Development of a Demonstration Prototype Expert System for Concrete Pavement Evaluation

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A computerized system has been developed to assist state highway engineers in evaluating concrete highway pavements. The system uses information collected by the engineer to determine what mechanisms have caused the distresses present in the pavement, so that the rehabilitation techniques that would be most effective in repairing the distresses and preventing their recurrence can be identified. The evaluation procedure has been developed in the form of an expert system that simulates a consultation between the engineer and an expert in concrete pavement evaluation and rehabilitation. The system was developed through extensive interviewing of concrete pavement experts. The system operates on an IBM-compatible personal computer with two disk drives. The steps in the development of the expert system are described for the benefit of those interested in improved pavement evaluation procedures and in exploring expert systems applications in pavement design, evaluation, and rehabilitation. The work performed demonstrates that an expert system capable of diagnosing pavement deficiencies and their causes at a level approaching that of a human expert in the field can be developed and applied as a component of a practical engineering procedure for comprehensive evaluation and rehabilitation of concrete pavements.

Concrete pavement evaluation is a difficult engineering problem that defies traditional solution methods because of the large number of factors that must be considered, the interactions of these factors, and the shortage of organized information on the ways in which these interacting factors influence performance *(1, 2)*. Although analytical techniques are available to examine particular factors that are known to influence performance, comprehensive pavement evaluation requires the consideration of so many factors that it is still a task best performed by individuals in the pavement field with considerable knowledge about pavement performance and considerable experience in evaluating pavements.

The most appropriate way to develop a formal concrete pavement evaluation procedure thus appears to be through studying and attempting to duplicate the way in which pavement experts evaluate pavements. Two knowledgeable and experienced pavement engineers, whose combined areas of expertise encompass all aspects of concrete pavement evaluation and performance, were involved in the development of this evaluation procedure. Through every step in the development of the procedure, these experts submitted to exhaustive questioning on their reasoning methods.

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For the initial development of the evaluation procedure, the scope of the problem was limited to jointed, reinforced, concrete pavement (JRCP). Adaptation of the procedure for jointed plain and continuously reinforced concrete pavements is also under way.

The system was developed for use on an IBM-compatible personal computer using the Insight 2+ expert system shell developed by Level V Research, Inc. An expert system shell is a software tool that allows the expert system developers to concentrate on acquiring knowledge from the experts and expressing it in the form of rules. The shell provides a suitable development environment (with text editor, compiler, etc.) and a control structure to access and use the rules.

SOLUTION APPROACH

Major Problem Areas

The experts identified 12 problem areas that they felt must be considered in an evaluation of a jointed reinforced concrete highway pavement:

1. Structural capacity,
2. Drainage,
3. Foundation stability,
4. Roughness,
5. Concrete durability,
6. Skid resistance,
7. Transverse joint condition,
8. Longitudinal and transverse joint construction,
9. Load transfer,
10. Slab support,
11. Joint sealant reservoir design, and
12. Shoulder condition.

The experts agreed that a thorough assessment of a pavement's present condition required a determination of whether or not one or more deficiencies serious enough to warrant corrective measures existed in each of the 12 major problem areas.

Interviewing Pavement Experts

By far the most difficult task in developing the evaluation procedure was formalizing the reasoning processes by which the experts determined whether or not a particular pavement deficiency existed. As is typical of difficult problems in any field, the irony exists that the individuals best able to solve problems are often the least able to explain how they solved them. This is a natural result of having solved similar problems so often that the answers become intuitive. Extensive interviewing of the experts is required to learn how they reach conclusions from the information made available to them.

The process of acquiring the knowledge possessed by the experts began with asking the experts to identify the information needed to determine which deficiencies were present in a pavement. These discussions were guided with questions such as

- What facts do you need to know to determine whether a particular pavement deficiency exists?
- If a piece of information is unavailable, can you still guess at whether or not the pavement deficiency exists, or are you unable to reach a conclusion?
- How precise do you need a piece of quantitative information to be? (For example, is the amount of annual precipitation essential information, or would designation as a wet climate suffice?)
- Why is a particular piece of information important?

