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Knowledge based expert system pavement management optimization

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Knowledge based expert system pavement management optimization

by

Omar Ghaleb Smadi

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Transportation Engineering

Major Professor: Tom H. Maze

Iowa State University

Ames, Iowa

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Major Professor

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For the Major Program

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For the Graduate College

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ABSTRACT

Knowledge based expert systems and dynamic programming are used for the development of a comprehensive pavement management system tool to help engineers and planners make objective, consistent, and cost effective decisions regarding pavement maintenance, rehabilitation, and reconstruction.

Knowledge-based expert systems provide a flexible tool to allow for acquisition of knowledge from experts in the field and to incorporate that knowledge in building an efficient pavement management decision support tool. Knowledge-based expert systems are also used to develop a pavement condition forecasting model and treatment strategy selection model. The forecasting model is capable of predicting pavement condition based on historical data and expert opinion.

The treatment strategy selection model considers the forecasted condition and other inventory parameters to select feasible treatment strategies for each pavement section for all the years in the planning or analysis period. The expert system will also determine a cost and improvement in condition due to the application of the selected treatment strategy.

Finally, a dynamic programming model takes the output from the treatment strategy selection knowledge-based expert system model and determines a list of projects and their associated treatment strategies, cost, and time to implement each to optimize a specific objective function. The dynamic programming model can consider different objectives functions (minimize cost or maximize benefits, for example) to achieve optimal allocation of resources.

INTRODUCTION

Pavement management, in its broadest sense, involves managing all the activities related to the pavement network. These activities include, but are not limited to, planning and programming, design, construction, maintenance, and rehabilitation. A pavement management system (PMS) provides effective tools and methods that can assist decision makers in formulating efficient strategies for providing and maintaining a serviceable pavement network over a given time period (the planning horizon). A good pavement management system requires an organized and systematic approach for agencies (state or local, public or private) to conduct pavement management activities.

The objective of this research is to develop a comprehensive and systematic pavement management system utilizing knowledge-based expert systems and mathematical programming techniques. The use of knowledge-based expert systems and mathematical programming provides for an organized and systematic approach to the pavement management process at any level (project, project selection, and/or network levels).

The modeling framework for a pavement management system can be divided into three basic components: performance prediction; treatment strategy selection; and resource allocation and project selection. Figure 1 is a flow chart of the three components. The following is a brief description of the three models and its proposed use in this research.

1. Pavement performance prediction. This is accomplished in conjunction with a model of the pavement's condition over time and/or use. This model forecasts future pavement condition. It can be seen from Figure 1 how using the existing condition and the performance parameters, future pavement condition is forecasted.

2. Treatment strategy selection. The treatment selection process is performed based on existing historical data, current agency practices, and the experiences of pavement management engineers. This model produces feasible treatment strategies based on condition and other pavement characteristics. Figure 1 shows that future pavement condition and existing pavement characteristics are used in the treatment selection model to determine the feasible maintenance alternatives.

3. Resource allocation. This model is designed, using mathematical programming techniques, to take into consideration the results from the two previous steps (see Figure 1). This model produces a list of projects and their associated treatment strategies for each year in the analysis period.

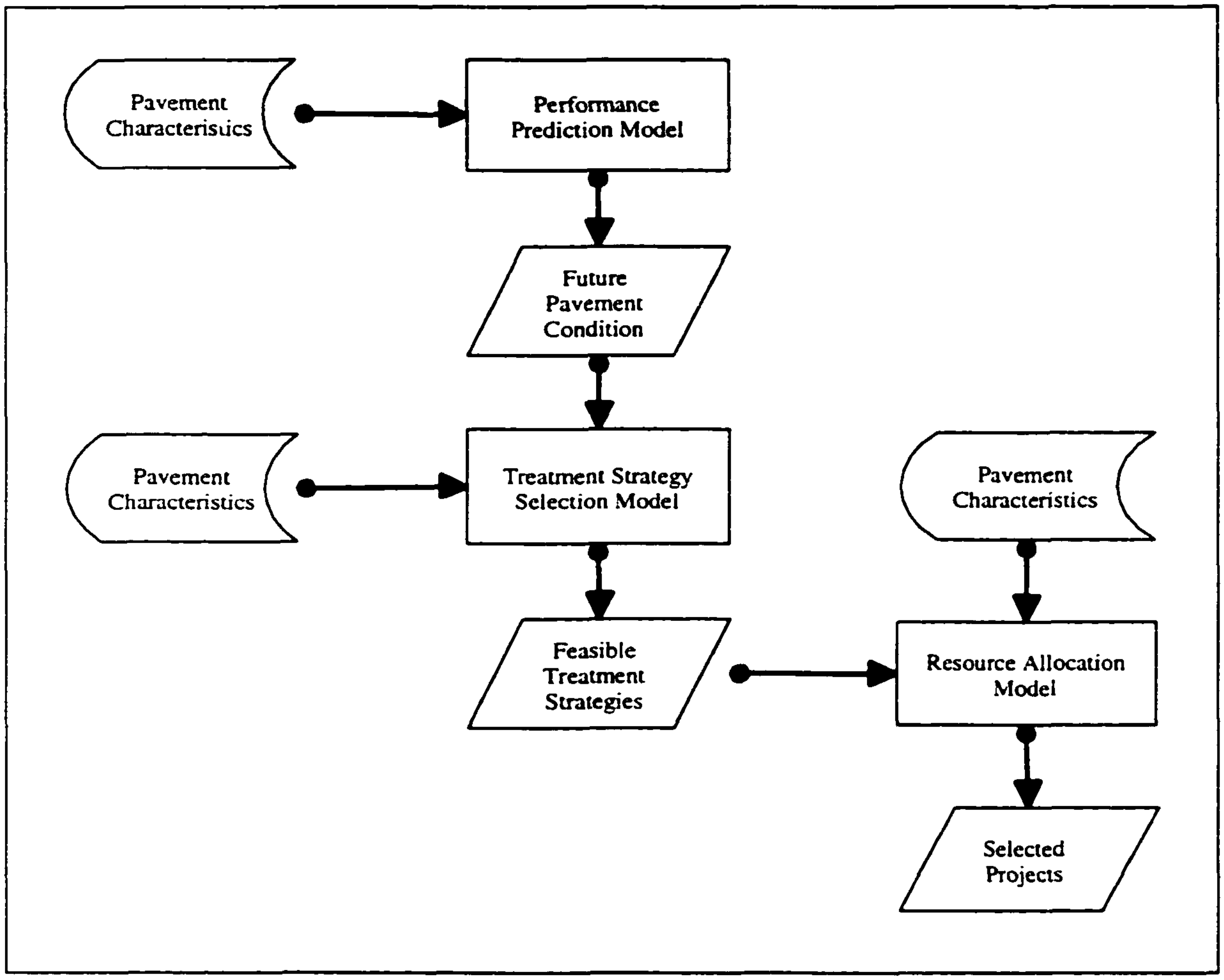


Figure 1. Pavement Management Components Flow Chart

Knowledge-based expert systems (KBES) are used to develop both the performance forecasting and treatment selection models, while dynamic programming is used to develop the resource allocation and project selection models. These models interact together to form a comprehensive pavement management system that provides for the systematic and consistent management of the pavement network.

Knowledge-based expert systems (KBES) have emerged from decades of artificial intelligence (AI) research. They are often referred to as the practical application of AI (1). Artificial intelligence is a product of the idea that "computers can be programmed to assume capabilities thought to be like human intelligence, such as learning, reasoning, adaptation, and self correction" (2). There are numerous potential applications for KBES ranging from medical diagnosis and library acquisition, to engineering problems.

KBES applications in pavement management systems have been specific and have only dealt with the diagnosis of the causes of pavement distress at the project level. Most of the KBES developed for pavement management are stand-alone models used for treatment selection at the project level. This research examines the feasibility of using KBES for network level pavement management systems and also expands the use of KBES from diagnosis of distress to include performance forecasting.

A mathematical program (dynamic programming) is employed in the resource allocation process. Dynamic programming is used to optimize the allocation of resources and the selection of projects for all the years in the planning or analysis period. The use of dynamic programming as a resource allocation tool in pavement management systems has been investigated before by the author and the application of dynamic programming to pavement management is based on earlier research (3).

Research Importance

The importance of this research stems from the importance of managing the pavement infrastructure in the most cost effective and efficient manner. State and local agencies have an enormous investment in their highway networks and the effective management of the maintenance and preservation of this investment should be a top priority. Any improvement in the methods and tools used for the management of the highway network will result in substantial benefits in terms of improved pavement condition and more efficient use of available funds. The use of KBES in the pavement management system provides for a more appropriate and flexible approach for performing condition forecasting and treatment selection. This would result in managing the highway network in a more consistent and efficient manner.

The use of KBES to develop pavement management tools is both feasible and beneficial. This research demonstrates the feasibility of using KBES for developing accurate pavement condition forecasts and treatment strategy selections. The results from these two processes feed into a resource allocation model developed using dynamic programming for the determination of the optimal allocation of resources and project selection. Pavement management applications provide a unique environment for the use of KBES for the following reasons (4):

1. Pavement management systems require periodic data collection and as more data become available, more knowledge (rules and facts) can be developed to replace the heuristics originally supplied by the experts.
2. Pavement management system goals and objectives change depending on condition, funding levels, and agency requirements.
3. Pavement management is a field in which the recognized experts, whose knowledge will be incorporated in the KBES, have as counterparts other experts who are experienced with local conditions. Their knowledge is crucial to the success of the pavement management system.

The research will also show the feasibility of using KBES in network and project selection level pavement management analysis. Previous applications of KBES, discussed in the literature review, were limited to only treatment selection at the project level. The use of KBES at the network level for forecasting pavement condition and treatment selection adds more flexibility and efficiency in dealing with different pavement types and special circumstances or conditions that arise in any pavement management system.

KBES are capable of accurately representing the pavement management knowledge from experts and from historical information. KBES also are capable of handling ill-structured problems or problems with missing data. Pavement management databases are riddled with missing data elements from traffic data to condition information. The ability to handle missing data, which exists in KBES, offers an advantage. All of these capabilities make the use of KBES in pavement management systems important and crucial to the development of efficient pavement management practices. KBES, through their user interface, are user friendly tools which should enhance user acceptance and utilization of the pavement management system, which in turn yields better management practices and more efficient use of available funds.

The use of dynamic programming for resource allocation and project selection has been proved to be feasible and beneficial in earlier research by the author (3). Dynamic programming reduces the problem size and guarantees optimal solutions. Optimization approaches, like dynamic programming, have been shown to provide agencies with increased benefits beyond those normally realized from using prioritization techniques. Using optimization approaches for project selection increase agencies benefits (expressed in longer life and/or improved pavement condition) by 20 to 40 percent (5). The use of dynamic programming for project selection and resource allocation in this research has been modified from the original research to take advantage of the added flexibility of using KBES for performance prediction and treatment strategy selection. This should result in a more efficient allocation of resources and project selection which means improved pavement condition and better utilization of available maintenance and rehabilitation funds.

Research Objectives

The research documented in this dissertation centers on the use of knowledge-based expert systems in pavement management. The objective of this research is to develop a comprehensive pavement management system using the following modules:

1. Condition forecasting. KBES is used to develop a performance prediction model capable of forecasting pavement condition (overall condition or individual performance parameters) for as many years as required in the planning or analysis period.
2. Treatment strategy selection. KBES is developed to determine the feasible maintenance and rehabilitation strategies for each pavement section based on its condition. The KBES is capable of generating multiple treatment strategies for each section and for each year in the planning or analysis period.

3. Resource allocation and project selection. Dynamic programming is used to develop a resource allocation and project selection model for the optimal allocation of available funds to projects and for the selection of the most effective treatment strategy for each section based on overall objective (minimum cost or maximum benefits) and bound by system constraints.

Research Organization

The remainder of this dissertation is organized as follows.

Literature Review

This chapter is divided into three parts. The first provides an in-depth review of the basic components of pavement management systems and how they relate to the decision making process. The second reviews the basic architecture of knowledge-based expert systems and discusses the feasibility of applying the technology to pavement management. Finally, example applications of knowledge-based expert systems to pavement management will be discussed to identify gaps in the current state-of-the-art in the pavement management field.

Problem Statement

This chapter provides a detailed description of the research. It will identify the main components of the pavement management system, and the variables and decisions involved in each component. A discussion of the necessary input data and the output from each component of the pavement management system is included. A complete description of data requirement and level of analysis will be discussed.

Methodology

This chapter consists of a detailed description of the solution procedure, followed by the specific design of all of the model components. The results from the developed model is evaluated to determine its feasibility and applicability to current and future pavement management practices. Example applications for each module are implemented and input and output elements are described.

Computer Models Formulation

This chapter describes the steps taken to formulate the computer programs that are used to solve the problem described earlier. After the completion of the different module formulation, a case study is conducted to examine the results from the different computer programs. Data from the Iowa Department of Transportation (Iowa DOT) Interstate system is used to formulate the case study.

Results

This chapter covers the results of the case study. A comparison between what the Iowa DOT currently uses as a pavement management system (multi-year prioritization) and KBES and dynamic programming will be presented.

Discussion and Conclusions

This chapter summarizes the result of this research. It uses the results from the example to comment on the research findings and suggests future research work in this area.

LITERATURE REVIEW

This chapter is divided into three major sections. The first section consists of a general, yet detailed, description of the main components of pavement management systems. Performance prediction and resource allocation models will be discussed. Management analysis levels (network and project-level) and data requirements for each analysis level will be covered in this section.

The second section covers the basic engineering architecture of knowledge-based expert systems. The main components of KBES, the knowledge-base, the context, and the inference engine are described. Some additional components such as the explanation and the knowledge acquisition facilities will also be discussed. The feasibility and applicability of knowledge-based expert systems to be used in pavement management applications are discussed.

Finally, the last section includes some examples from the pavement management literature on the application of knowledge-based expert systems to pavement management decision support tools. Examples covering the use of the knowledge-based expert system for treatment strategy selection (diagnosis) and performance prediction (forecasting) are presented. Last, the gaps in the current practices and applications of knowledge-based expert systems to pavement management decision support tools will be examined to highlight the importance of this research.

Pavement Management Systems

The Federal Highway Administration defines a pavement management system as "a set of tools or methods that (can) assist decision makers in finding cost-effective strategies for providing, evaluating, and maintaining pavements in a serviceable condition" (6). A somewhat simplistic description is that pavement management will help pavement engineers and top management in initiating cost-effective decisions relative to the "what," "where," and "when" in terms of pavement maintenance and rehabilitation. What treatment is cost effective?; where are treatments needed?; and when is the best time to program a treatment? The general structure of this approach includes nine basic elements (7, 8).

1. *Inputs.* A number of inputs, including different variables and objectives related to the pavement condition, must be established by the agency implementing the pavement management system,
2. *Models.* Since pavement management involves several strategies and objectives, several modeling tools are required to analyze and evaluate potential alternatives by the pavement management system,
3. *Behavior-Distress.* The behavior of distress associated with various inputs and their predicted reaction or performance must be identified. Prediction models for determining pavement response and distress behavior become an essential part of the pavement management system,
4. *Performance-Output Function.* Accumulated distress reduces pavement serviceability, which ultimately defines pavement performance over time,
5. *Safety.* Skid resistance and other safety records associated with each strategy employed must be maintained and included in the analyses of the different alternatives,
6. *Costs.* Life cycle economic analysis is a vital part of the pavement management process. All costs over the life of the pavement must be considered to assure accurate evaluation of alternative future pavement activities (maintenance, rehabilitation, and design),
7. *Decision Criteria.* The decision criteria are closely tied to economic analysis on allowable costs versus the resulting benefits related to a particular alternative.

These factors must be explicitly defined and considered in the analysis because of their influence in the selection of alternative strategies,

8. *Compare-Optimize*. Selecting the optimal alternatives or strategies is an important step in the decision making process, and
9. *Implementation*. Resource allocation and programming of the selected alternatives or strategies, and periodic maintenance plus rehabilitation when required constitutes full implementation of the pavement management analysis.

Even though, pavement management systems will differ depending on the size, organizational structure, and resources of each implementing agency, it should nonetheless, perform the following functions (2):

1. Improve the efficiency of decision making involving pavement management activities,
2. Expand the scope of the pavement management process by incorporating relevant information in the decision making process,
3. Provide feedback on the consequences of future decisions,
4. Facilitate communication, cooperation, and coordination of pavement management activities within an agency, and
5. Ensure consistency of decisions made at different management levels within the same organization.

