation techniques. Generating and evaluating all the possible combinations of techniques would be a formidable task even for a high-speed computer, if done using conventional programming methods. Using an expert system approach, however, rehabilitation strategies can be developed much more quickly and easily by generating *only feasible combinations* of techniques, thus greatly reducing the number of strategies that the engineer must consider. The system does this by applying restrictions on the generation of strategies that reflect heuristic knowledge about the compatibility of various techniques.

After one or more feasible rehabilitation strategies has been developed, the engineer must still choose the best alternative on the basis of life-cycle cost and other selection criteria. However, the engineer cannot perform a life-cycle cost comparison of alternatives without some idea of their expected lives. Deterministic knowledge can be applied here, by using available models for predicting rehabilitation performance in terms of key distress types. Several such models were developed in this study and incorporated in the system. Thus in rehabilitation, as in evaluation, deterministic and heuristic knowledge are combined to improve the quality of the problem solution.

Implementation of the System

One approach to knowledge-based system development is to implement a prototype with a commercially available, off-the-shelf software tool known as a "shell" which provides a suitable development environment (text editor, compiler, and so on), and then to rewrite the system for maximum efficiency when most of the difficult development is finished (*3*). Initially, a shell was used to develop a demonstration prototype for the evaluation portion of the system. The shell used was Insight 2+ (developed by Level V Research, Inc.). Insight 2+ is a production-rule-based system shell, meaning that knowledge is expressed in terms of "if-then" rules. To incorporate the decision trees into the Insight 2+ shell, each path down each tree (a path being composed of a set of nodes and connecting branches terminating at a conclusion) was programmed as a single rule. The decision trees impose a structure on the solution strategy that would not exist in a typical production rule system.

Although the production rule approach using Insight 2+ was helpful in initial prototyping, it soon became too restrictive for continued development of the system. Representing the decision trees with a set of rules was inefficient and unwieldy. Long compilation and execution times slowed the development of the system and detracted from the program's ease of use. It was also very difficult to interface the decision trees with other sections of the system (e.g., data entry and retrieval). To circumvent the limitations of the system as implemented in the shell, the system was rewritten using Turbo Pascal (Borland International, Inc.). This transformation changed the system from a traditional production rule system to a hard-coded system. Hence, some of the transparency of the knowledge was lost, and modifications became more difficult. These problems were more than offset, however, by the increased ease of interfacing the different parts of the system, the ease of programming the predictive models for future performance with and without rehabilitation, and the 10-fold increase in execution speed.

DESCRIPTION OF EVALUATION AND REHABILITATION SYSTEM

The expert system consists of three separate computer programs, one for each of three concrete pavement types (JRCP, JPCP, and CRCP). The steps in evaluation and rehabilitation design are the same in all of the programs.

Project Data Collection

The engineer collects key inventory (office) and monitoring (field) data for the project. Inventory data include design, traffic, materials, soils, and climate. Monitoring data include distress, drainage characteristics, rideability, and other items collected during a field visit to the project. Monitoring data are collected by a sample unit; a sufficient number of sample units distributed throughout the project's length should be surveyed to obtain an accurate representation of the project's condition. The data are entered into a personal computer using a full-screen editor.

Extrapolation of Overall Project Condition

The overall condition of the project is extrapolated by the system from the sample unit monitoring data, and extrapolated distress quantities are summarized.

Evaluation of Present Condition

Evaluation decision trees are used to analyze all data and to develop a specific detailed evaluation in each of the major problem areas identified for that type of pavement. These consist of the following seven areas for all three pavement types: roughness, structural adequacy, drainage, foundation stability, concrete durability, skid resistance, and shoulders. JRCP and JPCP are evaluated in five additional problem areas: transverse and longitudinal joint construction, transverse joint sealant condition, loss of support, load transfer, and joint deterioration. JCRCs are evaluated in two additional problem areas: longitudinal joint construction and construction joints/terminal treatments.

In several of the problem areas, certain distress quantities and present serviceability rating (PSR) levels are considered indicative of deficiencies. Default values for these critical distress levels are incorporated in the system. The engineer may modify these default values if desired to reflect his or her own experience or agency policies.