Questions such as these prompted the experts to think about the relative significance they attached to various data items. In answering such questions, experts rely heavily on heuristic rules, commonly referred to as rules of thumb. Examples of heuristic rules related to concrete pavement evaluation are

- Longitudinal cracks between the centers of two adjacent lanes are due to either foundation movement or poor longitudinal joint construction.
- Standing water or cattails in the ditches indicate an inadequate ditch grade.

Heuristic rules are generalizations that are true in most, but not necessarily all, cases. By relying on them even though strictly speaking they are not always valid, the expert's reasoning moves rapidly to a tentative conclusion of which the expert is reasonably confident. In applying these rules, what differentiates the expert from less knowledgeable people in the field is that the expert knows from problem-solving experience the ranges of validity of the rules and what other factors that are not included in the rules might also be important.

Decision Trees

As discussions with the experts continued, it became increasingly apparent that a problem solution could not be achieved by extracting as many heuristic rules as possible from the experts and applying these rules to evaluating pavement projects in a random fashion. It appeared far preferable to organize the rules in a manner that simulated the patterns in which the experts used them. In other words, not only the knowledge but also the reasoning used by experts in performing concrete pavement evaluation had to be incorporated in the system.

Decision trees were selected as an appropriate means of exploring the experts' reasoning and incorporating it into the expert system. For each of the 12 major deficiency areas, a decision tree was developed that used the pieces of information identified as important for that area, in order of importance. The use of decision tress was welcomed by the experts as a means of ensuring that the many possible combinations of the data items were investigated to the fullest extent possible.

As stated earlier, problem solving on an expert level is highly intuitive. Research in education and psychology *(3)* indicates that experience in solving a particular type of problem contributes to the development of expertise in solving that type of problem (and to a limited extent, increased skill in solving similar problems in different domains), but does not contribute significantly to increased ability to articulate problem-solving approaches. The ability to explain one's line of reasoning appears to be possessed by different people to different degrees independently of their level of expertise in a particular field.

This reflects the experience of the project staff in developing the decision trees for the 12 major problem areas. The number of times that a decision tree had to be revised before it met with a experts' approval was generally more dependent on its complexity than on who had originally drafted it.

Needed Information

Each of the capabilities envisioned for the expert system had associated with it a need for some type and amount of data. The most significant of these capabilities and their associated data needs are as follows:

1. Expert-level performance. In order to perform at a level approaching that of a human expert, the expert system had to collect sufficient data to determine whether one or more deficiencies existed in each of the 12 major problem areas.
2. Data collection effort. In order for users to consider the system a useful tool for project-level evaluation, the system had to operate with information that was readily accessible to a state highway engineer from office records and an inspection of the project site.
3. Efficiency. In order to make efficient use of engineering resources and computer facilities, the system could collect only data essential to the problem solution.
4. Rehabilitation selection. In order to select appropriate rehabilitation techniques, data on specific distress types and severities were necessary.
5. Cost analysis. Ranking of rehabilitation strategies according to cost requires quantity estimates for the individual rehabilitation techniques, and thus data on specific distress quantities and measurements were necessary.
6. Representative sampling. A 100 percent project survey is unreasonable for preliminary project-level evaluation. Data had to be collected for a smaller portion of a project (e.g., 10 to 30 percent) and extrapolated to represent overall project condition and produce reasonable rehabilitation cost estimates.

Meeting all of these data needs was accomplished in the following way. The experts identified the specific data items they would need in order to determine whether or not the pavement was deficient in any of the 12 major problem areas. They were asked to select only data items that they definitely needed in order to make a decision, and not include information that would simply be "nice to have." They were also asked to consider whether the data items they were requesting would be accessible to state highway engineers.

Project Survey

The data items that were identified as important were summarized in a project survey for JRCP. The project survey consisted of two parts: inventory data and monitoring data. Inventory data included

- Project identification (state, highway designation, direction of survey, and project limits),
- Climate,
- Thickness design,
- Layer materials,
- Joint design and construction,
- Shoulder design and construction,
- Shoulder design, and
- Traffic.