Implementing a pavement management system in an agency can result in several benefits. The case history of successful and beneficial implementations of pavement management systems is well known and rich. Even though, it is sometimes difficult to measure the direct economic benefits of implementing a pavement management system, one unquestionable benefit lies in the selection of the most cost-effective maintenance and rehabilitation alternatives. This benefit allows, at a minimum, for the most efficient use of funds available to an agency. In addition to direct economic benefits, a pavement management system has many other potential uses, including (9):

1. More accurate and accessible information on the pavement network,

2. Quantify the assessment of the condition of the pavement network,
3. Ability to track the performance of specific treatment strategies,
4. Identify needs to plan future activities and expense budgets,
5. Support requests to state legislatures for additional funding for pavement maintenance and rehabilitation activities,
6. Justify and support decisions as to project prioritization when dealing with local politicians or the public,
7. Improve credibility when dealing with top management within the transportation agency,
8. Provide a basis for allocating funds among different districts or agencies, and
9. Help select the best rehabilitation measures or strategies for different pavement management sections.

The full range of benefits will not be completely realized until complete implementation is achieved. One important factor to consider when implementing a pavement management system, is to have a full understanding of what complete implementation means. Operating a pavement management system is not the same as implementing a pavement management system (10). Smith and Hall have defined implementation to occur "when pavement management becomes the critical component for making pavement management decisions" (11). This definition extends beyond the purchase of pavement management system software, and even, the development of supporting databases and personnel. It involves the actual and ongoing use of the pavement management system's result to support decision making at all levels.

The question of why an agency should implement a pavement management system can be easily answered by the perceived and/or potential benefits of pavement management. Another reason for implementing a pavement management system, is the large investment that agencies have in their pavement network. The United States has approximately 3.9 million miles of roads, including 2.3 million miles of paved highways (12). Approximately 50 percent of the primary, secondary, and urban roads and 43 percent of the interstate highways are rated in only fair condition (13). Since 1956, over one trillion dollars have been invested in the United States highway system and approximately $400 billion would have been spent repairing pavements at the end of the 20th century (13). In 1992, capital improvements represented 46.5 percent of total expenditures for highways while maintenance activities accounted for 27 percent (12). Any modest improvement in the methods or tools used for the allocation of these limited resources will result in a substantial benefit of improved pavement condition and more efficient use of funds.

All pavements deteriorate over time because of traffic application and environmental factors. Figure 2, based on research conducted by the Utah Department of Transportation (14), shows the average deterioration rate and the change in repair costs ($/Sq.yd) as the pavement deteriorates. It is clear from Figure 2 that with more frequent early treatments in the life of the pavement, overall life costs will be less than waiting for the pavement to deteriorate. This is the basic principle behind pavement management systems (i.e. it is less expensive to maintain pavements in good condition) (15). Pavement management practices are based on the concept of finding a cost-effective combination of treatment strategies to apply at any given time to a specific pavement section to maintain or achieve a desired serviceability level.

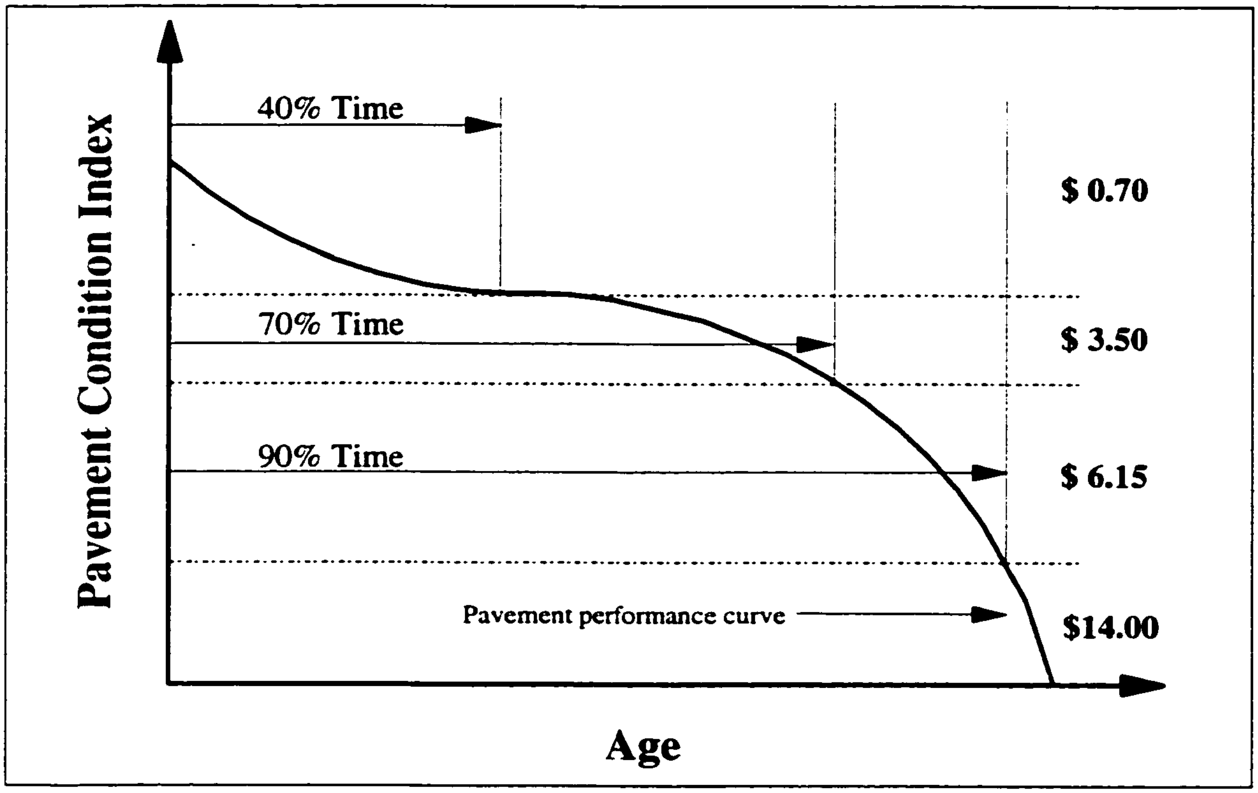


Figure 2. Effect of Treatment Timing on Repair Costs (14)

Pavement management systems can generally be classified into two levels, network and project levels. The differences between the two extend beyond the level at which decisions are being made, to include differences in the amount and type of data collected, personnel involved, and decisions made. The purpose of network-level PMS is normally related to budgeting, identifying needs, and determining the impacts of different funding programs on the overall pavement condition.

At the project-level, the pavement management system provides the most cost-effective maintenance or rehabilitation strategy for a selected pavement management unit given available funds. The two levels of PMS will be discussed later.

Since pavement management is defined as a set of tools or methods used in a systematic manner, there should be a process for each pavement management system to follow. This process defines the basic building blocks of a generic pavement management system. Figure 3 shows the pavement management process (16) in its two levels (network and project-highlighted in black). Figure 3 shows how a PMS at the network level deals with budgeting issues and how when the move is made to project level, project selection and maintenance alternatives are dealt with.

Pavement Management Levels

Two levels of pavement management decisions should be included in a comprehensive pavement management system; network level and project level. Some researchers and practitioners then split the network level pavement management system into two tiers: the program level and the project selection level (8). The following is a discussion of each level and its components focusing on the types of decisions made, data requirements, and differences between them. The two tiers of the network level PMS will be discussed under the network level portion of the discussion.

Network-level pavement management system

Network-level decisions are concerned with work programs and policy issues for the entire pavement network under one or more jurisdictions within overall budget constraints. Network-level pavement management systems provide an overall assessment of the highway network condition. In addition, network level PMSs answer "what-if" questions regarding

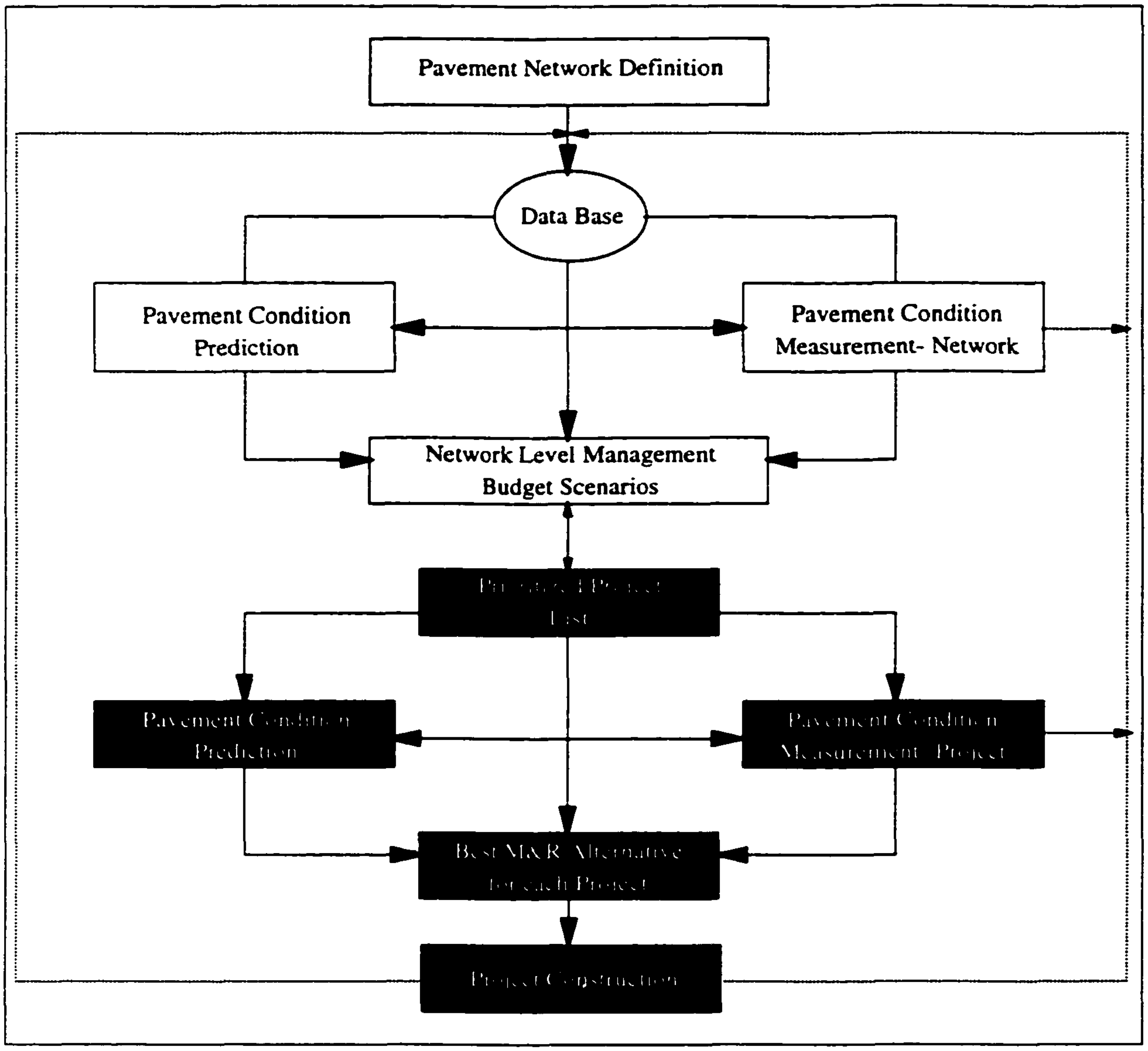


Figure 3. Pavement Management Process (16)

varied budget scenarios and funding criteria. In general, network level PMS data requirements are less detailed and different than those of project level PMS data requirements. Figure 4 gives a general overview of the apparent differences between these pavement management levels (network and project levels) (8).

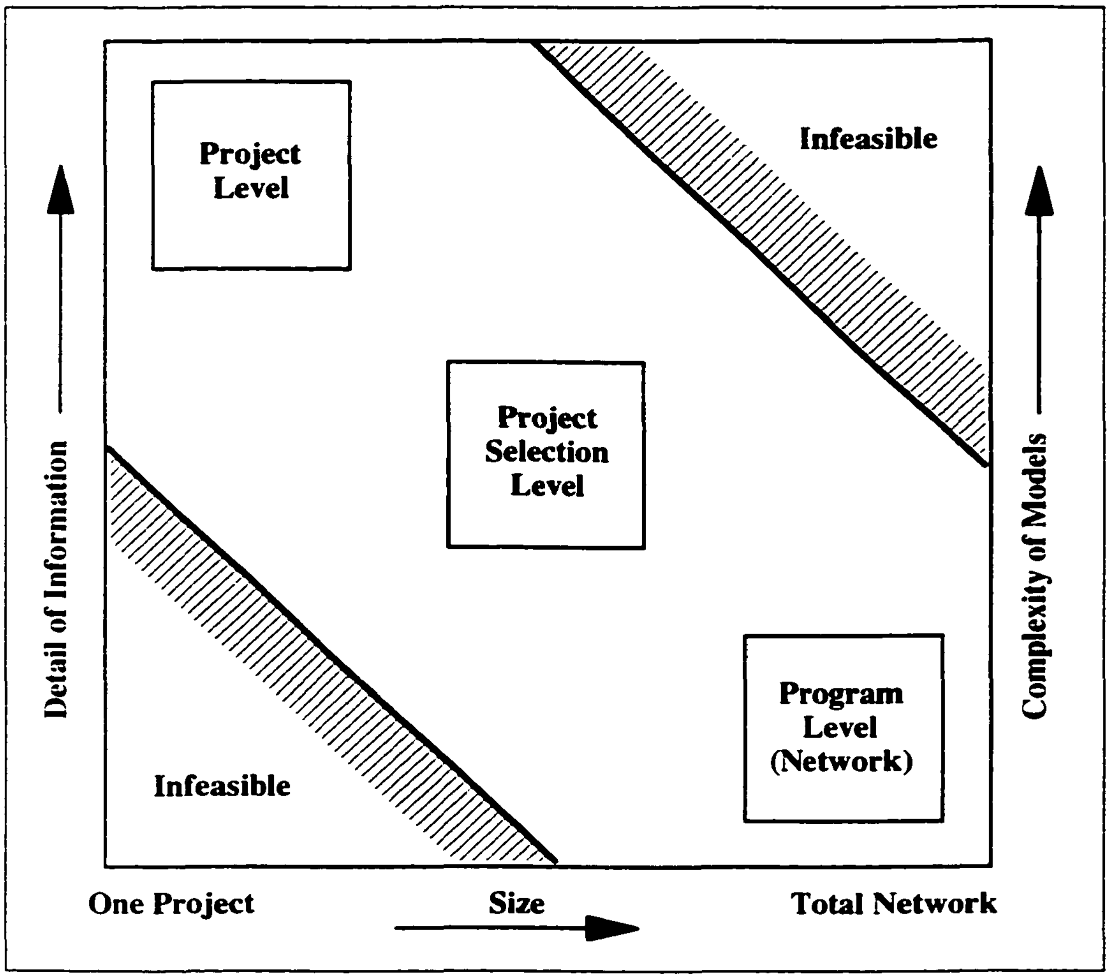


Figure 4. Information Detail and Complexity of Models for a Three Level PMS (8)

Figure 4 shows the difference between the project selection level pavement management system and the program level. The project selection level, which is considered a network level PMS, requires more detailed data than program level and also requires more complex models to accomplish the defined goals of that sort of analysis. Project selection level PMS involves decisions regarding individual projects or group of projects, while program level PMS involves general budget allocation decisions for the entire highway network. Decision making models used at the project selection level are constrained by budget and/or condition requirements and involve prioritization, near-optimization, or optimization techniques for both resources allocation and project selection.

Program level pavement management systems involve policy decisions regarding maintenance or rehabilitation for the highway network as a whole. Budget allocation is the primary focus at the program levels. Decision making models are used to optimize the use of funds allocated for maintenance and rehabilitation. The goal is to consider the effects of budget allocations on the overall condition of the highway network. Also, budget allocations provide guidance on the distribution of funds between maintenance and rehabilitation activities.

Project-level pavement management system

Project-level pavement management system decisions are directed toward individual and/or specific sections or subsections of the pavement network. Budget constraints are usually not considered at the project level. As shown in Figure 4, project-level PMSs require more detailed pavement data and the decision making models tend to be more complex than those of network-level PMSs.

Data requirements for project level PMSs include pavement condition, pavement construction history, inventory (material, traffic, initial design thickness, etc...), and past maintenance activities. The specific set of data needed to conduct project level activities differs depending on the decision making model used and agency needs. The typical outcome from a project-level PMS is in the form of a set of design strategies that minimize the total life cycle cost of the pavement section including construction, maintenance, and user costs, while satisfying minimum performance requirements meeting funding limits.