Prediction of Condition Without Rehabilitation

Current traffic level [annual 18-kip equivalent single axle load (ESAL)] and anticipated ESAL growth rate are used in predictive models to project the condition of the pavement for 20 years into the future, to illustrate the consequences of not performing rehabilitation in the current year. Performance is predicted in terms of serviceability and key distress types: faulting, cracking, joint deterioration, and pumping for JRCP and JPCP, and failures (punchouts, steel ruptures, and full-depth repairs) for CRCP. The predictive models are calibrated to the existing condition of the pavement and cumulative traffic loadings at the time of the survey.

Physical Testing

The initial data collection does not require physical testing. On the basis of the evaluation results, the system recommends specific types of physical testing needed to verify the evaluation recommendations and to provide data needed for rehabilitation design. Types of testing that may be recommended include nondestructive deflection testing, destructive testing (coring and boring), laboratory testing, and roughness and friction measurement. Types of deficiencies that may warrant physical testing include structural inadequacy, poor rideability, poor surface friction, poor subdrainage conditions, poor concrete durability (D-cracking or reactive aggregate distress), foundation movement (due to swelling soil or frost heave), loss of load transfer at joints, loss of slab support, joint deterioration, and evidence of poor joint construction.

Selection of Main Rehabilitation Approach

On the basis of the evaluation results, the engineer then interacts with the system to select the most appropriate main rehabilitation approach for each traffic lane and shoulder. These include all 4R options: reconstruction, recycling, resurfacing (with concrete or asphalt), or restoration. A decision tree has been developed for each pavement type to assist the engineer in selecting the most suitable rehabilitation approach. The decision tree for JPCP is shown in Figure 2.

Development of Detailed Rehabilitation Strategy

Once an approach is selected, the engineer proceeds to develop the detailed rehabilitation alternative by selecting a feasible

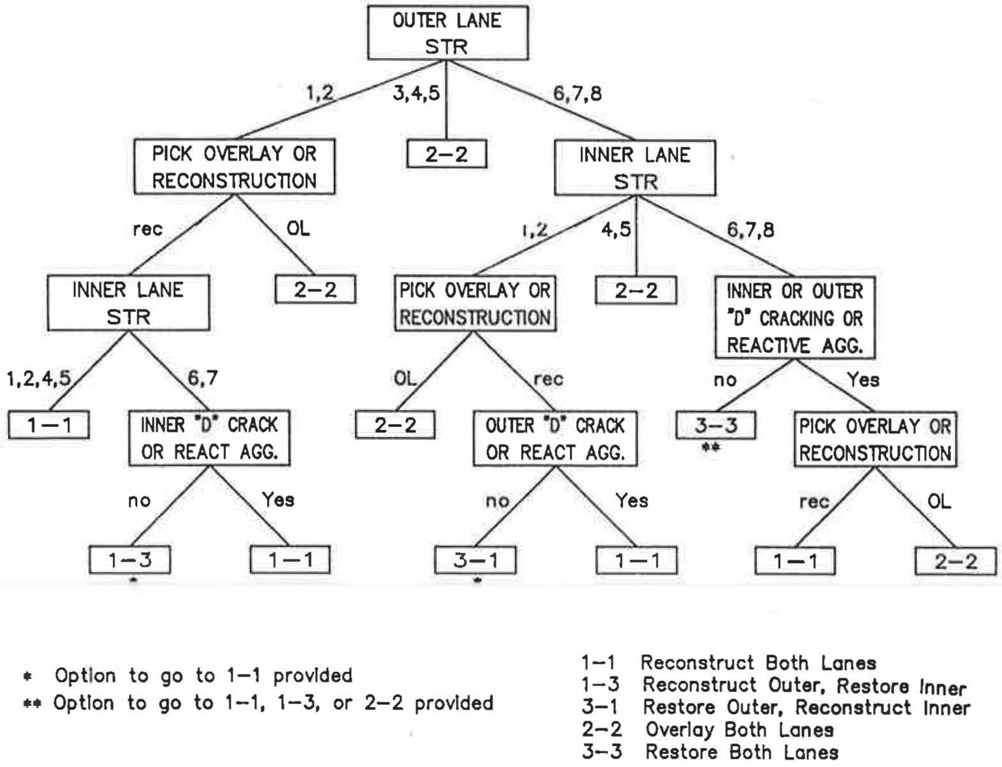

FIGURE 2 Decision tree for selecting rehabilitation approach for JPCP.