Monitoring data consists of all the information about the pavement's present condition that must be collected during a field inspection of the project, including

- Ride quality,
- Cracking and corner breaks,
- Transverse and longitudinal joint condition,
- Settlements and heaves,
- Drainage conditions,
- Pumping and faulting,
- Concrete surface condition,
- Joint sealant condition,
- Concrete durability,
- Previous repair, and
- Shoulder condition (AC or PCC).

All inventory data and the ride quality portion of the monitoring data are collected for the project as a whole. The remaining monitoring data are collected on sample units within the project. The recommended procedure is to survey a minimum of 500 ft at each milepost, equal to approximately 10 percent of the project length. However, the expert system can accommodate any number and length of sample units that the engineer feels adequately represent the overall project condition. A set of monitoring data sheets must be completed for each sample unit surveyed; extrapolating overall project condition is then performed by the expert system.

Distress types, severities, and quantities are recorded on the monitoring data sheets in a manner consistent with standard distress identification procedures. Monitoring data must be collected for each traffic lane and shoulder. Each of the lanes and shoulders is evaluated separately by the expert system.

Survey Data Entry

In the office, the data recorded on the project survey sheets are entered into a computer using a full-screen data entry program. The screens created by the program follow the format of the project survey sheets. The data entry program writes the inventory data for the project and the monitoring data for each sample unit to computer files for permanent storage.

A separate data summary program converts the data into the form needed for evaluation by the expert system. The major purpose of the data summary program is to read the distress quantities entered for each sample unit, compute their averages, and extrapolate distress quantities for the entire project length. The data summary program then writes the computed overall project information to file for evaluation by the expert system.

Refining the Solution Approach

Initial development of the project survey sheets and the pavement deficiency decision trees was followed by a painstaking process of review and refinement. In developing the decision trees, additional data items of importance that had to be added to the survey were uncovered. Some data items were not used. Had they been unintentionally omitted, or were they really not as significant as originally thought? Every line of reasoning used in every flowchart was reviewed, discussed, and challenged. If two different values of a data item led to the same conclusion, did that imply that the data item was not significant, or that the reasoning leading to the conclusion was faulty? In some cases, decision trees that were not reasonable or efficient were discarded entirely and redrawn from scratch, using a totally different approach. The project survey sheets were also revised repeatedly, as the system developed and the data needs cited previously became more apparent.

During this refinement period, both the decision trees and the project survey sheets were revised many times. This refining process resulted in dozens of major changes and hundreds of smaller changes that greatly improved the quality of the expert system.

EVALUATION CONCLUSIONS

Need for Evaluation Conclusions

It was originally intended that the evaluation procedure would reach a determination of whether or not a deficiency existed in each of the major problem areas. This intention posed two problems. First, the experts found it too restrictive; they wanted the system to explain to the users how conclusions were reached and why particular factors were important in reaching the conclusions. Second, it was not specific enough to make the evaluation results useful in selecting appropriate rehabilitation techniques and estimating costs.

For these reasons, individual evaluation conclusions were written by the experts for most of the paths in the decision trees. In some cases, the conclusions were written generally enough to apply to more than one combination of the data items.

The decision trees and evaluation conclusions developed for roughness and for transverse and longitudinal joint construction are shown in Figures 1 and 2. Roughness evaluation ratings are defined as follows.

RGH 1: Rideability is acceptable.
RGH 2: Poor rideability is indicated by more than 50 in. of faulting per mile and an unacceptably low PSR for pavement ADT level.
RGH 3: Poor rideability is indicated by 5 in. or more of settlements per mile and an unacceptably low PSR for pavement ADT level.
RGH 4: Poor rideability is indicated by 5 heaves or more per mile and an unacceptably low PSR for pavement ADT level.
RGH 5: Poor rideability is indicated by 25 deteriorated joints per mile or more and an unacceptably low PSR for pavement ADT level.
RGH 6: Poor rideability is indicated by an unacceptably low PSR for pavement ADT level.

Longitudinal joint construction evaluation ratings are defined as follows.