Pavement management levels interaction

The two levels of pavement management decisions must interface with one another. There should be interaction between project and network levels and also interaction between the two tiers of network level analysis. Interaction between the project selection and program level is evident in terms of estimating the budget required at the program (network) level because it requires cost estimates for candidate projects. Also interaction between project selection and project level is evident when different projects are selected for final design from the candidate list at the project selection level. Budget guidelines from the program level must be adhered to at the project level.

From this discussion, it appears evident that at whatever level the PMS is operating, specific pavement data, decision making models, and interaction procedures should be considered. Depending on the level of the pavement management system and agency needs, those different parameters can be more accurately identified.

Performance Forecasting Models

Pavement performance forecasting models are an integral part of any complete pavement management system. A forecasting method is described as " a mathematical description of the expected values that a pavement attribute will take during a specified analysis period" (6). Pavement performance forecasting models are used at both the network (program or project selection levels) and project levels to analyze the condition and determine maintenance, rehabilitation, and reconstruction requirements and needs. At the network level, forecasting models are used for condition forecasting, budget planning, and work planning. They are also used for answering "what if" questions regarding the impact of varying budget levels on overall pavement condition.

Forecasting models at the project level are used to select specific treatment strategies to meet certain traffic and environmental conditions. Forecasting models provide the tools to conduct life-cycle-cost analysis to compare the cost and performance of different maintenance and rehabilitation alternatives.

Condition forecasting models are divided into two major categories: deterministic and probabilistic (stochastic). Depending on the pavement management system level (network vs. project), complexity of the pavement management system, and type of resource allocation models used, an appropriate condition prediction model can be selected.

Deterministic condition forecasting models

Deterministic models are usually developed using regression analysis (linear or non-linear) that relate pavement condition to age or traffic loading (Equivalent Single Axle Load, ESAL). Figure 5 shows an example of a non-linear deterministic performance curve describing the relationship between pavement condition and age. The points in the chart represent raw condition data, while the line represents regression analysis results. Regression curves are developed for different pavement types (asphalt, rigid, and/or composite) or for pavement families (pavement type, traffic levels, geographic area, etc...) which cause differences in pavement performance. One performance curve is then used to forecast the pavement condition for each pavement section that belongs to that pavement family. Some agencies actually develop performance curves for individual pavement management sections instead of pavement families. This process requires a large database of historical pavement condition information.

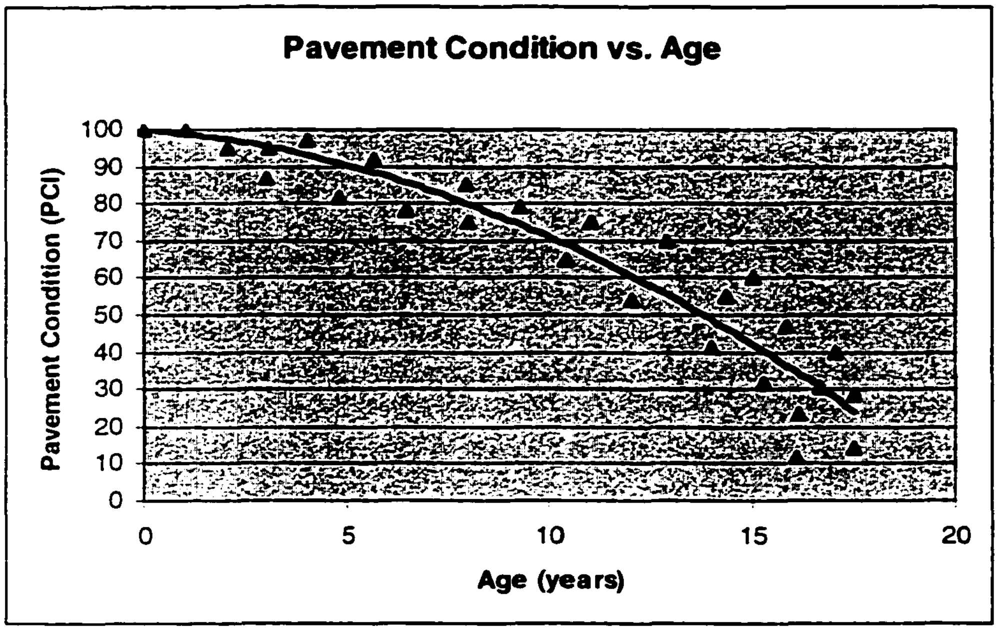


Figure 5. Deterministic Performance Curve

Deterministic performance curves are developed for composite pavement condition indices or for individual distresses (cracking, roughness (IRI), rutting). Composite indices are usually used to determine changes on the overall pavement condition while individual distress indices are used for trigger limits and treatment selection.

To develop deterministic performance curves that represent the existing condition with an acceptable degree of accuracy, a long term database of historical, construction, and condition information is required. The accuracy of the performance prediction models depends on the quality of the condition data, consistency of data collection, and the extensiveness of the historical data available to classify pavements into different performance families or categories.

In cases where historical information is not adequate, regression analysis can still be used, if it is supported by expert opinion. For example, the South Dakota Department of Transportation developed a set of individual distress indices using the available historical information and expert opinion (17). A panel of pavement experts from the areas of maintenance, materials, construction, pavement design, and field engineers was convened to develop the performance curves. The panel developed a questionnaire to collect expert opinions from pavement experts around the state. Performance models were developed for individual distresses for different pavement types. The panel recommendation was to evaluate those models on a regular basis and modify them as more historical data become available (17).

Another method used to support historical data are Bayesian statistics. The Bayesian statistical methodology combines the historical data collected for different pavement categories with information elicited from experts (18). This approach is useful because it provides for validation of the performance model by experts. Expert opinion increases the reliability and predictive power of the performance model, and it facilitates the quantification and comparison of the influence and contribution of the expert judgment which increases the acceptability of the performance models by the pavement management system users (18).

Probabilistic condition forecasting models

Probabilistic models are usually developed using historical data supported by expert opinion. Probabilistic models capture the subjective experiences of local engineers and pavement experts. Transitional probability model (or matrix) based on the Markov process, is one of the most common methods used to develop a probabilistic condition forecasting model. In the Markov process, the future state of the pavement is estimated solely from its current state. The state of the pavement is defined using condition measures such as cracking and roughness. For modeling purposes, the condition measures are defined based on ranges. A condition state will represent the different condition measure ranges for that state. For example, a condition state that is based on a cracking value (range from 1 to 5) can be used to describe a pavement section state depending on the value of the cracking index. Each pavement section can be in one of five states (1 to 5) depending on the cracking value. The transitional probability model defines the probability that a pavement section in an initial condition state will be moving into a future condition state (through deterioration) in one year. Figure 6 offers an example of a Markov process transitional probability matrix. The cells in the matrix define the probability of moving from one state to an other in a year based on a 5 state system. For example, the first cell (0.9) defines the probability that a pavement section in state 1 (cracking value 1) will stay in that state during a one year period 90 percent of the time. The second cell (0.1) defines the probability that a section in state 1 will transfer to state 2 in one year 10 percent of the time. Each row in the transitional probability matrix must sum to 1 to account for all pavement sections in the network.

	To State				
From State	1	2	3	4	5
1	***0.9***	***0.1***			
2		***0.8***	***0.2***		
3			***0.6***	***0.4***	
4				***0.5***	***0.5***
5					***1.0***

Figure 6. Markov Process Transitional Probability Matrix

Transitional probability matrices are developed for routine maintenance and other rehabilitation strategies to show the impact of maintenance and rehabilitation treatments on the pavement condition. The matrix in Figure 6 is an example of a transitional probability matrix for routine maintenance or the do-nothing alternative. For example, a pavement section in state 2 has an 80% probability of remaining in condition state 2 and a 20% probability of moving to condition state 3. Since Markov probability matrices define the transition from one condition state to more deteriorated condition states, other factors that affect the pavement behavior are handled by defining multiple probability matrices. Pavement type, pavement thickness, traffic volume, and physical characteristics (subgrade type and thickness) are used to define different transitional probability matrices (different pavement families). For example, individual transitional probability matrices will be developed for asphalt, concrete, and composite pavements.

Project Selection and Resource Allocation Models

Project selection and resource allocation models are considered to be two of the most important components of a pavement management system. Project selection and resource allocation models consider all of the pavement management data (history, inventory), performance prediction models, system constraints, and limitations and produce a list of recommended projects with rehabilitation alternatives and timing. Depending on the complexity of the analysis, the mathematical models used, and the length of the analysis period, project selection and resource allocation models can be divided into three major categories. These categories are:

1. Ranking models (single year prioritization)
2. Multi-year prioritization models (heuristics)
3. Optimization models

Depending on which model is used, data requirements, procedures, and output will be determined. The complexity of the project selection and resource allocation model will increase from the ranking models to the optimization models. Data requirements are also dependent on the model used. The following is a brief description of the different categories.

Ranking models

Ranking models are the simplest form of prioritization The methodology consists of ranking projects according to the pavement condition or any other parameter. Each year, the pavement sections are ranked according to the ranking criteria and projects with the highest ranking will be selected until the maintenance and rehabilitation budget is exhausted. In the ensuing years, the process is repeated to determine a maintenance and rehabilitation program for the number of years in the analysis period. Ranking criteria can be weighted using additional factors that are important to the agency managing the pavement. Such factors as traffic and functional classification are most commonly used.

The ranking criteria selected vary among transportation agencies. The following is a list of potential ranking methodologies:

1. Rank by pavement condition
2. Rank by benefit to cost ratio
3. Rank by life cycle cost
4. Rank by initial cost

In most cases, the pavement condition (measured using different distress measurements - cracking, roughness, rutting, patching, etc...) is used to determine the feasible maintenance or rehabilitation alternative. Typically, two or three alternatives are selected for each project. After treatments are assigned, the final cost is determined and a final list of projects based on the available budget will be determined. Figure 7 illustrates the ranking process and shows the major steps needed to complete the analysis. Starting from existing or current conditions, treatment strategies are selected and costs are determined. Finally, projects are ranked according the agency's criteria and final projects and treatments are selected.

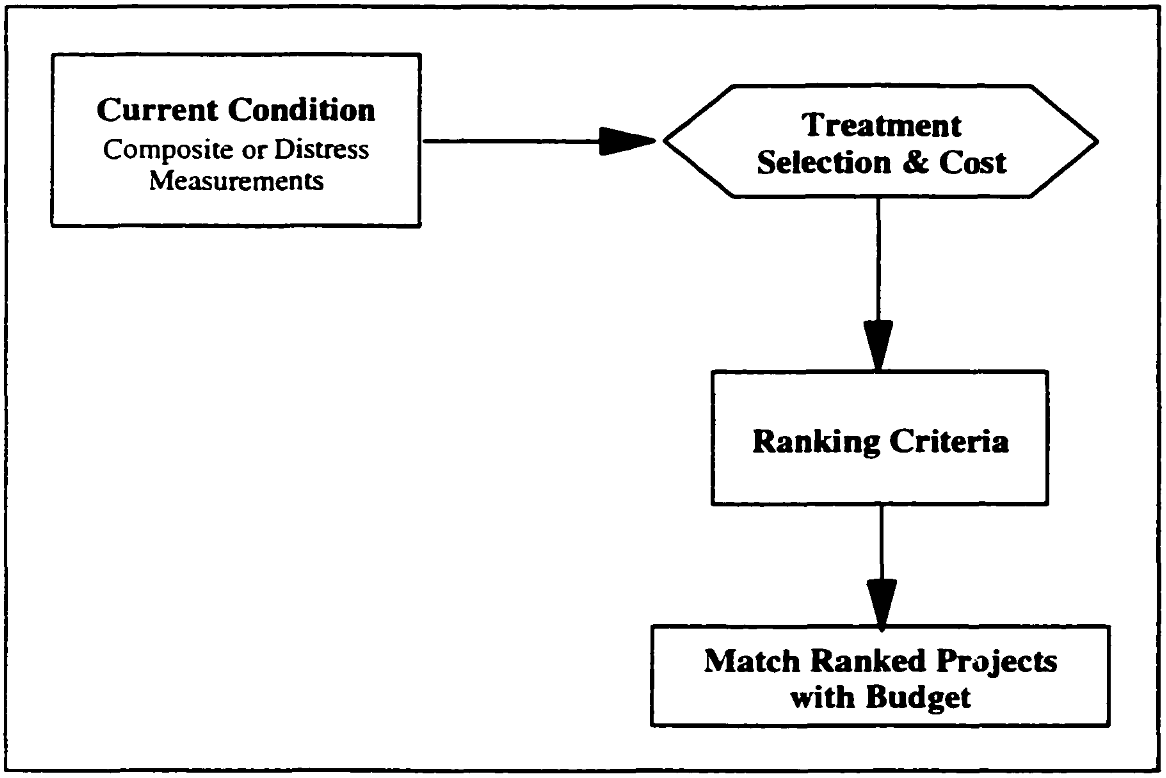


Figure 7. Ranking Process

Multi-year prioritization models

Multi-year prioritization (MYP) is a more sophisticated approach to project selection and is close to being optimal. MYP approaches are usually referred to as near-optimization and/or heuristic techniques. MYP approaches are mathematically easier than full optimization and require less computation time and resources. At the same time they achieve results that are near optimal. The MYP process is similar to the ranking models with a major difference in treatment selection and timing. While in ranking models treatments are selected based on existing conditions, MYP models consider multiple years and existing and future pavement condition (using condition forecasting models) for the selection of feasible treatment strategies. Figure 8 shows the MYP process with the treatment selection and the analysis boxes highlighted to show the differences between ranking and MYP models. Figure 8 also shows the types of analysis methods (incremental benefit cost-IBC, marginal cost effectiveness-MC, or benefit cost analysis-BC). These methods will be explained later.

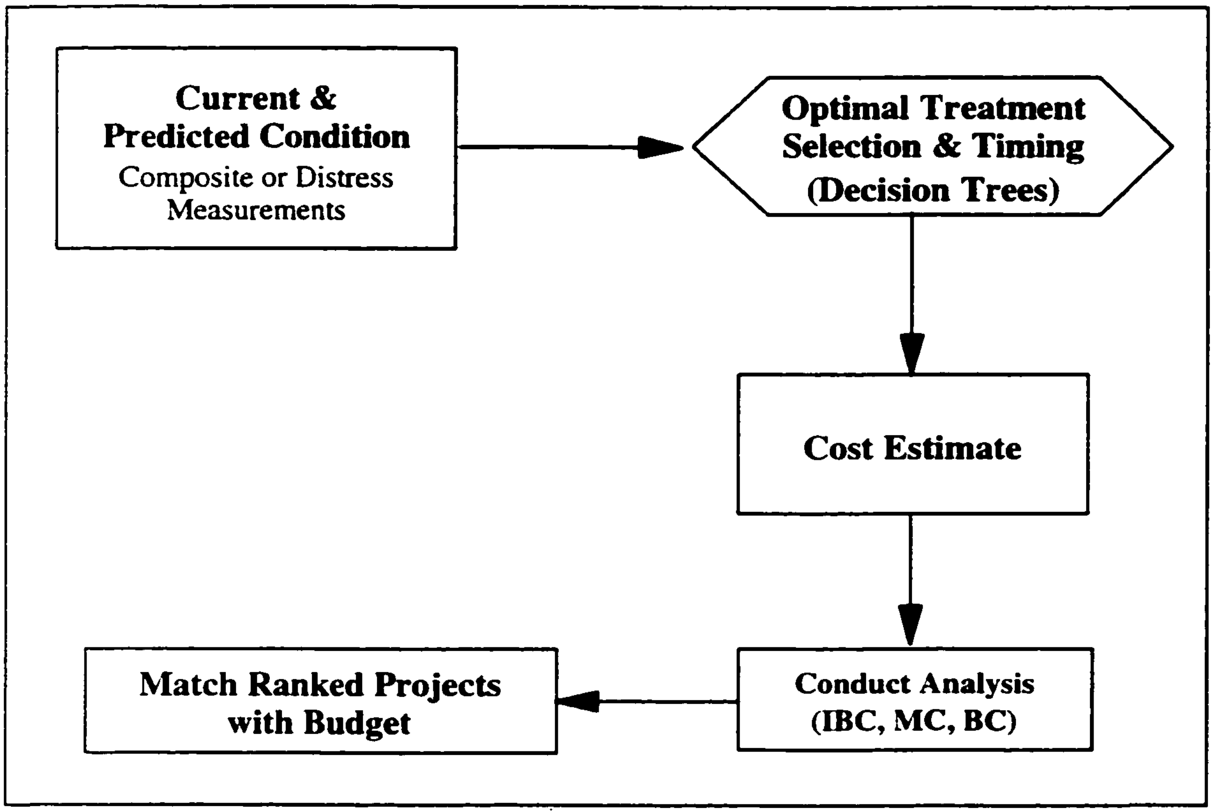


Figure 8. Multi-Year Prioritization Process

MYP approaches use mathematical models to achieve the best combination, over a specified time period (analysis horizon), of the following:

1. The pavement management sections in the network to receive a treatment strategy (reconstruction, rehabilitation, or maintenance)
2. A treatment and/or a combination of treatments to apply to each pavement management section or project

3. The most effective timing for applying the appropriate treatment strategy over the analysis period.

To achieve these three objectives, models that estimate future pavement condition (deterministic condition forecasting models or remaining service life models), procedures to define the required treatments strategies for different conditions, trigger limits based on decision trees or decision matrices, and finally, models to measure the effectiveness of the treatment and timing selection (incremental benefit cost analysis or marginal cost effectiveness analysis) are needed.