set of individual rehabilitation techniques to correct the deficiencies present. These techniques may include such items as subdrainage, shoulder repair, full-depth repairs, and joint resealing. These are performed for each traffic lane and shoulder by interaction with the system. A set of decision trees has been developed to guide the rehabilitation strategy development process.

Prediction of Rehabilitation Strategy Performance

The future performance of the developed rehabilitation strategy is then predicted in terms of key distress types for 20 years into the future, based upon assumed traffic growth. Faulting, cracking, joint deterioration, and present serviceability rating (and punchouts for CRCP) are projected for concrete restoration, overlays, and reconstruction. Rutting and reflection cracking are projected for asphalt overlays.

Since the system currently addresses only pavements in their first performance period, the strategies developed do not include future maintenance or rehabilitation. The *life* of the strategy is defined as the length of time that the strategy extends the pavement's life, i.e., until a critical level in serviceability or distress is reached. For many strategies the life will be less than the 20 years for which projections are provided. The engineer must evaluate the results and determine whether or not the strategy provides an acceptable life. If so, a cost estimate can be prepared for it. If not, the engineer can develop other rehabilitation strategy alternatives.

It must be noted that most of the predictive models used by the system have significant limitations and should not be used outside the ranges of data from which they were developed. The models should be evaluated for validity with respect to the pavement designs and climatic conditions of the state in which the project under consideration is located.

Cost Analysis of Alternatives

Approximate quantities for each rehabilitation technique included in the alternative strategy are computed from the extrapolated distress quantities for each lane and shoulder. The engineer then must compute the cost for each item and total all costs for the strategy. The engineer then determines the life of the strategy as described above and computes an annual cost for the strategy.

Selection of Preferred Rehabilitation Strategy Alternative

Typically two to four feasible strategies exist for a given project. To select the preferred alternative, the engineer must consider not only life-cycle cost but also constraints that exist for the project, such as traffic control, construction time, and available funding. On the basis of estimated initial and annual costs, expected life and performance, and various constraints, the engineer selects the preferred rehabilitation strategy from among the feasible alternatives available.

APPLICATION OF EVALUATION AND REHABILITATION SYSTEM

Project Description

A 7.5-mile section of Interstate 10 near Tallahassee, Florida, was surveyed on September 30, 1986. The pavement is a 9-inch JPCP over a cement-treated aggregate base and a silty (A-4) subgrade. The joints are undoweled and are spaced uniformly at 20 feet. The shoulders are asphalt concrete. This section of Interstate 10 was constructed in 1974. Its two-way average daily traffic (ADT) at the time of the survey was 12,000 (40 percent trucks). Approximately 5.6 million and 0.8 million ESALs had been accumulated in the outer and inner lanes, respectively, over the life of the pavement.

Evaluation of Present and Future Condition

The project was evaluated in 12 problem areas defined for JRCP. In general, the outer lane was in significantly worse condition than the inner lane. Observed distresses included pumping, joint and crack faulting (0.08 and 0.18 in. in the inner and outer lanes, respectively), longitudinal cracking (26 and 116 ft/mile in the inner and outer lanes, respectively), transverse cracking (948 ft/mile in the outer lane), corner breaks (11/mile in the outer lane), and poor sealant condition noted for both lane/shoulder joints. The predicted future performance of the pavement without rehabilitation is illustrated for PSR and three key distresses in Figure 3 (joint deterioration, which is predicted to be negligible over the next 20 years, is not shown).