JTC 1: Pavement deterioration may be accelerated by infiltration of water permitted by poor longitudinal joint sealant condition.
JTC 2: A longitudinal joint construction deficiency is indicated by longitudinal joint spalling.
JTC 3: A longitudinal joint construction deficiency, likely because of an inadequate depth of saw cut, is indicated by more than 100 ft of longitudinal cracking per mile.
JTC 4: A longitudinal joint construction deficiency, likely because of late sawing, is indicated by more than 100 ft of longitudinal cracking per mile.
JTC 5: A longitudinal joint construction deficiency, likely because of an inadequate depth of plastic insert placement, is indicated by more than 100 ft of longitudinal cracking per mile.
JTC 6: A longitudinal joint construction deficiency, likely because of use of a plastic joint forming insert, is indicated by more than 100 ft of longitudinal cracking per mile.

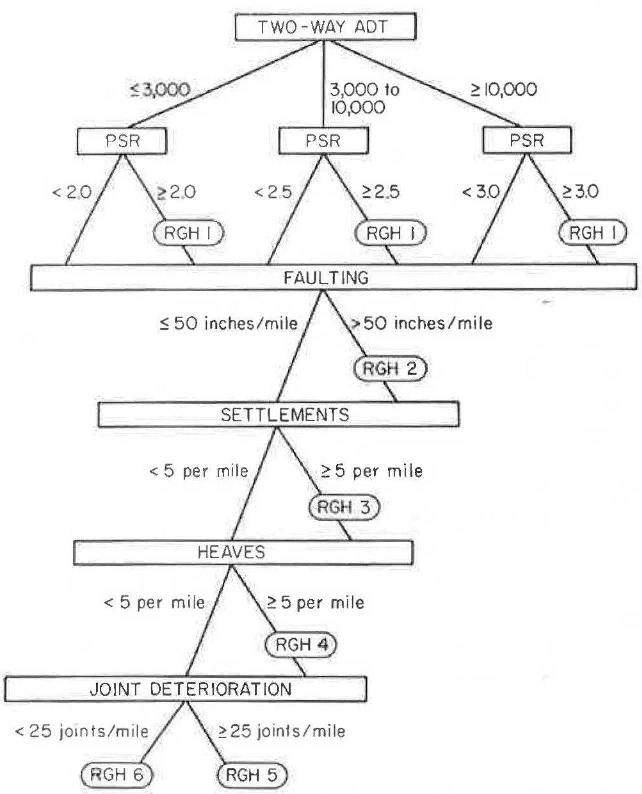

FIGURE 1 Roughness decision tree.

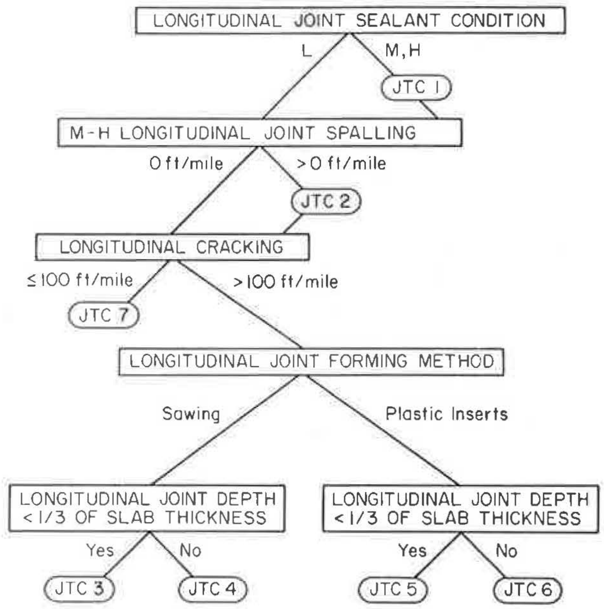

FIGURE 2 Longitudinal joint construction decision tree.

Types of Conclusions

All of the conclusions state as a minimum whether or not a deficiency is indicated by the data and, if so, what factors were significant in reaching this decision. The following conclusion from the drainage decision tree is an example:

> A drainage deficiency is indicated by a wet climate, absence or poor functioning of longitudinal subdrains, and a fine-grained soil base.

An example of multiple paths to a conclusion is the following, from the roughness decision tree. This conclusion can be reached through three different paths, because a difference minimum acceptable PSR is assigned to each of three different ranges of ADT.