Deterministic condition forecasting models were discussed earlier in this chapter. The remaining service life (RSL) is a similar approach to deterministic performance prediction with a slight difference in that it considers the number of years until a specific pavement section will become unserviceable. RSL considers threshold values which defines when a pavement becomes unserviceable for different performance criteria (overall pavement condition index, individual distress index).

To calculate the remaining service life for each pavement management section, threshold values, condition indices, and performance curves must be defined. Figure 9 illustrates the concept of calculating the remaining service life of a pavement section for an individual condition index considering the current condition, performance curve, and the threshold value. The condition index performance curve is used to predict when the pavement section performance reaches the threshold value (a point at which pavements are considered serviceable if above it and unserviceable if below it as shown in figure 9) defined for that specific condition index. The time in years it takes to go from the current condition to reach the threshold condition is defined as the remaining service life (see Figure 9) for that condition index on that pavement section. The RSL must be calculated for each condition index before the pavement management section RSL is calculated. Each pavement management section can only have one RSL, which is the minimum of all the RSLs calculated for each condition index. If an agency has three condition indices to consider for a remaining service life analysis and the resulting RSL for one pavement section is 4, 3, and 6 years respectively, then the RSL for that pavement management section is calculated to be 3 years.

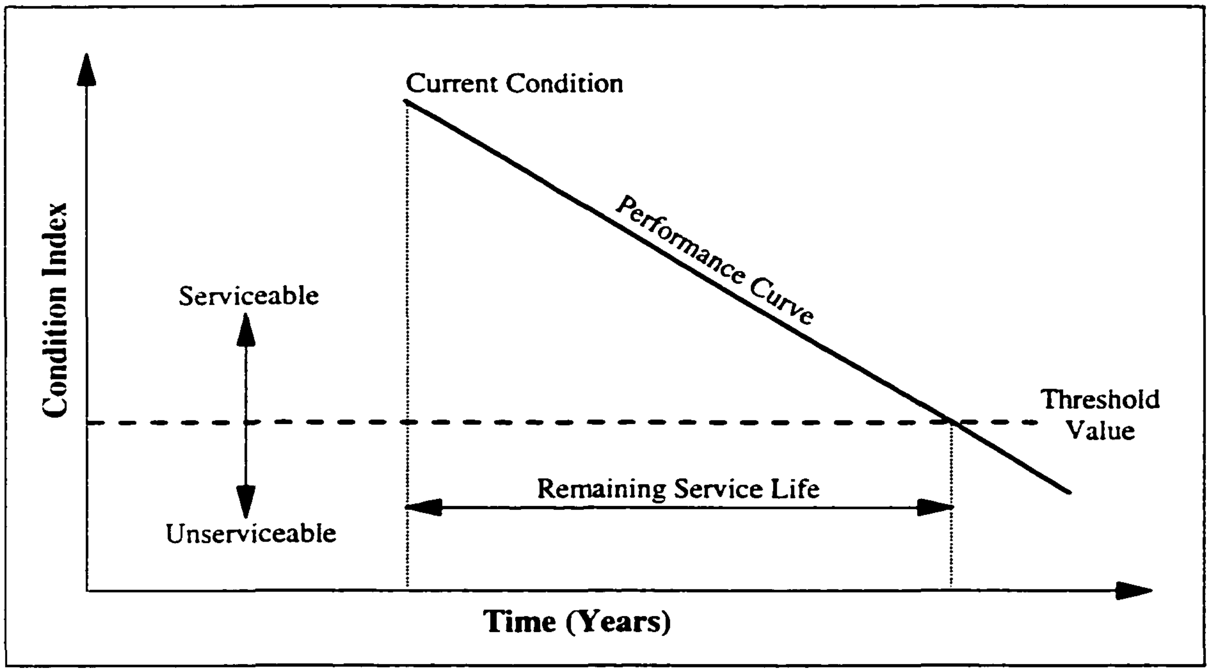


Figure 9. RSL Calculation for an Individual Condition Index

Trigger limits, whether based on decision trees or decision matrices, are used to establish a set of rules (based on pavement condition, pavement characteristics, traffic) to determine the feasible treatment strategy for each pavement management section through the analysis period. While a decision tree defines treatment strategies using branches which define various sets of conditions, a decision matrix defines the condition through the use of tables rather than branches. Figures 10 and 11 illustrates the two types of treatment selection making techniques.

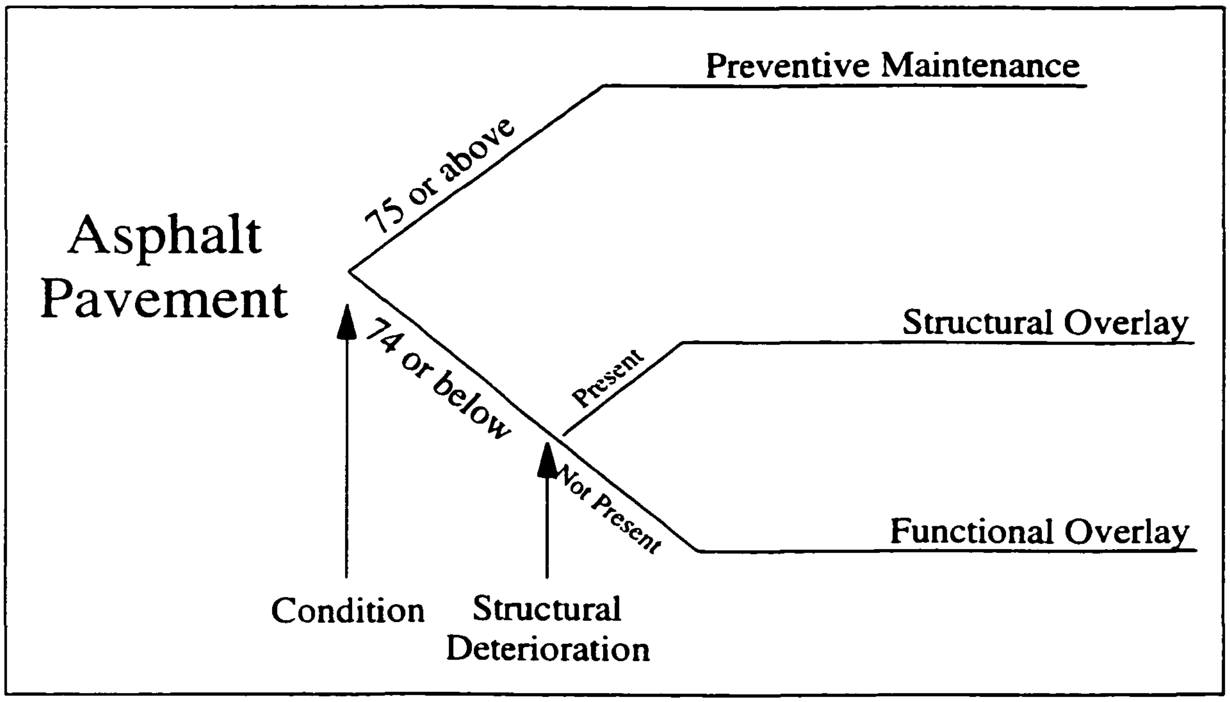


Figure 10. Treatment Decision Tree

Treatment Type	Surface Type	Condition Level	Structural Deterioration
Preventive Maintenance	Asphalt Concrete	75 - 100	N/A
Functional Overlay	Asphalt Concrete	0 - 74	Not Present
Structural Overlay	Asphalt Concrete	0 - 74	Present

Figure 11. Treatment Decision Matrix

The development of decision trees or decision matrices is based on the replication of the agency experience and their thought process of the manual treatment selection. The level of detail required is based on the agency needs and the complexity of their pavement management system decision support tool. Decision tree branches (Figure 10) or decision matrices levels (Figure 11) depend on one or more of the following parameters:

1. Pavement surface type or construction history
2. Functional classification or traffic
3. One or more condition index (overall, individual distress, roughness)
4. Physical characteristics (geometry or material)

The final component of the MYP process covers the mathematical models used to calculate the effectiveness of applying a specific treatment strategy at a specific time for each section. Two common approaches are used to perform this sort of multi-year prioritization: incremental benefit cost and marginal cost effectiveness.

In the two approaches, a measure of the benefits that results from applying a treatment strategy is calculated based on the additional life provided by the implementation of that treatment strategy. Figure 12 shows the calculation of the benefits using the area under the performance curve to quantify the benefits. From Figure 12, it can be seen how the benefits are calculated by comparing the existing condition with the new condition and performance resulting from the implementation of a specific treatment strategy. Each alternative treatment strategy is compared to the existing condition and the difference is the benefit of implementing a specific treatment strategy. The cost of the treatment, initial and life cycle cost, are also defined for each alternative. The cost effectiveness and the benefit cost ratio are calculated based on the benefits and total cost for each alternative. The recommended treatment alternative for each pavement management section is the one that provides for the highest cost effectiveness, largest benefit to cost ratio, or the greatest incremental benefit cost ratio.

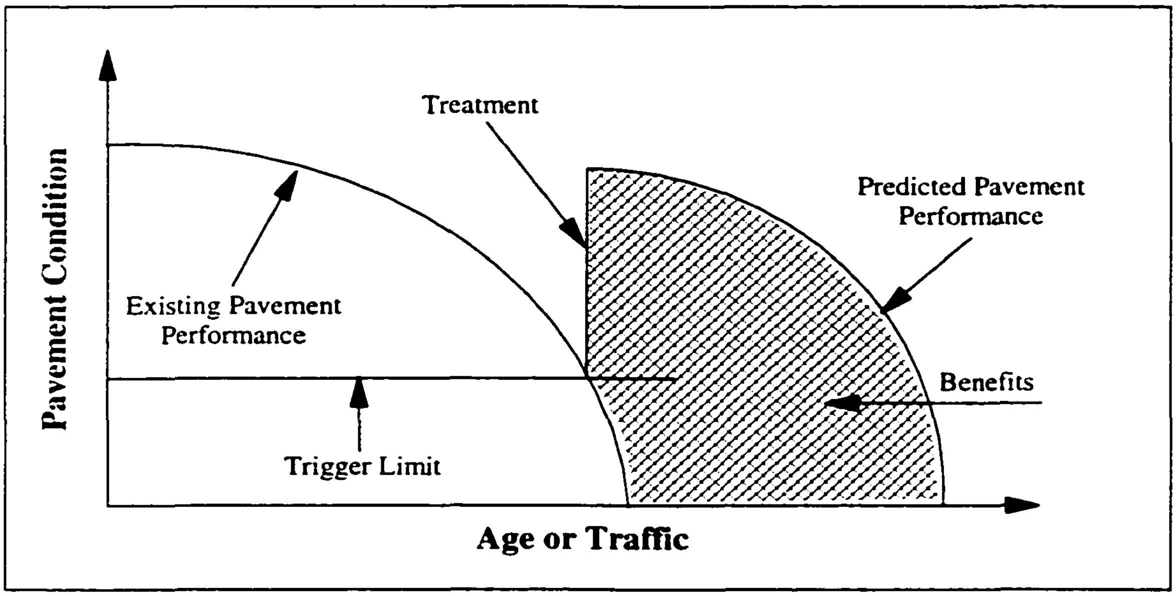


Figure 12. Benefits Calculation

As mentioned earlier, all of the different maintenance alternatives should be considered as part of the analysis. The different alternative treatment strategies are selected based on the trigger limits defined earlier in this section (using decision trees or matrices). Different treatment strategies and different application times (specific years) for the same treatment strategy will be compared and the alternative that provides the greatest benefit to the agency or to the users will have a higher priority in the program development process. Figure 13 shows how different treatment alternatives are considered as part of the benefit calculation process. The use of trigger limits for treatment selection is also shown in Figure 13. Two different triggers are used to select two different treatment strategies at different times in the analysis period. Since multiple treatment strategies are considered for each pavement management section, this process lends itself to the use of computers to develop priorities for the final program.

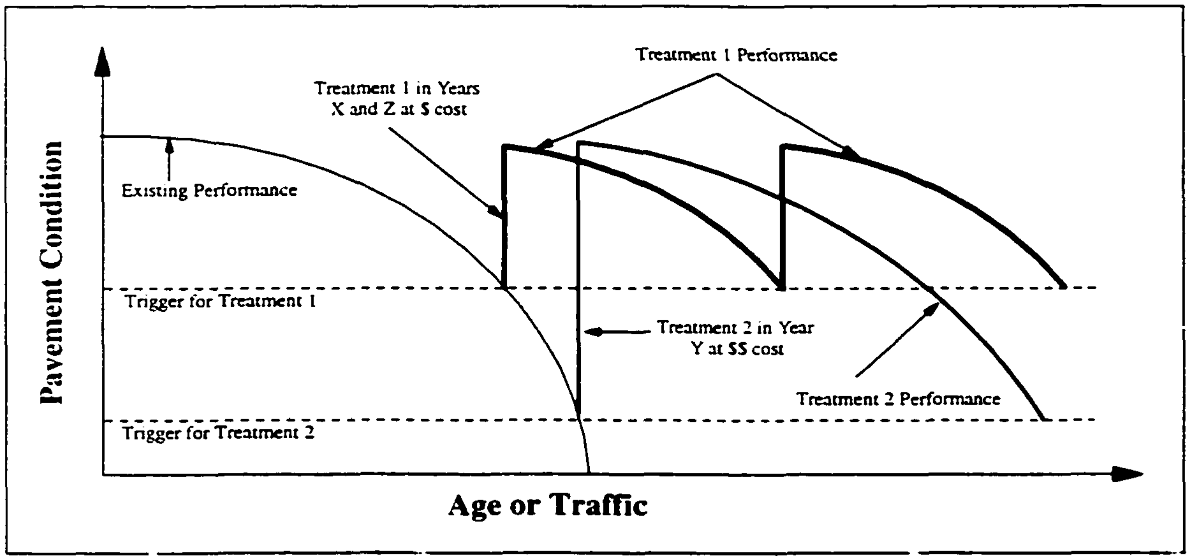


Figure 13. Alternative Treatment Strategies for MYP Analysis

The MYP process differs from the ranking process in a number of ways. First, in most cases, a number of alternative treatment strategies are considered in the MYP. The use of the benefit calculation generally identifies the alternative that provides the most benefit to an agency while ranking considers only one assigned option for a specified condition level. MYP approaches enable the users to simulate future condition through the use of performance models which enables considering the expected performance of different treatment alternatives.

MYP solutions closely represent results obtained using optimization techniques. Heuristic approaches such as incremental benefit cost analysis, provides solutions similar to those obtained utilizing integer programming (19, 20). MYP approaches also allow the users to set targets for future levels of serviceability and impacts of various funding levels on the overall average pavement condition network.

Optimization models

Optimization models are the most sophisticated form of multi-year pavement management system analyses. Through the use of mathematical models, optimal solutions are obtained in accordance with agency established goals and conditions. Agencies using pavement management optimization systems select a factor to optimize. Those factors may be to maximize user benefits, minimize agency cost, minimize total cost (agency and users), or maximize asset value. Depending on the objective of the agency, a set of constraints or conditions would have to be taken into account. Minimum condition (performance) levels and annual budgets are just two attributes commonly used as constraints. Figure 14 shows the optimization process steps showing the budget and condition input (constraints) and optimization models.