Rehabilitation Strategy Development and Performance Prediction

The outer lane of this section of I-10 has a sufficient amount of cracking to warrant a structural improvement. The rehabilitation approaches permitted by the system for this example include bonded and unbonded concrete overlays, asphalt overlay, crack and seat and asphalt overlay, reconstruction of the outer lane only, and reconstruction of both lanes.

For each of these alternatives, rehabilitation techniques for each lane and shoulder were selected by interaction with the program, and the strategy's performance over the next 20 years was predicted. A set of techniques making up an AC overlay alternative is shown below as an example:

Rehabilitation Technique	*Quantity*
Outer lane	
AC structural overlay	52,941 yd^2
Full-depth repair of cracks	15,882 yd^2
Stitch longitudinal cracks	874 ft
Subseal at joints and cracks	1,936 ft^3 of grout
Install/repair longitudinal subdrains	39,706 ft
Inner lane	
AC structural overlay	52,941 yd^2
Outer shoulder	
AC overlay	44,117 yd^2
Reseal lane/shoulder joint	39,706 ft
Inner shoulder	
AC overlay	26,470 yd^2
Reseal lane/shoulder joint	39,706 ft

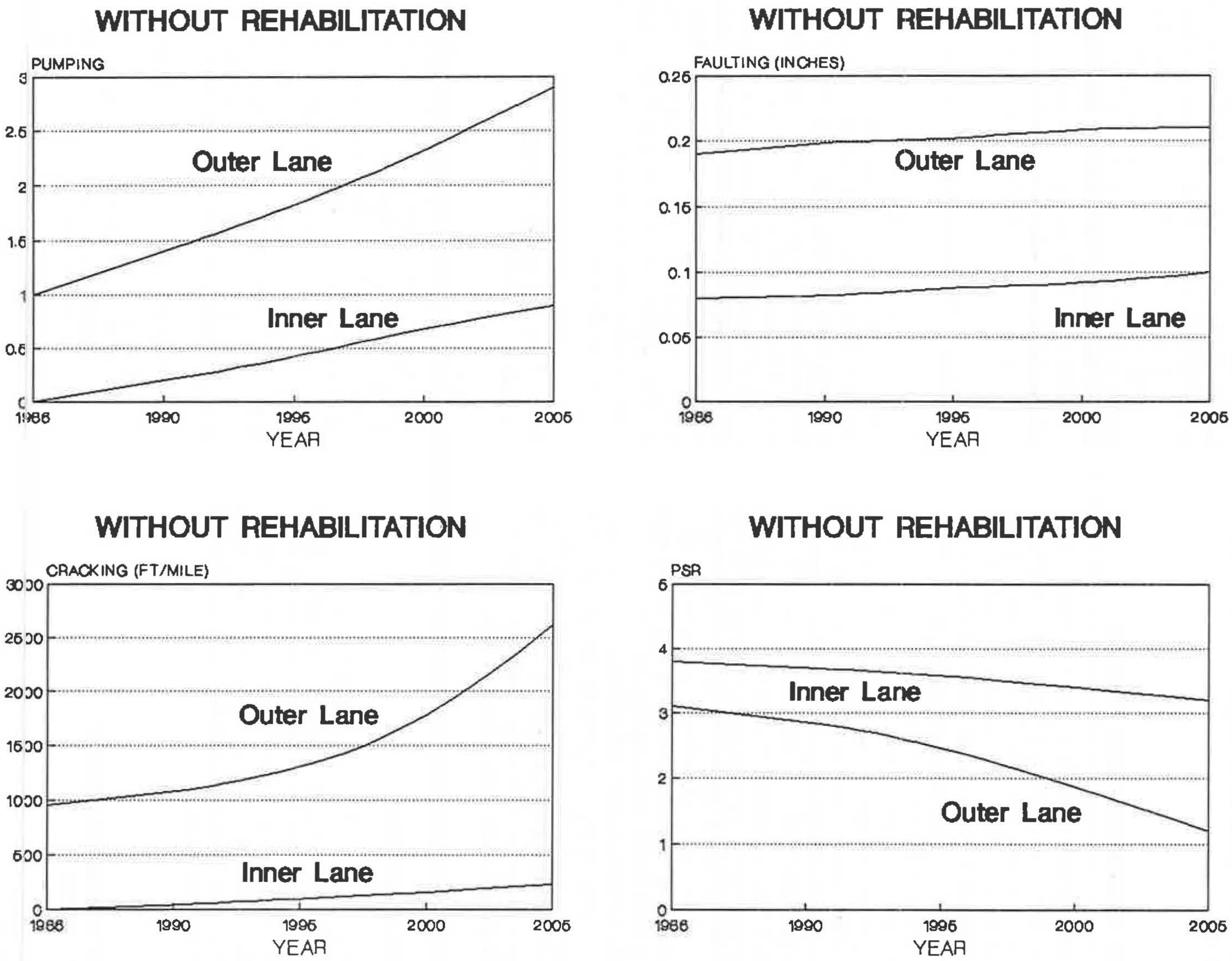

FIGURE 3 Predicted performance of I-10 example without rehabilitation.

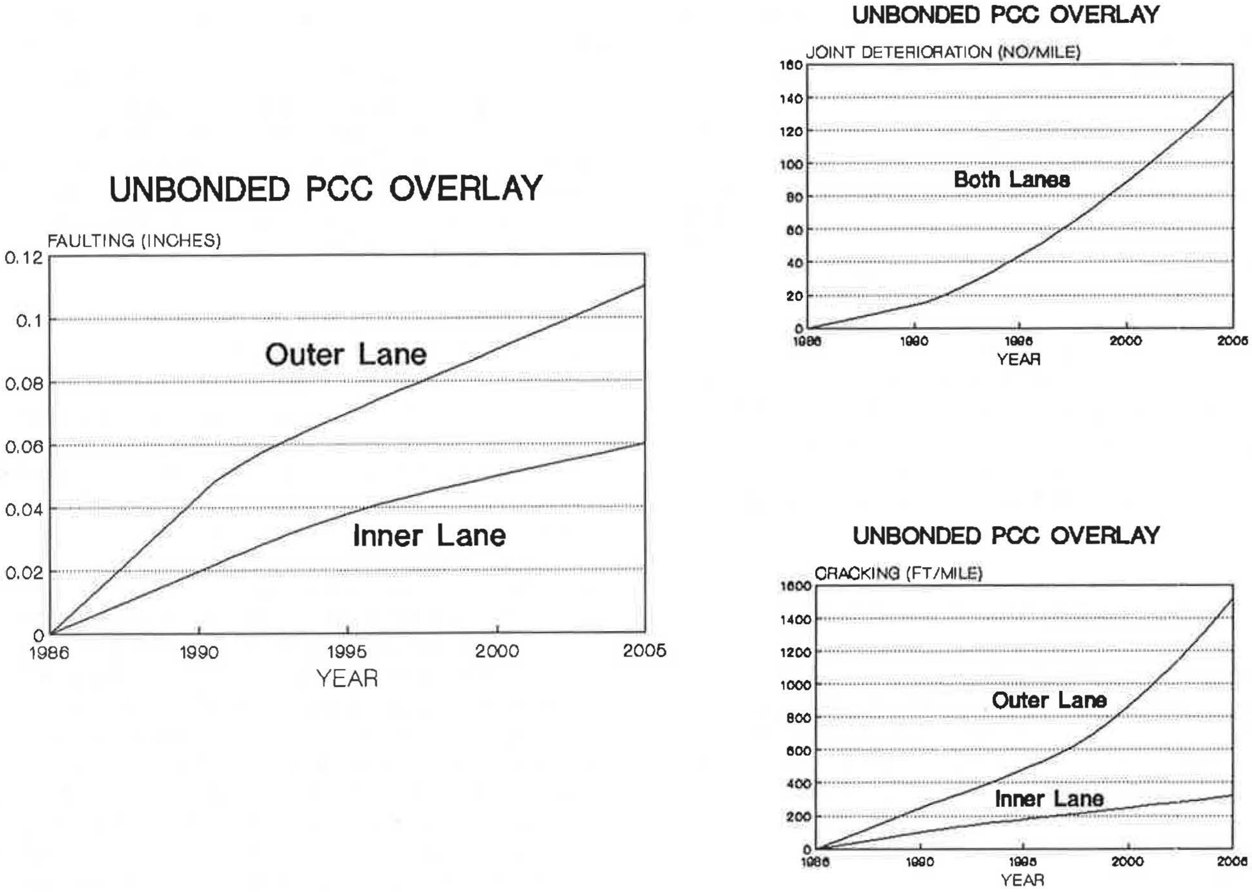

FIGURE 4 Predicted performance of unbonded overlay for I-10 example.