> Poor rideability is indicated by 25 or more spalled joints per mile and an unacceptably low PSR for the pavement's ADT level.

The experts believed that some of the conclusions required a little more explanation to justify to the user that the deficiency was significant enough to warrant corrective action. The following conclusion from the shoulder condition decision tree is an example:

> Excessive dropoff along the lane-shoulder joint constitutes a safety hazard.

In some cases, the experts felt that the evaluation conclusions could not be stated with absolute certainty. In these cases, the conclusions were presented accordingly, with descriptive explanations about the deficiencies and their probable causes. The following conclusion from the transverse joint condition decision tree is an example:

> A high potential for compressive stress buildup and joint deterioration exists, due to the use of Unitube joint forming inserts, the presence of expansive reactive aggregate, and large joint movements associated with the long joint spacing. This may lead to joint blowups and/or spalling.

Number of Possible Conclusions

A total of 114 different evaluation conclusions were written for the 12 decision trees. For a pavement with two lanes in the direction of survey, at least 11 conclusions are reached for the outer traffic lane, at least 10 for the inner lane (longitudinal joint construction and sealant condition are evaluated for the outer traffic lane), and at least 1 for each shoulder, for a total of at least 23 conclusions. More than 23 conclusions are possible because many of the decision trees are capable of reaching multiple conclusions. This multiplicity was permitted in order to indicate when two or more different specific problems grouped within a single deficiency category required corrective action, or when the presence of a single deficiency was supported by two or more lines of reasoning.

EXAMPLE EXPERT SYSTEM PAVEMENT EVALUATION

A 1-mi section of I-74 north of Urbana, Illinois, was surveyed by members of the project staff on August 1, 1986. The pavement consists of 10 in. of jointed reinforced concrete over a dense-graded aggregate base and a silty clay (A-6) subgrade. The joints are doweled and spaced uniformly at 100 ft. The shoulders are asphalt concrete (AC).

This section of I-74 was constructed in 1957. Its current two-way ADT is 26,100 (with 17 percent commercial trucks). Approximately 13 and 3.9 million ESALs have been accumulated in the outer and inner lanes, respectively, over the life of the pavement.

On initial passes over the surveyed section at the posted speed limit, ride quality was rated in each of the two traffic lanes. On subsequent passes, the car was driven slowly along the shoulder while pavement distresses, joint condition, and previous repairs were noted. The condition of the inner and outer shoulders was also noted. The entire project was treated as one sample unit due to its short length. The survey required about 60 min to conduct.

Expert System Evaluation

The survey data were entered into the computer using the full-screen editor and stored on disk. The expert system evaluated the project by reading the data file and solving each of the 12 decision trees to identify deficiencies. Deficiencies were identified in the following areas:

Problem	*Outer Lane*	*Inner Lane*
Structural capacity	yes	yes
Drainage	yes	yes
Foundation movement	no	no
Roughness	yes	no
Concrete durability	no	no
Skid resistance	yes	yes
Joint deterioration	yes	yes
Joint construction	no	no
Load transfer	yes	no
Loss of support	yes	no
Joint sealant deterioration	yes	yes
Shoulder deterioration	yes	yes

The evaluation conclusions generated by the expert system from the survey data for this 1-mi section of I-74 are as follows.

Outer Lane

- Structural deficiency of the pavement is indicated by 700 ft or more of deteriorated transverse cracks per mile.
- Structural deficiency is indicated by a wet or wet-dry climate, a slab thickness of 10 in., and 0.7 million annual 18-kip ESALs.
- A drainage deficiency is indicated by pumping that occurs in a wet climate.
- The pavement shows no indications of either a frost heave problem or swelling soil problem.
- Poor rideability is indicated by an unacceptably low PSR for the pavement's ADT level.
- The pavement shows no indications of significant surface or concrete durability deficiencies.
- Loss of skid resistance is indicated by polished wheel paths.
- A high potential exists for joint deterioration due to poor joint sealant condition permitting infiltration of incompressibles, and large joint movements associated with the long joint spacing.
- Pavement deterioration may be accelerated by water infiltration permitted by poor longitudinal joint sealant condition.
- The pavement shows no indications of a longitudinal joint construction deficiency.
- The pavement shows no indications of a transverse joint construction deficiency.
- Dowels are providing inadequate load transfer at the transverse joints, as indicated by mean transverse joint faulting of more than 0.20 in.
- A load transfer deficiency is indicated at deteriorated transverse cracks by mean crack faulting of more than 0.20 in.
- A load transfer deficiency is indicated at undowelled full-

depth repairs by mean full-depth repair faulting of more than 0.20 in.