Mathematical programming techniques used in pavement management systems can be one of the followings:

1. Linear programming
2. Non-linear programming
3. Integer programming
4. Dynamic programming (DP)
5. Goal programming

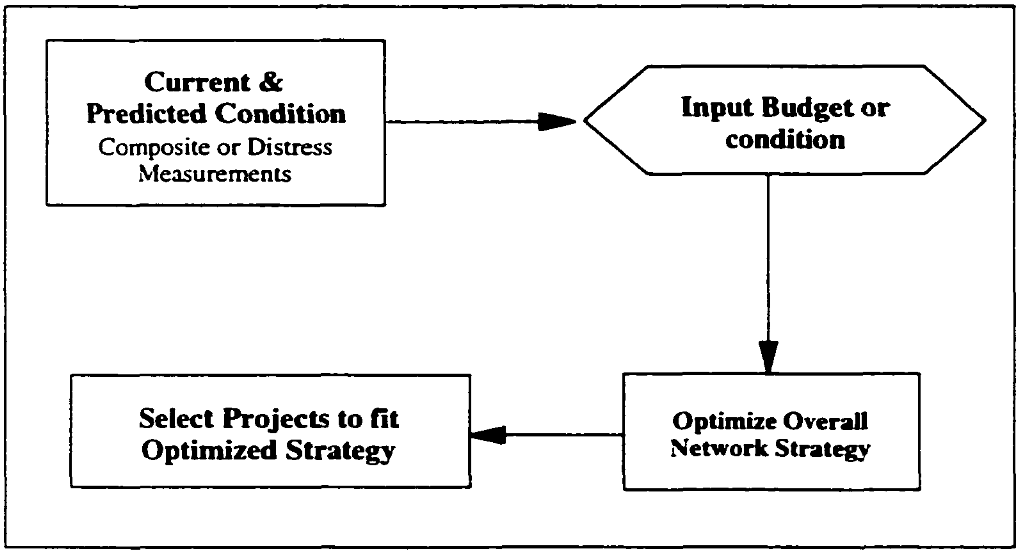


Figure 14. Optimization Process

An optimization analysis considers the optimization goal and uses mathematical programs to find the best solution from a very large number of possible solutions to the pavement management problem. Figure 15 shows an example of a simple linear programming model with only two decision variables (two dimensional space). Any point contained in the feasible region (infinite number of points) represents an alternative solution. The feasible region is defined using system constraints. Linear programming mathematically identifies the optimal solution to this simple problem. The pavement management problem is more complex in terms of the number of decision variables and system constraints considered in the analysis.

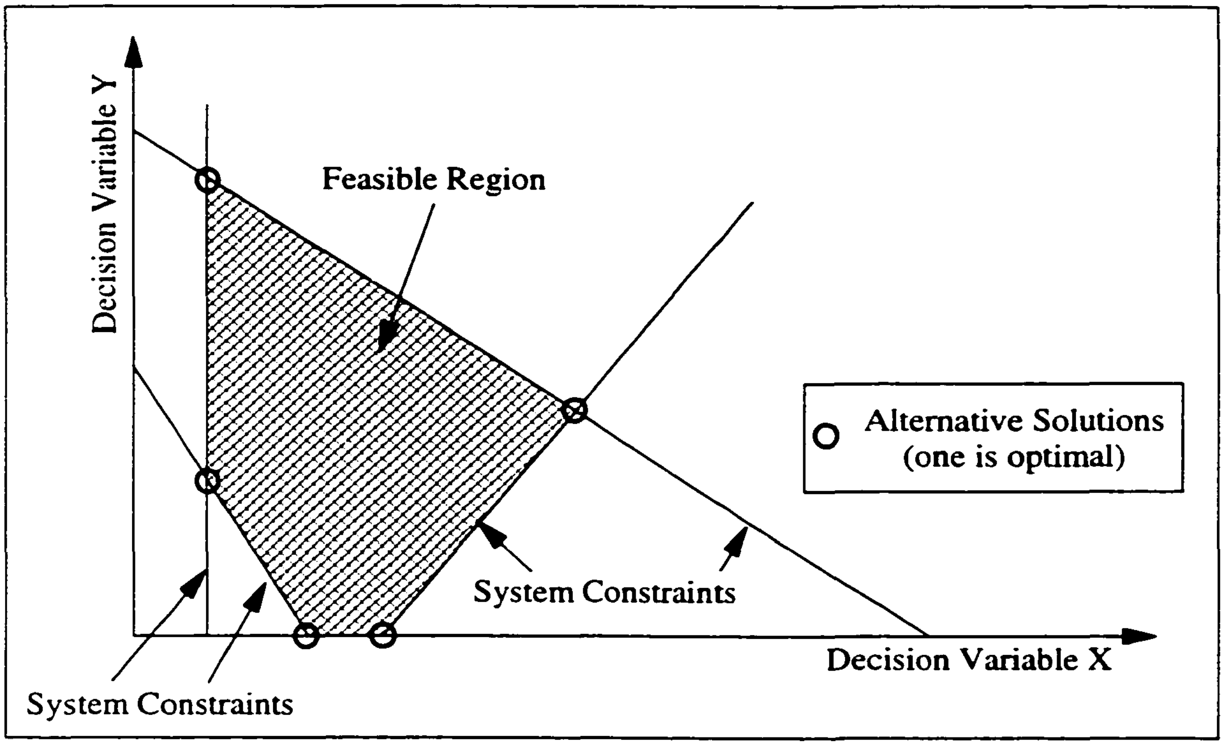


Figure 15. Linear Programming Example

Optimization analysis is usually conducted on the network rather than project level. Results tend to describe overall conditions instead of individual pavement management projects. As in MYP models, optimization models require the use of pavement management performance models to forecast the pavement condition. Performance models used in pavement management optimization systems tend to be probabilistic in nature. Markov chain models are one of the most commonly used condition forecasting technique in pavement management optimization systems. The optimization technique used for this research utilizes deterministic dynamic programming (DP), which provides a systematic procedure to determine the decision or combination of decisions that increase the overall effectiveness of the system. Each dynamic programming problem consists of a number of stages and states. Stages are defined as the number of years in the analysis period, while states are defined as the various conditions a pavement section can have (21). A state can be defined using a distress measure like cracking and patching for example, or by using a condition index (a combination of individual distress measures).

Optimization systems consist mainly of three components. The following is a brief description of each.

1. Objective function. This represents the agency's goal. Objective functions can be to minimize or to maximize a goal. It represents a function of all the decision variables in the pavement management model. For example, consider an objective function that minimizes the agency's cost. The objective function will be an equation that contains all of the decision variables multiplied by the cost of different decisions. The goal will be to select those decisions that minimize (optimize) the total cost.
2. Decision variables (Figure 15). These represents the different decisions. For example, if a project level optimization is considered, individual projects will be considered as decision variables. Each decision variable will be associated with alternative decisions (maintenance and rehabilitation strategies).
3. Constraints (Figure 15). System constraints define the feasible alternatives for the pavement management optimization problem. Constraints can be in the form of performance levels, budget numbers, and resources (material, equipment, labor, and time).

Dynamic Programming:

As discussed earlier, each dynamic program problem is divided into stages and states. Policy decisions, a component of each dynamic program, define the pavement maintenance or rehabilitation alternatives. Another component is the transition function. Transition functions determine the future state (pavement condition) for each individual pavement section from one stage (year) to another. Transition functions can be either deterministic or probabilistic. The use of deterministic dynamic programming means that the state (which depends on pavement condition) at each successive stage (years in the analysis period) is determined or defined by the state and policy decision (type of maintenance and rehabilitation alternative to apply) at the current state.

The dynamic program process begins the solution procedure at the final stage (year) of the analysis period. In dynamic programming terms, that is defined as stage 0. The same procedure will then be carried out for the remaining stages until stage N or year 0 is reached.

Knowledge-Based Expert Systems

Knowledge-based expert systems (KBES) are computer programs that include a simulation of the reasoning and problem solving processes of human experts. KBES attempt to embody the heuristics (private knowledge and rules of thumbs gained from experience) of experts, organize the knowledge, save it, and then apply the knowledge to help solve similar problems (22). KBES are capable of performing tasks ordinarily requiring a well-trained specialist in a given domain or expertise (1). Knowledge-based expert systems have emerged from decades of artificial intelligence (AI) research. They are often referred to as the practical face of AI. Artificial intelligence is a product of the idea that "computers can be programmed to assume capabilities thought to be like human intelligence, such as learning, reasoning, adaptation, and self-correction" (2). KBES programs also aid in solving ill-structured problems or problems with ill-defined or even missing parameters. The usefulness of a KBES depends on how accurately it reflects the knowledge, reasoning, and decision making processes of the contributing expert or experts. It also depends on the level of expertise of the experts in the problem area and how user friendly the system is.

KBES vs. Algorithmic Programs

KBES are different from conventional or algorithmic programs in architecture and the method information is stored and used (the use of knowledge). Conventional programs contain precisely defined logical formulas and data. The operation of these formulas never varies because the problem solving sequence is predetermined by the programmer. If an element is missing, the program will not run. KBES, on the other hand, contains non-numeric knowledge and can function with incomplete or missing information. KBES includes concepts and processes that can not be expressed in equations as knowledge is represented in conventional programs. This and the separation of knowledge from the control strategies are the key features that allow KBES to function with incomplete data which is one of the key features that distinguishes between KBES and algorithmic programs. The following provides a summary of the differences between the two systems (23):

1. Use of knowledge. KBES has the ability to use the knowledge when it is needed. In conventional programs, all possible conclusions with their internal relations must be explicitly coded while the program is developed and the order of

processing is strictly predetermined. In KBES, the knowledge is used only when a situation requires conclusions to be drawn.

2. KBES are able to explain how the results were reached and gives explanations on why certain information is required to develop conclusions.
3. The symbolic and declarative way the knowledge is expressed in KBES gives the users an easy way to understand the knowledge stored and how it is used in the system. This reduces the possibility of misunderstanding between the expert and the programmer.
4. KBES are capable of producing conclusions with incomplete information. KBES are capable of efficiently using all the knowledge they contain which enables the system to draw conclusions even with missing information.

Basic Components of KBES

A knowledge-based expert system includes three basic modules or components: the knowledge-base; the inference engine; and the short term memory. The following is a brief summary of each module (22, 23).

1. The knowledge-base serves as the storage place for the KBES's domain specific knowledge needed for understanding, formulating, and solving the problem. It contains the facts (database) and rules of thumb or other knowledge representations (heuristics) that direct the use of knowledge to solve a problem. The knowledge-base contains permanent facts and rules that an expert uses to derive conclusions while solving a problem.
2. The inference engine processes the knowledge to solve problems. It receives data about the problem from the user or from another information system, then uses the contents of the knowledge-base to reach conclusions while aiming to solve the given problem. The reasoning process continues by using the conclusions as new data which might be used to solve a future problem. The inference engine represents the brain of the KBES. It is the main component of the KBES. It comprises the control strategy or the problem solving mechanism used to develop solutions to the users problems.
3. The short term memory (dynamic memory) contains the dynamic or specific knowledge, the user input, and other information generated by the system. It is also known as the working memory of the KBES.

The separation of the inference engine from the knowledge is one of the most typical characteristics of the KBES. It makes the coding of the knowledge much more flexible than conventional programs. The goal of any KBES is to keep the inference engine untouched and just change the knowledge-base.

KBES also have additional components that makes them user friendly and flexible. The following is a brief description of each component (22, 23).

1. User interface. It provides the means for the users to communicate easily with the KBES. It receives instructions and data from the users and transmits the results, conclusions, and requests for more information back to the user. In some KBES, it allows the user to access the knowledge-base and make changes to the control and reporting requirements. This facilitates proper use of the KBES and proper use of the results coming from the system.
2. Knowledge acquisition. This process is considered to be a subset of the knowledge-base. It plays a crucial rule in building the knowledge-base. The main objective of the knowledge acquisition facility is to efficiently and easily build the knowledge domain from the experts knowledge. This process functions as the transfer medium of knowledge from the expert to the KBES knowledge-base. The presence of a good knowledge acquisition facility will eliminate the need for a special knowledge engineer to transfer the knowledge from the human experts to the KBES program.
3. Explanation facility. This process gives the KBES the capability of explaining the reasoning process and to provide definitions and other information to the users. It adds to the system credibility and increases the user friendliness aspect of the KBES. It also helps the expert in checking the KBES reasoning when testing and modifying the KBES program.

All of these components function together to bring the user a flexible and easy to use knowledge-based expert system model that provides an efficient and accurate way of solving problems not easily modeled using conventional programming techniques. Figure 16 shows the interaction and the relationship among the different components of the KBES with the inference engine being the component that ties everything together (23). Figure 16 also

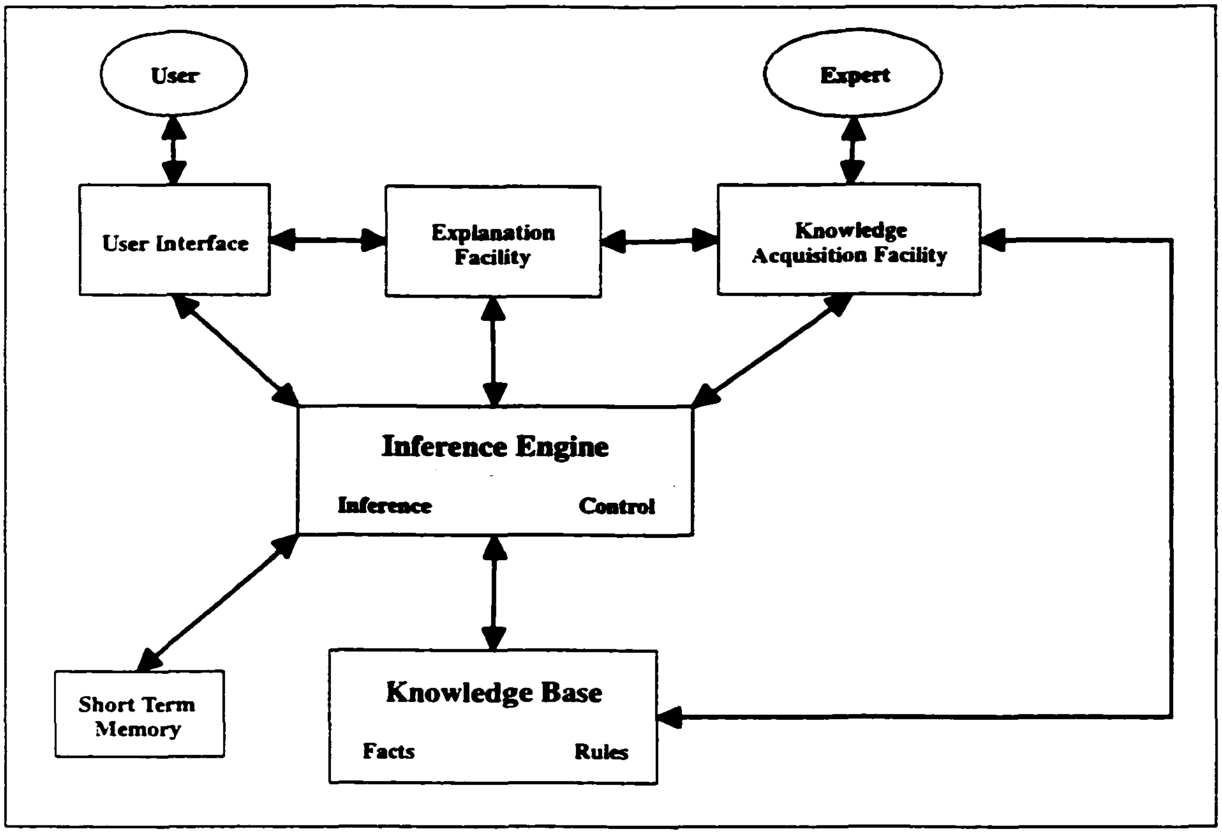


Figure 16. The Basic Structure of a KBES (23)

shows the interaction between the basic components (knowledge-base, inference engine, and short term memory) and additional components (user interface, explanation facility, and knowledge acquisition) of the KBES.

Knowledge-base

The knowledge-base is where the expertise of the system is stored. It contains the knowledge captured from human experts. The typical knowledge-base includes facts and rules or other knowledge representations. A fact is "simply an assertion that a relationship on a set of objects is true" (22). While a rule is "an assertion that some fact(s) is (are) true provided that another set of facts is true" (22). In simple terms, the knowledge-base represents a collection of decision rules that can be used to conclude new facts from existing facts (23). The rules are not used in the order they are written. Instead, they are used when their condition parts become true.

The relationship between the rules and facts is termed the knowledge presentation scheme. KBES has different knowledge presentation schemes. The two most common schemes are rule-based and frame-based. The research in this dissertation will be implemented through the use of rule-based KBES rather than frame-based. Frame-based knowledge representation is primarily used for large KBES's that consist of highly structured knowledge. The following is a description of the rule-based approach used in this research.

The rule-base knowledge representation scheme is the most common and widely used approach in KBES. These systems are either fact-collection systems or condition-action rules (22). The second system is more amenable to pavement management systems and will be used in developing the KBES pavement management model. These rules have the form **IF 'condition x is true' THEN 'perform action y'**. The condition part of these rules consists of premises. Those premises are either known facts stored in the KBES knowledge-base, or provided by users as input to the system. The action part of condition-action rules typically consists of either an assertion that some fact is true or a procedure that the system will perform (22).