For a 4-in. AC overlay, reflective cracking is predicted to reach unacceptable levels (1,000 ft of medium- to high-severity reflective cracks per mile) within seven years, which is understandable, considering the short joint spacing, poor load transfer at undoweled joints, and the large number of full-depth repairs required for preoverlay repair. Greater overlay thicknesses could be investigated to extend the life.

Better performance can be obtained by cracking and seating the pavement prior to AC overlaying. An alternative life of approximately 12 years, constrained by rutting in the outer lane, is predicted for a 4-inch overlay, a seating roller weight of 50 tons, and a cracking pattern of 6 ft by 6 ft. Again, other overlay thicknesses and cracking and seating parameters could be investigated as well.

A 3-in. bonded PCC overlay is predicted to perform even better than the crack and seat. The life of this alternative is constrained by joint deterioration, which is predicted to reach a critical level of 55 joints/mile in the outer lane in approximately 19 years. The unbonded overlay alternative does not perform quite as well, as shown in Figure 4. Even at an overlay thickness of 9 in., with a 1-in. AC separation layer, a 15-ft joint spacing, and 1.25-in. dowels in the overlay, cracking in the outer lane is predicted to reach a critical level of 800 ft/mile in the outer lane within 15 years, although joint deterioration and faulting are not predicted to reach unacceptable levels over the next 20 years. However, it would be premature to assume that a bonded overlay is preferable to an unbonded overlay without performing a life-cycle cost analysis. It may be that the greater thickness of the unbonded overlay is offset by the savings in preoverlay repair.

The last alternative investigated for this example is a strategy for reconstructing the outer lane and restoring the inner lane. As it happens, there is no restoration work required for the inner lane, since it has no significant distress. The performance of this alternative was predicted using a reconstructed outer lane slab thickness of 12 in., with a 20-ft joint spacing, a stabilized base with a k value of 200 pci, 1.25-in. dowel bars, and a PCC modulus of rupture of 650 psi. This alternative design performs well for the entire prediction period. In the outer lane, PSR is predicted to reach a critical level of 3.0 after 19 years. In the inner lane, however, PSR becomes critical after 15 years (when the pavement in the inner lane is 27 years old). Thus the life of this alternative is 15 years. Since the inner lane requires no rehabilitation and performs acceptably almost as long as the outer lane, it seems unlikely that a strategy for reconstructing both lanes would have any cost advantage over the reconstruct/restore strategy.

Life-Cycle Cost Analysis of Alternatives

Using the rehabilitation quantities and predicted performance periods computed by the program, the five rehabilitation strategy alternatives may be compared on the basis of life-cycle cost. Typical unit costs were obtained from the Illinois Department of Transportation, Florida Department of Transportation, and other sources. A 5 percent discount rate was used in the analysis. The results are summarized below:

Alternative	*Initial Cost/Two-Lane Mile*	*Life (years)*	*Annual Cost/Two-Lane Mile*
AC overlay	$581,000	7	$100,410
Crack and seat	576,900	12	65,090
Bonded overlay	731,000	19	60,490
Unbonded overlay	403,000	15	38,820
Reconstruct/restore	353,300	15	34,040

For this example, the outer lane reconstruction strategy appears to be the most cost-effective. Of course, these costs are estimates for illustrative purposes only and should not be interpreted as indicating any one strategy's superiority over another. A variety of other factors in addition to life-cycle cost must be considered in the final selection of the preferred rehabilitation strategy alternative.