• Loss of slab support is indicated by average faulting greater than 0.20 in. at joints and cracks.

• A joint sealant deficiency is indicated by poor joint sealant condition and an inadequate joint sealant reservoir width for the existing sealant type.

Inner Lane

• Structural deficiency of the pavement is indicated by 700 ft or more of deteriorated transverse cracks per mile.

• A drainage deficiency is indicated by a wet or wet-dry climate, absence or poor functioning of longitudinal subdrains, a dense-graded untreated aggregate base, an A-6 subgrade, and heavy traffic of 0.9 million annual 18-kip ESALs.

• The pavement shows no indications of either a frost heave problem or swelling soil problem.

• Rideability is acceptable.

• The pavement shows no indications of significant surface or concrete durability deficiencies.

• Loss of skid resistance is indicated by polished wheel paths.

• A high potential exists for joint deterioration due to poor joint sealant condition permitting infiltration of incompressibles, and large joint movements associated with the long joint spacings.

• The pavement shows no indications of a transverse joint construction deficiency.

• No load transfer deficiency is indicated at transverse joints.

• No load transfer deficiency is indicated at deteriorated transverse cracks.

• No undoweled full-depth repairs are present.

• The pavement shows no indications of loss of slab support.

• A joint sealant deficiency is indicated by poor joint sealant condition and an inadequate joint sealant reservoir width for the existing sealant type.

Outer Shoulder

• Structural deterioration of the AC shoulder is indicated by extensive alligator cracking.

• Deterioration of the AC shoulder is indicated by extensive linear cracking.

• Pumping has resulted in extensive blowhole formation in the AC shoulder.

• Excessive infiltration of water beneath the pavement and AC shoulder is indicated by poor lane-shoulder joint condition.

Inner Shoulder

• Deterioration of the AC shoulder is indicated by extensive linear cracking.

• Pumping has resulted in extensive blowhole formation in the AC shoulder.

• Excessive infiltration of water beneath the pavement and AC shoulder is indicated by poor lane-shoulder joint sealant condition.

Future Pavement Condition

The expert system performed an evaluation of the current condition of this 1-mi section of I-74. Projection of the future condition of the pavement was performed using the concrete pavement evaluation system (COPES) models *(4)*. Using these models, future distress quantities are extrapolated from the current distress data collected during the project survey. Figure 3 shows the predicted progression of joint deterioration over the next 20 years.

The future condition of the inner and outer lanes expressed in terms of number of years remaining before critical levels are reached as predicted by the COPES models is summarized as follows:

	Time to Critical Level (years)	
Distress/PSR	*Outer Lane*	*Inner Lane*
Pumping	now	12
Faulting	now	15
Joint deterioration	10	12
Cracking	now	now
PSR	now	5

Rehabilitation is needed now to correct deficiencies triggered by distress levels that are already critical. The future condition predictions identify the times at which additional deficiencies will exist and will require rehabilitation. This information, along with the actual current distress quantities and projected future distress quantities, is necessary to plan and design rehabilitation needed on the project over the next 20 years.

CURRENT AND FUTURE WORK

Current Work

The expert system for JRCP evaluation is a portion of a larger expert system being developed for evaluation and rehabilitation of all three types of concrete highway pavement (JPCP, JRCP, and CRCP). Future pavement condition prediction will be performed for JRCP and JPCP using models developed under the COPES study *(4)*. The expert system will also use performance prediction models currently being developed for several jointed concrete pavement rehabilitation techniques from data collected on 161 rehabilitated concrete pavements in 24 states. Performance prediction of techniques in the expert system other than these eight (e.g., AC overlay) will use models developed in other studies. Future condition prediction and rehabilitation performance prediction for CRCP will rely on models that have been or are currently being developed for CRCP.