The primary type of inferencing (reasoning) used in rule-based KBES is deductive reasoning. This technique consists of either "forward chaining" - deriving facts from existing facts and rules, or "backward chaining" - proving that a given fact is true by combining selected facts in the knowledge-base with selected rules.

Inference engine

The inference engine is the problem solving component of the KBES. The role of the inference engine is to use the available knowledge (rules and facts stored in the knowledge-base) to draw conclusions and provide solutions to the problem presented. When the KBES is given a problem to solve, the inference engine will first try to find a solution in the knowledge-base. If the knowledge-base does not have a solution, then the inference engine will use the facts in the knowledge-base, information provided by the user, and the rules in the knowledge-base to derive a solution to the problem. The following is a list of the tasks that the inference engine will perform to accomplish this.

1. Selection of rules to use from the knowledge-base
2. Evaluation of the selected rules (true or false)
3. Generation of new facts based on the evaluation of rules
4. Retrieval of facts from both the knowledge-base and the user
5. Generation of problem solution

In a rule-based KBES, the mechanism that an inference engine uses to select the next rule to evaluate depends on the direction of reasoning (forward or backward). Rule-based KBES utilizing forward chaining deductive reasoning will iteratively combine the facts and rules in the knowledge-base to form new facts until the goal statement have been proven true, i.e., no new facts can be derived from the knowledge-base; or the system reached its assigned threshold based on facts or processing time (22). This system works well when there are few initial conditions being dealt with as part of the problem.

Rule-based KBES utilizing backward chaining deductive reasoning will typically attempt to prove that the goal statement is true by assuming it is true and then searching the facts (both in the knowledge-base and those provided by the user) to find facts and rules to support this assumption. This strategy is practical where the number of possible outcomes, or conclusions, is known and can be readily identified (22).

As a rule of thumb, if the set of possible final conclusions is small, backward chaining reasoning is better because it prevents asking irrelevant questions. On the other hand, if there is a large number of possible outcomes, then irrelevant questions will be asked and forward chaining reasoning might be more efficient (23).

There is a wide variety of tools to support the development of KBES inference engines and knowledge bases. Simple rule-based KBES can be developed using an expert system shell available for different operating systems. Expert system shells are, in essence, KBES without the knowledge. These systems typically provide the user interface and the inference engine. More sophisticated KBES are developed using high level expert system language such as LISP or C (24). With the advent of relational databases a KBES can be embedded in a database without the need for an expert system shell or a specific programming language. The KBES built for this research is embedded in an ACCESS™ relational database that resides in a pavement management system software tool, dTIMS™ (Deighton Total Infrastructure Management System). The software uses decision trees to represent knowledge and also if-then-else rules. This application will be discussed in more detail in chapters 4 and 5.

Potential Pavement Management Problems Solved by KBES

There are numerous applications for KBES ranging from medical diagnosis and library acquisition, to engineering problems. Several different categories of KBES have been discussed in the literature. This section focuses on some of the potential applications for pavement management system purposes. The following is a brief description of two such applications.

Diagnosis KBES

In diagnosis, the system's output (i.e., its symptoms) are examined and a cause or a remedy is determined for these symptoms. In pavement management, the symptoms could be distress data (extent and severity for each individual distress measure), the cause might be environmental or loading, and the remedy might be an overlay (functional or structural). The types of knowledge typically used in modeling diagnosis problems should be able to answer such questions (24):

1. What is the current condition of the system (whether it is through the use of an overall pavement condition index or individual distress extent and severity measures)?
2. How do specific symptoms (distresses) relate to specific causes (weather, traffic, material, etc...)?
3. How do specific causes relate to specific remedies (pavement maintenance and rehabilitation alternatives)?

The goal of diagnosis KBES is to categorize the system symptoms into either a specific cause or set of causes, and then develop from these causes the best solution (remedy) or set of recommended solutions. Diagnosis KBES are typically used for developing pavement maintenance and rehabilitation selection models.

Condition forecasting KBES

The basic problem in forecasting is to forecast the future state of a system based on the existing state of the system and knowledge of past events. In using forecasting pavement management systems, the existing conditions represent the individual distress measurements or an overall pavement condition measure, age, and/or traffic loading. The knowledge of past events might include the impact of freeze/thaw cycles on condition, for example. The kind of knowledge used in such systems typically includes (24):

1. What are the components of the system being studied (prediction or forecasting parameters)?
2. How are the components related to each other? How do they interact?
3. What rules govern the relationship between a given component's input and its outputs?

The goal of forecasting KBES is to determine the most likely condition that will result from the current condition with changes over time. The literature does not provide any examples of using forecasting KBES in pavement management applications. Chapters 3 and 4 offer a detailed description of how this will be accomplished for this research.

Examples of KBES Applications in Pavement Management Systems

This section provides a brief description of sample KBES applications in the field of pavement management systems. It is not a comprehensive list of KBES applications, but it gives an overall view of how KBES have been used in pavement management applications. The examples discussed include a range of KBES, from simple systems built in a LOTUS

1-2-3™ environment to a more sophisticated systems built using high level computer languages and expert system shells. Substantial research has been conducted to evaluate which expert system software to use and what evaluation criteria should be used (25). Also KBES applications in transportation engineering and planning in general have been studied (26). The following examples illustrate how KBES have been used in the field of pavement management systems.

KBES applications for flexible pavements

Several applications have been developed for flexible pavement maintenance and rehabilitation purposes. The KBES developed are typically diagnosis systems. The following items are examples using different software tools.

1. Expert system for flexible pavement management using LOTUS 1-2-3 (27). This example shows how a spreadsheet program, like LOTUS, can be used to embed a knowledge-base and use the programming language available in LOTUS (macros) to develop a KBES that selects the most appropriate maintenance strategy for a flexible pavement using the most dominant distress approach. The KBES has a user interface that uses menus and it allows the users to interact with the KBES by providing input information. The KBES uses LOTUS 1-2-3 macros to execute IF-THEN-ELSE statements for the diagnosis and selection of the maintenance or rehabilitation strategy.
2. An expert system for diagnosis and treatment of flexible pavement distress (28). This example uses an expert system shell (EXSYS) to develop a KBES to be used for the diagnosis of different distress mechanisms (causes of distress) associated with flexible pavements. The KBES takes input describing the pavement section from the user, based on the input, the user is presented with a diagnosis of the problems existing in the pavement section, and finally, the user is presented with an alternative maintenance or rehabilitation strategies. The expert system shell (EXSYS) provides the developer with tools to acquire the knowledge, build the rules for the system, and also provides for an explanation and user interface facilities. The system developed is also capable of interacting with other software. In this case, an interface was built to a pavement rehabilitation design program.

3. Expert system to estimate highway pavement routine maintenance work load (29). This example adds another feature to the diagnosis problem by adding quantities of work to be completed based on the diagnosis of the condition. The KBES developed only looks at routine maintenance alternatives for asphalt pavements and is written using LISP in an interactive manner. The KBES considers the pavement condition as input to the system and uses the facts and rules in the knowledge-base to determine the most appropriate diagnosis of the problem and then a maintenance alternative is selected. The KBES determines the quantities of the work to be completed and provides output to the user in terms of work load and percentages of the different maintenance alternatives to be completed.

KBES applications for concrete pavements

The following two examples are of KBES' developed for the diagnosis of concrete pavements. Both systems use expert system shells to develop the knowledge-base and the interface modules.

1. An expert system to evaluate concrete pavements (30). This example, Pavement Expert, was developed using an expert system shell with the knowledge-base coming from a distress manual and some human expertise. The program goal is to emulate the pavement condition rating (PCR) method for determining concrete pavement condition. The PCR method is widely used by local and state governmental agencies. Pavement Expert is a monitoring KBES more than a diagnostic system. The system interacts with the user and requires data input in the form of distress severity and extent and then the system outputs a PCR value and other indices values used in the PCR method.
2. Airfield pavement consultant system (31). This example describes a KBES built for airfields. The knowledge-base addresses the three different components of the system including the runways, taxiways, and aprons. The KBES, AIRPACS, uses the knowledge of planners, constructors, airfield managers, and designers to evaluate difficult problems related to the rehabilitation of the airfield system components. The system looks at the functional, structural, operational, and safety aspects of the airfield system. A knowledge-base rule-based system was developed to handle all of these aspects of the decision making process. AIRPACS determines the condition and then recommends a treatment strategy. Once a strategy is selected, AIRPACS uses mechanistic, heuristic, and empirical design methods to select the new treatment layer thicknesses and joint spacing requirements.

The previous examples of KBES demonstrated the feasibility of using this methodology in the field of pavement management. Examples of diagnosis and monitoring rule-based systems have been presented. All of the KBES application presented were, however, stand-alone applications and not part of a comprehensive pavement management system. The literature search did not yield any studies conducted on the use of KBES in performance forecasting or monitoring. Moreover, all of the applications of KBES in pavement management systems were project-level oriented and did not cover project selection or network level activities. Applications presented did show that the use of KBES in pavement management is feasible and beneficial. The next two chapters will cover how KBES was used in this research and will explain the differences between the system developed for this research and the systems discussed in the literature review section.

PROBLEM STATEMENT

The purpose of this research is to develop a comprehensive set of pavement management system tools to assist pavement managers in making consistent, objective, and cost effective decisions regarding pavement maintenance and rehabilitation. The tools cover the three different components of pavement management systems. They will include:

1. Performance forecasting module
2. Treatment strategy selection module
3. Project selection and resource allocation module

Highway agencies at all levels (federal, state, local) must make decisions every year regarding project selection and resource allocation for maintenance and rehabilitation needs. Since funds are limited, making cost effective allocations of resources becomes crucial for the maintenance of the highway network. This research assesses the feasibility and benefits of using KBES for developing condition forecasting and treatment strategy selection modules. Project selection and resource allocation is performed utilizing deterministic dynamic programming.

The following sections cover the components of each module and how they apply to pavement management tools. The application of KBES is discussed in detail (the topic of this research) while dynamic programming use (previous research conducted by this author (3)) for project selection and resource allocation is covered in brief to provide an overview of its use as an optimization tool.

KBES Applications

This section covers condition forecasting and treatment strategy selection modules. KBES are used to develop these two modules. It is shown that the use of KBES for forecasting pavement condition and diagnosis of condition (treatment strategy selection) is both feasible and beneficial. Traditional pavement management systems use either deterministic or probabilistic condition forecasting models. These models have limitations and might not provide the desired level of effectiveness. The use of KBES to develop pavement condition forecasting tools adds flexibility and efficiency in dealing with different pavement types and special circumstances or conditions. Pavement management applications provide a unique environment for rule-based KBES for the following reasons (4):

1. Pavement management systems require periodic data collection and as more data becomes available, more knowledge (rules and facts) can be developed to replace the rules originally supplied by the experts.
2. Pavement management systems goals and objectives are changing depending on condition, funding levels, and agency requirements.
3. Pavement management is a field in which the recognized experts, whose knowledge will be incorporated in the KBES, have as counterparts other experts who are experienced with local conditions and their knowledge is crucial to the success of the pavement management system.

The major task of building the two expert systems is to transfer the knowledge and expertise of one or more experts to the knowledge-base. The goal of expert system developers (knowledge engineers) is to transform this knowledge and to ensure that the performance of the resulting expert system can reach the desired functionality and accuracy levels. The next two sections describe the processes followed to develop the KBES and the input and output parameters necessary for the KBES to function.

Condition Forecasting KBES (F-KBES)

The KBES module for pavement condition forecasting will to be used in conjunction with a deterministic performance model. Performance curves developed using regression analysis (age vs. condition) provide the initial input to the KBES. Additional pavement characteristics such as construction quality, number of freeze-thaw cycles in the previous year, and construction materials (mainly aggregate type), will be part of the input to the KBES. The knowledge-base will store the facts and rules that relate the effect of the additional pavement characteristics on the condition of the pavement. The knowledge-base facts and rules are developed using both historical information and expert opinion. The steps listed below are followed to estimate future pavement condition.

1. Determine the current pavement condition using either deterministic performance curves that are age based or using field data. Inputs are pavement type and age. Output from this process is the initial pavement condition index (PCI_ini, on a scale of 0 to 100).
2. Determine the additional pavement characteristics (construction quality factor (CQ), number of freeze-thaw cycles, and materials factor (MQ)).
3. Use the knowledge-base rules and facts (if-then-else) to adjust the initial pavement condition index (PCI_ini). Output from this process is a new PCI value that reflects the impact of those additional characteristics (PCI_new).
4. Based on the PCI_new value, determine a calculated age from the performance curve. The age value can be used for the treatment selection and resource allocation processes.

The forecasting KBES (F-KBES) is a rule-based knowledge-base and utilizes a forward chaining approach to determine the results. The reason for selecting a forward chaining approach is the limited number of input parameters. The following describes the main components of F-KBES.

1. The knowledge-base. It includes all the rules and facts that describes the impact of construction, weather, and material quality on pavement condition. The information included in the knowledge-base was obtained using historical data and expert opinion. A construction quality (CQ) index and a material quality (MQ) index are developed to quantify the relationship between pavement condition and these factors. The number of freeze-thaw cycles is used to measure the impact of the weather on pavement condition.
2. Performance curves. Individual performance curves (age vs. PCI) have been developed for the different pavement types used, asphalt concrete pavements (ACC), portland cement concrete pavements (PCC), and composite (ACC laid over PCC) pavements (COM). Those performance curves will be used to determine the PCI_ini value based on current age.
3. Inputs. The F-KBES uses the PCI_ini values, construction and material indices and the number of freeze-thaw cycles for each pavement section under consideration. All of the inputs are compiled in a file and are used directly in the KBES.
4. Outputs. F-KBES outputs a PCI_new value and a calculated age based on the new PCI values and the deterministic performance curve. The calculated values are used for the treatment selection KBES and the resource allocation modules.

Treatment Selection KBES (TS-KBES)

The KBES used for treatment selection is a decision tree of "if-then-else" rules based on historical information and expert opinions of field maintenance engineers, design engineers, and construction engineers. The knowledge-base houses all the facts and rules that relate a specific treatment strategy (maintenance, rehabilitation, and reconstruction) to the pavement condition. Multiple treatment strategies might be selected at different points in time depending on the overall pavement condition index (PCI) and individual distress measurements (ride, rutting, cracking, and patching). The following steps are used to select the appropriate and feasible treatment strategies for each section.

1. Input the PCI_new value and calculated age determined through the use of F-KBES. In addition to the PCI value, individual distress measurements are considered. The extent (amount) and severity of each distress is used as input to the TS-KBES.

2. Use the knowledge-base facts and rules to determine the appropriate treatment strategy based on the input parameters. This process will be conducted for the number of years included in the planning horizon. F-KBES will be used to forecast the PCI values and individual performance curves will be used for the remaining distress measurements.
3. Pass the treatment strategies to the resource allocation model for final project selection and resource allocation using dynamic programming.

The treatment selection KBES (TS-KBES) is rule-based (decision tree) and will utilize forward chaining as its inferencing mechanism. This will allow for multiple treatment strategies to be selected for individual pavement sections. The following describes the main components of the TS-KBES.

1. Knowledge-base. This will include the decision tree for the selection of treatment strategies and pavement types formulated as "if-then-else" rules. The rules in the knowledge-base were mainly obtained from experts using surveys and some historical information. The rules consider one or more individual distress measurements to select a feasible treatment strategy. Treatment strategies are divided into three categories: maintenance; rehabilitation (functional or structural); and reconstruction.
2. Inputs. PCI values (current and future) from the F-KBES are used in addition to individual distress measurements. Pavement type and other inventory information is used too (traffic, section length, locations, etc...). All the inputs are compiled in a file and used directly by the KBES.
3. Outputs. The TS-KBES outputs a file that contains a set of pavement sections with the estimated pavement condition value (PCI_new) following the application of the selected treatment strategy for each year in the planning horizon. Individual sections might have one or multiple treatment strategies selected each year based on the model results.

Dynamic Programming

Deterministic dynamic programming is used for the resource allocation model and will also be used for project selection through optimizing a multi-year pavement management program. It provides a systematic procedure for determining the decision or combination of decisions that increases the overall effectiveness of the system (21). Dynamic programming, used to solve a multi-decision process, reduces the problem size (computational complexity and processing time) and still guarantees an optimal solution (3). The following describes the dynamic programming module's major components.