CONCLUSIONS AND RECOMMENDATIONS

A practical and comprehensive system to assist practicing engineers in concrete pavement evaluation and rehabilitation has been developed, using a new and innovative approach that combines human knowledge and analytical techniques into a user-friendly personal computer program.

Conclusions

Concrete pavement evaluation and rehabilitation is a complex engineering problem that defies traditional analytical solutions, because of the large number of interacting factors involved and the lack of adequate analytical models to solve all (or even most) aspects of the problem.

Successful concrete pavement evaluation and rehabilitation currently rely heavily on the knowledge and experience of authorities in the pavement field for diagnosis of the causes of distress and for selection of feasible rehabilitation techniques that cost-effectively correct the deterioration.

Concrete pavement evaluation and rehabilitation is an ideal subject for an expert system application, by which human expertise is compiled, formalized, and applied to evaluation and rehabilitation of specific concrete pavement projects.

An expert system for concrete pavement evaluation and rehabilitation must incorporate not only the rules but also the reasoning processes used by knowledgeable pavement engineers in order to reach solutions in an efficient manner. Decision trees adequately represent factual knowledge and reasoning processes in a way that is easy to understand, examine, and revise.

An evaluation/rehabilitation procedure must be based on identifying and correcting mechanisms of deterioration in order to produce cost-effective rehabilitation strategies.

The inclusion of analytical models to predict the future performance of the pavement with and without rehabilitation was essential for the system to perform as desired. *Combining the human knowledge base with analytical techniques helps to provide feasible solutions for the evaluation and rehabilitation of concrete pavements.*

An expert system for concrete pavement evaluation and rehabilitation has been developed to the stage of a demonstration prototype. The system provided reasonable results in a few example applications but has not been fully tested over a wide range of conditions. More than 30 person-months of effort were expended in the development of the system to this stage. The results achieved thus far demonstrate that the system approach shows great promise in addressing this difficult engineering problem.

Recommendations for Future Work

Extensive field testing, including review by state department of transportation personnel and case studies on concrete pavement projects throughout the United States, is needed to increase the quality, efficiency, speed, and reliability of the system to the level of a research prototype.

Life-cycle cost analysis procedures would greatly increase the usefulness of the system. The analysis should be able to address unequal performance periods of different alternatives, additional rehabilitation needs within the analysis period, and additional costs that cannot now be computed by the system (e.g., bridge clearance, guardrail replacement, side slope improvements, traffic control, user-related costs). A first step toward providing this capability is the computation of rehabilitation quantities currently performed by the system.

The system currently assumes that the rehabilitation work will be performed immediately after the evaluation, which is almost never the case. *Routines need to be added to allow the engineer to specify the year of rehabilitation and have the system design rehabilitation strategies appropriate for the pavement's projected condition in that year.* This may be difficult to implement, since predictive models are lacking for some types of distress (e.g., shoulder deterioration, D-cracking).

Many models are used by the system to predict the future performance of the existing pavement with and without rehabilitation. Most of these models have significant limitations, and are not applicable nationwide over the range of climatic zones. *The development of improved models is a necessity to improve the validity of the system.* These may best be developed for individual states or regions of states (e.g., the southeastern United States). The existing models are most deficient in predicting the effect of retrofit subdrainage on the performance of the rehabilitated pavement.

Other rehabilitation techniques that are not now included in the system could be considered if performance prediction models for them become available. Some techniques that could be added include AC overlays with fabrics, interlayers, or sawed and sealed joints, and CRCP overlays.

The importance of *physical testing* to concrete pavement evaluation and rehabilitation design is addressed to a limited extent in the current system. However, the improvement of the physical testing recommendations and incorporation of physical testing results into the procedures for evaluation and rehabilitation strategy development remain among the most urgently needed improvements to the system.

The system should be extended to existing AC-overlaid concrete pavements. The system currently is restricted to pavements in their first performance period. Many concrete pavements exist that have already been overlaid with AC and are in need of further rehabilitation. Work on this addition to the system is currently under way.

Adaptation of the system to different pavement geometries (e.g., other than two lanes in each direction) would make the system more applicable to the variety of pavement geometries throughout the United States.

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