The expert system is currently being documented in manual

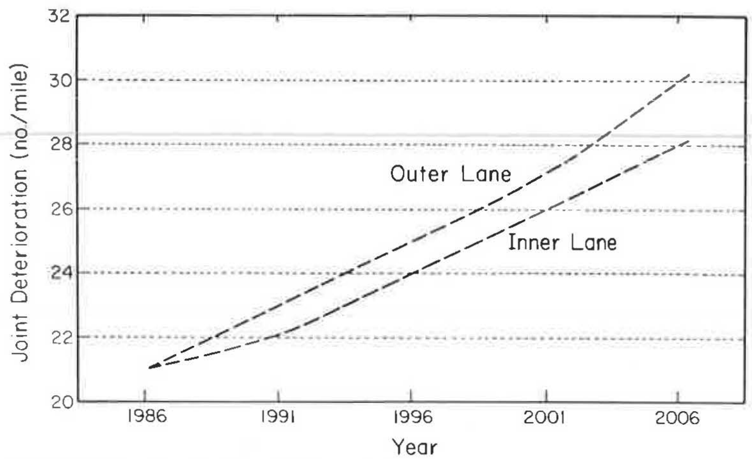

FIGURE 3 Prediction of future joint deterioration for I-74 example.

form and programmed to operate on an IBM-compatible personal computer.

Future Work

Development of large expert systems for research and education purposes is a long-term process. David Waterman, author of *Building Expert Systems (5)*, describes five stages in the evolution of an expert system:

1. Demonstration prototype—a small demonstration system that solves a portion of the problem that will eventually be addressed, suggesting that the approach is viable and full system development is achievable.
2. Research prototype—a medium-sized system capable of credible performance on a number of test cases, but that may be fragile due to incomplete testing and revision.
3. Field prototype—a medium- to large-sized system that has been tested by users in the field and revised until it displays good performance with adequate reliability.
4. Production model—a large system that has been extensively field tested and displays high-quality, reliable, fast, and efficient performance in actual field applications.
5. Commercial system—a production model used on a regular basis in the field that displays near-optimum quality, reliability, speed, and efficiency.

To date, few engineering expert systems have progressed beyond the research prototype stage. This expert system, which is in the demonstration prototype stage, needs to be validated and improved by means of a thorough program of field testing by several state transportation department personnel. Such a testing program would answer the following questions:

- Does the system make decisions with which concrete pavement experts would generally agree?
- Is the logic used in the decision trees correct, consistent, and complete?
- Are the evaluation conclusions adequate for explaining how and why conclusions are reached?
- Are the rehabilitation techniques appropriate for the evaluation conclusions with which they are matched?
- Are the system's outputs well organized, well presented, valid, and of value to the user?
- Is the system efficient and easy to use?

Field testing is a cyclic process that continues through the research prototype stage until the system achieves levels of quality, reliability, speed, and efficiency sufficient to qualify it as a field prototype, suitable for public release.

CONCLUSIONS

1. Concrete pavement evaluation is a complex engineering problem that defies traditional analytical solutions because of the large number of interacting factors involved, suggesting the desirability of a computerized solution method.
2. Concrete pavement evaluation relies heavily on the knowledge and experience of experts in the field for accurate and complete diagnosis of the causes of distress and other pavement deficiencies.
3. Concrete pavement evaluation is an ideal problem for expert system application by which human expertise in pavement evaluation is compiled, formalized, and applied to pavement evaluation problems.
4. A concrete pavement evaluation expert system must incorporate not only the rules but also the reasoning processes used by experts in order to reach conclusions about the presence of several possible pavement deficiencies in an efficient manner.
5. An expert system for concrete pavement evaluation has been developed to the demonstration prototype stage, and application on example problems has demonstrated its feasibility.
6. Extensive field testing and review are needed to improve the quality, reliability, speed, and efficiency of the expert system to the level of a research prototype.

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