1. Objective function. This is a mathematical representation of what the agency considers its goal. For the purpose of this research, the objective function would be to minimize total cost or maximize benefits. The optimization of the objective function is carried out with specific system constraints (discussed later).
2. System constraints. The set of constraints include the physical or performance limitations that are placed on the system. Depending on whether the objective is to minimize cost or maximize benefits, specific performance or funding constraints can be implemented. If the goal is to minimize total cost, performance constraints will be used. If the goal is to maximize benefits, then funding (budgetary) constraints will be used. Additional constraints include human resources, number of projects, number of miles, etc...
3. Decision variables. They include a set of the available treatment strategies to be applied to the pavement section.
4. Solution procedure. Dynamic programming problems are characterized based on stages and states. The system, through the decision variables, transfers each pavement section from one state to another state (based on condition) associated with the next stage (years in the planning horizon). The solution procedure starts with the final stage and works its way backward to the first stage.

The resource allocation model (dynamic program) divides the problem into stages, with a decision required at each stage. That is the way in which dynamic programming reduces problem size and still guarantees an optimal solution. As mentioned earlier, deterministic dynamic programming will be used. This refers to the fact that the condition of the pavement section (represented by a state in the dynamic program) is completely defined or determined by the state and decision at the current stage. The resource allocation process has three steps.

1. Formulate the dynamic program. This process includes the development of the objective function, decision variables and constraints to the system. The definition of stages and states is also included in the setup.
2. Inputs. Depending on the number of states selected and state determination, a number of inputs to the dynamic programming model are required. PCI values from the F-KBES (current and future) and feasible treatment strategies (decision variables) from the TS-KBES are used by the dynamic programming system to setup the network. Other information such as section identification and inventory information (length, pavement type, traffic, etc...) is needed.
3. Outputs. This is typical of any other pavement management system. The results will list each pavement section considered in the analysis and the recommended treatment strategy for each year in the planning horizon. The program will also calculate the cost based on the selected treatment strategy and the length of the section.

METHODOLOGY

This chapter presents the interaction between the three modules presented as part of the problem statement. It also provides a complete description and example for each module used in the development of the pavement management system.

The condition forecasting KBES (F-KBES) is based on using deterministic performance curves. The pavement condition index (PCI) for the three pavement types (ACC, PCC, and COM) is used. The PCI value will be adjusted depending on the construction quality, material quality, and number of freeze-thaw cycles. The Iowa Department of Transportation (Iowa DOT) interstate system PCI curves are used for performance forecasting of the overall condition of the pavement sections. Individual distress indices are used to forecast future distress values based on historical information and regression analysis.

The construction quality factor (CQ) is based on the difference in pavement performance between the different contractors involved in interstate construction projects (for example: A, B, C, or D). The material quality factor (MQ) is based on the type of aggregate used in the pavement. It is also based on the type of base and sub-base material (for example: 1, 2, 3, or 4). The effect of the number of freeze-thaw cycles was determined using regression analysis with historical performance values and expert opinion. Three different ranges for the freeze-thaw cycles were used in developing the rules for the F-KBES (for example: 1, 2, or 3).

Knowledge-base rules and facts are formed using decision trees based on "if-then-else" statements. The following is an example explaining the process using assumed and simplistic values for all of the inputs considered.

1. From the inventory information, determine the current PCI using aged based performance curves and pavement type (PCI_ini = 80). Also, construction quality and material quality factors are determined using construction and material information (CQ = C and MQ = 2). The range of freeze-thaw cycles is also determined using inventory information.
2. Adjust the PCI_ini value based on the CQ, MQ, and the number of freeze-thaw cycles using the decision tree (if-then-else). The CQ factor is a reduction of five percent (4 PCI points) and the MQ factor is a reduction of five percent (4 PCI points) from the initial PCI. The freeze-thaw cycle causes a reduction of 2 PCI points. PCI_new = 70.
3. Determine the calculated age of the pavement section using the PCI equation and the adjusted PCI value.
4. Use the PCI equation (PCI_new = PCI_ini - 5) with the new age to determine the PCI value for each year in the planning horizon (5 years). Table 1 shows the results from this process.

Table 1. PCI values for the Planning Period

Year	PCI
1	70
2	65
3	60
4	55
5	50

This process is repeated for the rest of the performance indices used in the decision making tool for treatment selection. Individual distress indices such as the international roughness index (IRI), present serviceability index (PSI), structural rating index (SRI), and a rutting index (RI) are all used to forecast the value of each distress in each year in the planning horizon to be used by the TS-KBES for diagnosis and treatment selection. The if-then-else rules will be discussed in the computer model formulation chapter.

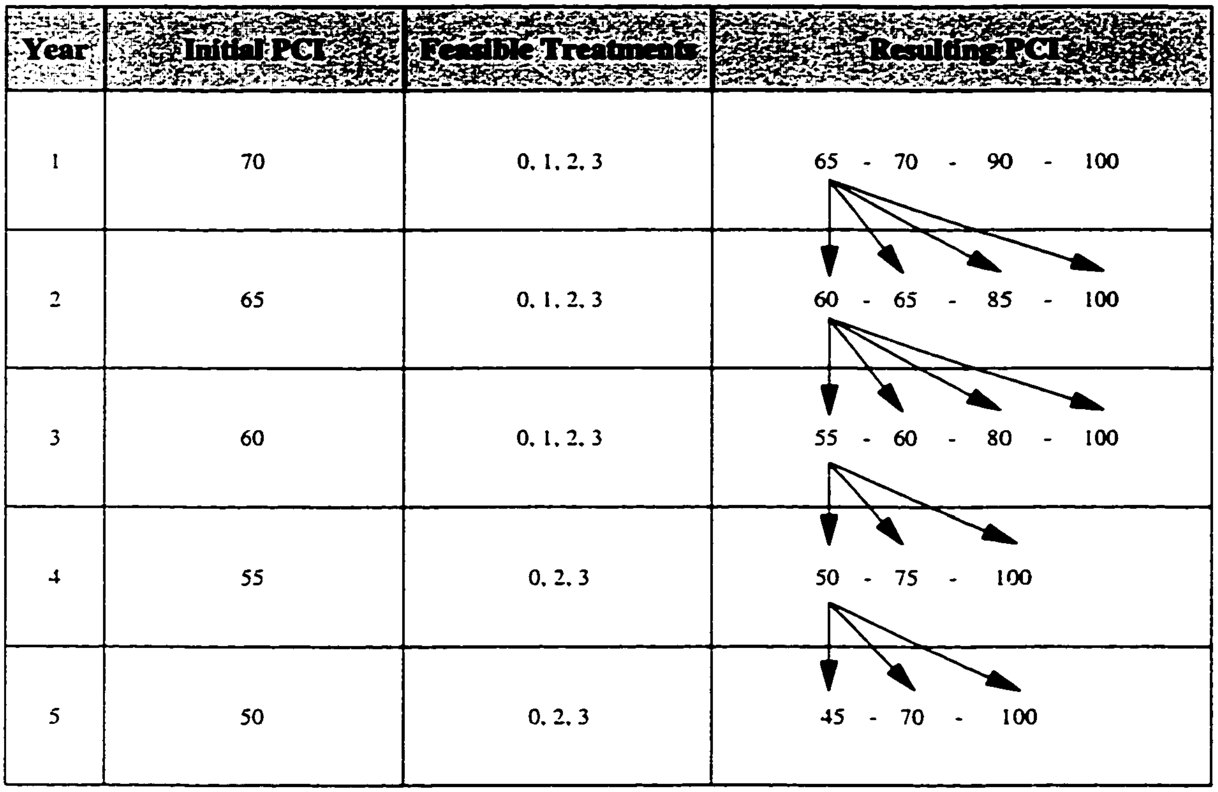
The TS-KBES is also built using if-then-else rules (formulated as decision trees or decision matrices) in the knowledge-base. The decision matrix uses the output from the F-KBES (future PCI, calculated age, individual distress values) and other inventory information (pavement type, material) and determines the feasible treatment strategy for each section of the pavement network for the years in the planning horizon. Figure 17 shows a simple example of a decision matrix using only the PCI.

The following is a simplified example showing the steps to this process using assumed values for all inputs considered.

1. Using expert opinion and historical information, determine a set of available maintenance and rehabilitation strategies for each pavement types. In this case, 4 different strategies are available: 0 (do-nothing); 1 (maintenance); 2 (rehabilitation); and 3 (reconstruction).
2. Determine the impact of implementing each strategy on the pavement condition (resulting PCI, IRI, SRI, and RI). In this example, only the PCI is used. The do-nothing basically follows the performance curve and is a reduction of 5 PCI points for each year. Maintenance maintains the current level of service (no change). Rehabilitation results in a 20 PCI points increase and reconstruction restores the section to a PCI of 100.
3. The knowledge-base rules considers all the inputs and selects the feasible treatment strategy and the resulting PCI for each section for all the years in the planning period. To complete the input to the dynamic program (next step), the

TS-KBES also considers the resulting PCI and determines treatment strategies for each one for the remaining years in the planning or analysis period. Figure 17 shows how this process is completed. For example, at year 1, the PCI is 70 and all 4 treatment strategies are feasible. The resulting PCI is 65 for do-nothing, 70 for maintenance, 90 for rehabilitation, and 100 for reconstruction. Then, each resulting PCI is considered and a new set of treatment strategies is selected. In this example, only the first iteration is shown. As can be seen from Figure 17, once the pavement condition (PCI) goes below 60, maintenance is no longer a feasible treatment strategy.

4. The TS-KBES produces a file that has all the feasible treatment strategies and their resulting PCI and cost information to be used in the project selection and resource allocation module (performed using dynamic programming).



Year	Initial PCI	Feasible Treatments	Resulting PCIs
1	70	0, 1, 2, 3	65 - 70 - 90 - 100
2	65	0, 1, 2, 3	60 - 65 - 85 - 100
3	60	0, 1, 2, 3	55 - 60 - 80 - 100
4	55	0, 2, 3	50 - 75 - 100
5	50	0, 2, 3	45 - 70 - 100

Figure 17. Treatment Selection Decision Matrix

The next chapter will discuss the complete formulation of the decision matrices for each pavement type considered in the analysis. The next step will be to run the deterministic dynamic program to select projects and allocate available resources.

To set up the dynamic programming module, some parameters associated with dynamic programming need to be identified and explained. The following dynamic programming characteristics are defined:

1. Each dynamic programming problem is divided into different stages, with a policy decision required at each stage. In the pavement management problem, a stage represents one year of the planning or analysis period. In our example, we will have 5 stages for the 5-year analysis period considered.
2. Each stage consists of a specific number of states depending on the characteristic of the problems. In our example, states are based on the pavement condition (PCI) and each bracket of 5 PCI points represents a state (100-95, 95-90, 90-85, 85-80, 80-75, etc...).
3. The purpose of making a decision at each stage is to transform the current state into a state associated with the next stage. In the pavement management problem, this is accomplished by implementing a feasible maintenance strategy with its associated cost and condition improvement.
4. Dynamic programming starts the solution by working the last stage (year 5) and then working its way to the first stage (year 1). Given the current state, an optimal policy of the remaining stages is independent of the policy adopted in previous stages.
5. The deterministic approach means that the state in the next stage is completely defined or determined by the state and decision at the current stage. In our example, this is accomplished by using the results from the TS-KBES which identifies all the possible decisions and their resulting PCI values.

The dynamic program setup results in the buildup of a decision process with an optimal result depending on the objective of the problem (maximizing benefits or minimizing cost). Figures 18 and 19 present examples of the decision process to be solved using the dynamic programming module. Figure 18 describes the decision process for the example considered in this chapter. Each arrow in the decision process is associated with a cost and a PCI value. The objective to be achieved for this example is minimizing the cost while maintaining a PCI of more than 60. The dynamic program considers the last stage (year 5) first and then moves to year 1. Since the performance constraint is not to allow any section to go to a PCI below 60, the costs associated with these activities will be large numbers to prevent their selection.

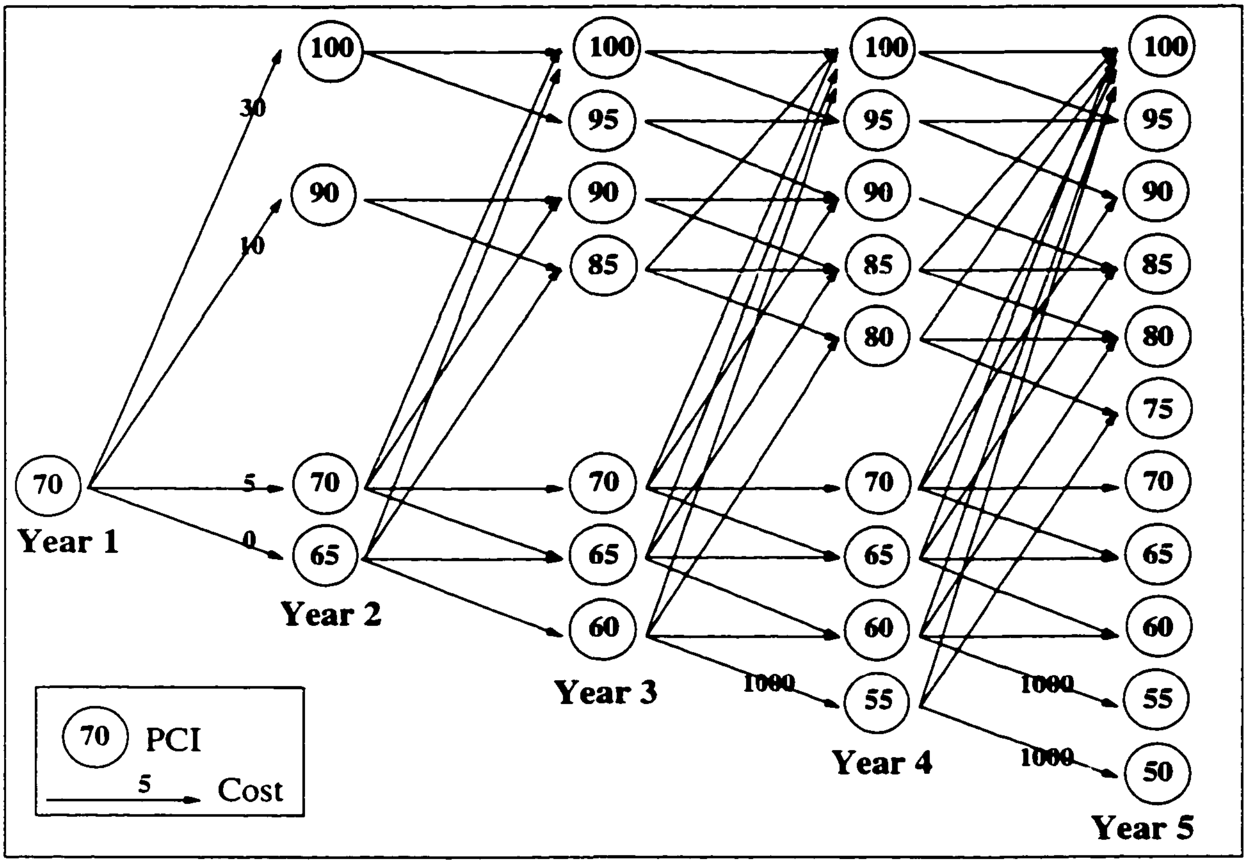


Figure 18. Example Dynamic Programming Decision Process Network

As shown in Figure 18, activities that allow the pavement section to go below a PCI of 60 are associated with a large cost (1000 units) while the rest of the activities are associated with actual cost numbers. Since the objective is to minimize total cost, associating an activity with a large cost will prevent its selection. The dynamic program determines the optimal strategy at each stage and then moves backward until the first stage is reached. The objective is to find the combination of decisions (treatment strategies) that minimizes the cost and maintains the performance constraints imposed on the system. The complexity of the decision process network depends on the number of feasible treatment strategies selected for each section by the TS-KBES. Figure 19 shows the dynamic program decision process network for a pavement section that has an initial PCI of 100. It can be seen that the number of policy decisions (treatment strategies) is much lower than the case considered in the previous example (Figure 18).

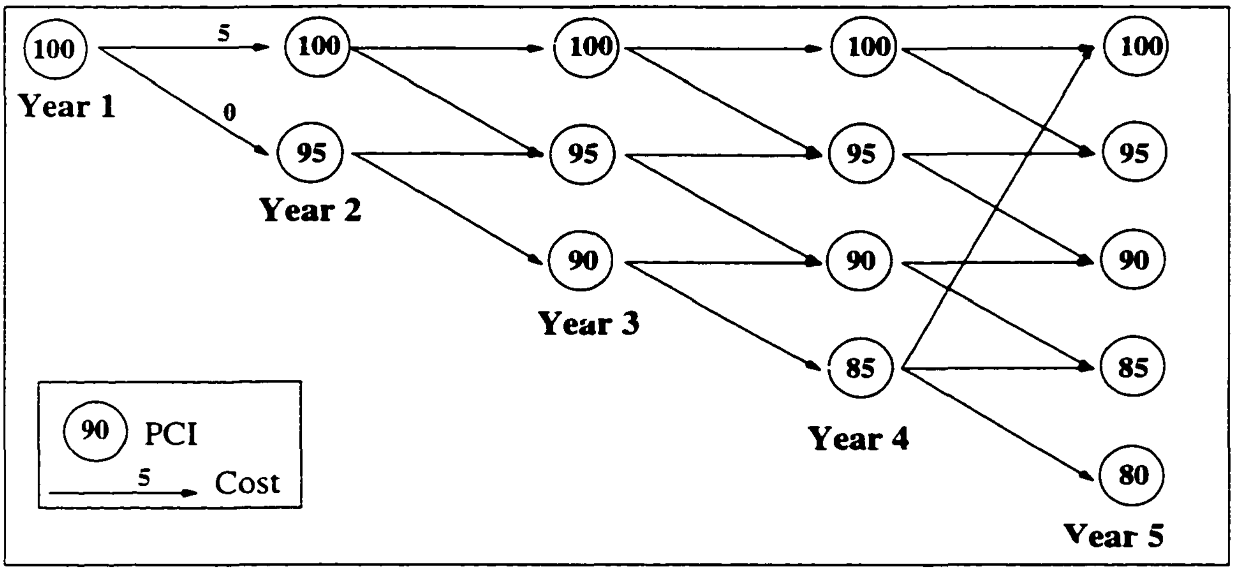


Figure 19. Simple Dynamic Program Decision Process Network

This process is completed for all of the pavement sections under consideration for all of the years in the analysis period. The dynamic program builds a large decision process network comprising all of the sections with their associated feasible treatments for each year (stage). To solve this problem, a computer model was written in FORTRAN to solve the dynamic program network. The computer program was developed through earlier research (3). The program will be discussed in more detail in the next chapter.

COMPUTER MODELS FORMULATION

This chapter describes the formulation of the three modules used in the pavement management system (F-KBES, TS-KBES, and the dynamic program). The KBES formulation describes the knowledge acquisition and presentation. The knowledge bases for the expert systems are built based on expert opinion and historical data. The dynamic program formulation was developed as part of earlier research completed by this author. Some minor modifications to the FORTRAN program developed in prior research are required, to accommodate new information input from the KBES modules.

The next three sections will describe the formulation of each module in detail and will present all of the knowledge-base rules used in the KBES as well as present the dynamic program setup.

Performance Forecasting Knowledge Base Expert System

The F-KBES is built using a forward chaining approach. The KBES considers the input variables (CQ, MQ, and Freeze-Thaw) that affect pavement condition and uses the knowledge-base rules to determine the impact of these variables on the overall condition of the pavement section (PCI). The KBES is used in conjunction with deterministic performance curves developed with regression analysis. Iowa DOT historical condition information was used in this process. Only three pavement types (concrete, asphalt, and composite) are used in this setup but additional pavement types can be added later with minor modifications to the knowledge-base containing all the rules and facts. Figures 20-22 show the three deterministic performance curves used for forecasting PCI based on age (years).

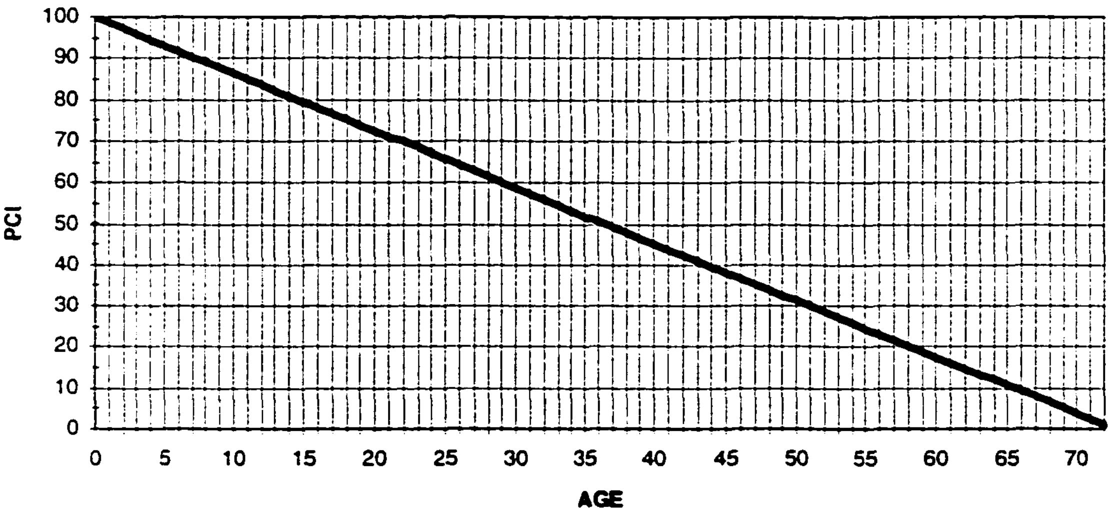


Figure 20. Concrete Pavement (PCC) PCI Curve

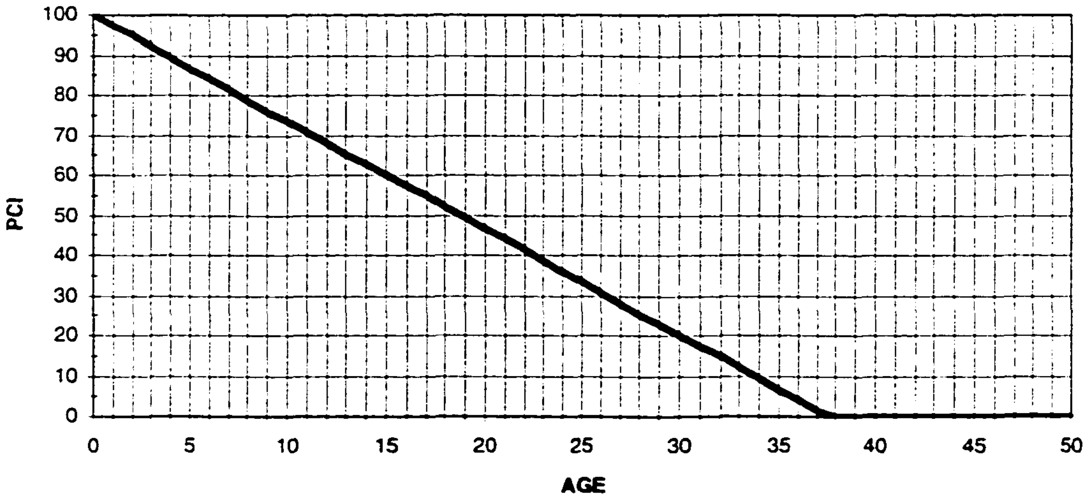


Figure 21. Asphalt Pavement (ACC) PCI Curve

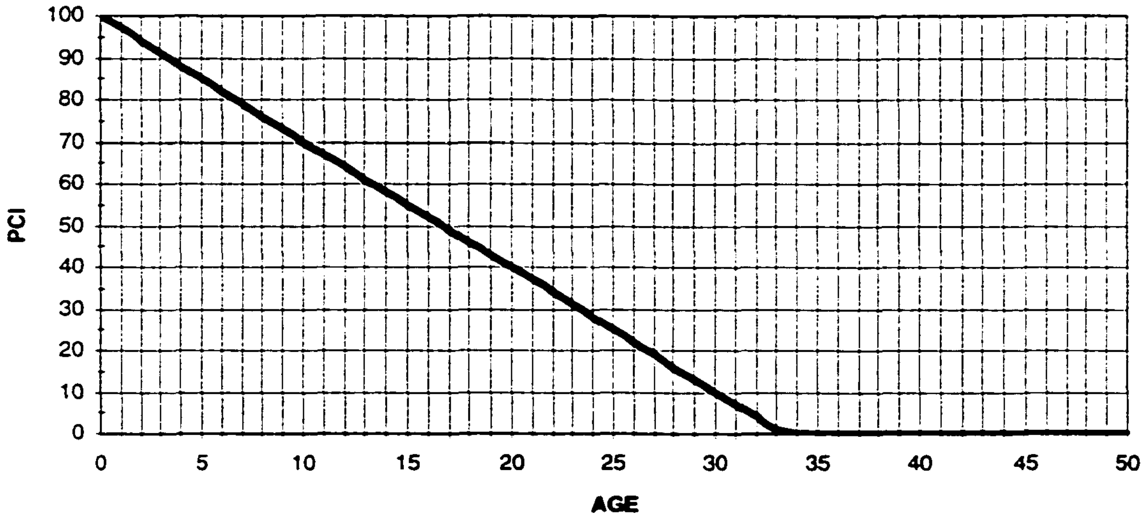


Figure 22. Composite Pavement (COM) PCI Curve

Figure 20 shows the performance curve used for portland cement concrete (PCC) pavement sections. The PCI range was between 100 and 0 over a time period of seventy years. Figure 21 show the asphalt cement concrete (ACC) pavement sections performance curve with a PCI range between 100 and 0 in 40 years. Finally, Figure 22 describes the composite (COM) pavement sections performance curves with PCI ranging from 100 to 0 in 35 years. All performance curves shown in Figures 20-22 are linear. The fact that the performance curves are linear is not necessary for the development of the F-KBES.

For each pavement section in the analysis, an initial PCI is calculated based on its age and pavement type according to the performance curve (PCI_ini). Additional information to identify the construction quality factor (which depends on the contractor doing the initial construction) and the material quality factor (depending on the aggregate used in the mix) is included for each pavement section with location and identification information (route, section number, county, beginning mile post and ending mile post).

The knowledge-base rules for the construction quality factor determine the increase or decrease in the value of the PCI for each section depending on its CQ factor value. Table 2 shows the impact of construction quality on the PCI. Those values were calculated using expert opinion and historical information considering different contractors.

Table 2. Construction Quality Factor

Construction Quality Code (CQ)	Change in PCI (%)
A	(+5)
B	(+3)
C	No Change
D	(-2)
E	(-3)

The knowledge-base rules will use the form (IF CQ = A, THEN PCI = 1.05 x PCI_ini, ELSE (IF CQ = B, then PCI = 1.03 x PCI_ini) ELSE ....). Since there are only 5 different alternatives, the forward chaining approach works very well in this case and does not require a large set of conditions to test. Several contractors are included in each group. If more data were available, CQ factors would have been developed for each contractor.

The same procedure applies to the material quality factor (MQ). Table 3 shows the values associated with the four different material quality factors. The MQ factor is based on the durability of aggregate used in the surface mix. Additional materials factors (base and sub-base) can be easily included in the knowledge-base as more data become available. This added flexibility and adaptability to accommodate changes and additional data are two of the main reasons for using KBES for the development of performance forecasting models. The impact of aggregate durability is determined using historical information. As more testing is done, a more accurate measure of the impact can be calculated and the knowledge-base can be updated to reflect those changes. Expert opinion can also be used to augment the information presented in Table 3.

Table 3. Material Quality Factor

Material Quality Factor	Change in PCI (%)
1	(-7)
2	(-3)
3	No Change
4	(+5)

The same format used for the knowledge-base rules as the CQ factor are used for the MQ factor to determine the impact on the PCI. The last factor to consider is the freeze-thaw factor. The freeze-thaw factor is based on three regions within the state (north, central, and south). As more weather information becomes available, a more accurate measure of freeze-thaw cycles, in terms of numbers, can be determined and the impact on the PCI can be calculated. At this point, only expert opinion was used to determine the impact on the PCI. Table 4 shows the freeze-thaw factors for the three regions in the state with the northern region having a negative impact on condition and the southern region having a positive impact on condition.

Table 4. Freeze-Thaw Factor

Freeze-Thaw Facor (by region)	Change in PCI (%)
North	(-5)
Central	No Change
South	(+3)

The knowledge-base was built in dTIMS (Deighton Total Infrastructure Management System). dTIMS is basically operated as an expert system shell. It allows the user to build decision trees and knowledge-base rules in "if-then-else" format for any system. dTIMS is the pavement management software adopted for use by the Iowa DOT, which made dTIMS available for this research. The knowledge-base rules are contained in filters in dTIMS and each filter is examined in a forward chaining approach. Filters are nested if-statements that contain all the information from the decision tree or matrix. dTIMS is capable of running the analysis over a 20-year period (a 5-year planning horizon was used for the case study). The output from F-KBES is presented in the form of a modified PCI value with a calculated age that corresponds to the new PCI value. Figure 23 shows the output from the F-KBES with the forecasted PCI values for 5 years for each section (PCI_01 for year 1, PCI_02 for year 2, etc...).

The calculated age is determined by solving the pavement condition index performance curve (PCI) equation for age.

$$\mathbf{PCI = A - B*Age}$$

where;

PCI = Pavement Condition Index
A, B = Constants depending on pavement type
Age = Years since last major work

$$\mathbf{C\_Age = (A - PCI\_new)/B)}$$

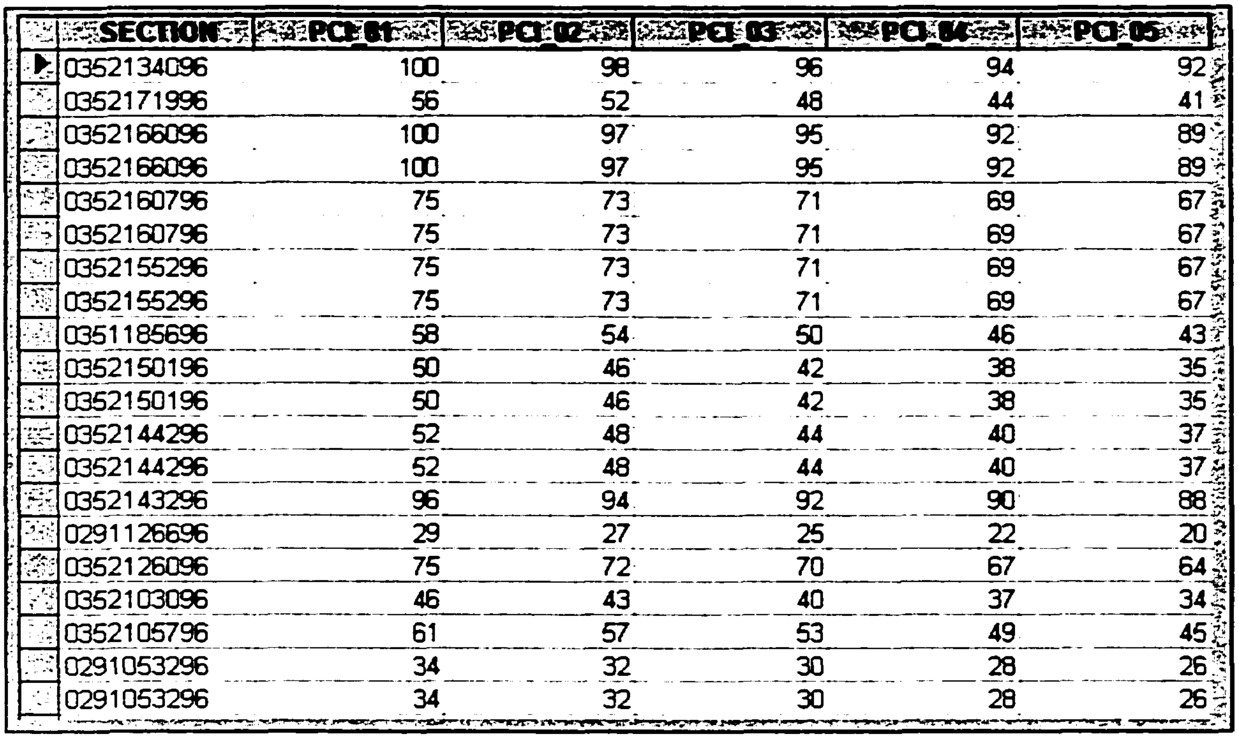
where;

C_Age = Calculated age
A, B = Constants depending on pavement type
PCI_new = New PCI value determined using F-KBES

The new, predicted PCI values, and calculated age are used as input to the TS-KBES for treatment selection. Appendix I has sample output from the F-KBES for Iowa DOT's interstate sections for a 5-year period.

Treatment Selection Knowledge Base Expert System

The TS-KBES is also built utilizing the same forward chaining approach used for F-KBES. Since only a limited number of parameters (decision tree branches) is used for each pavement type, it is feasible to use the forward chaining approach . If more treatment strategies are added, this approach might need to be investigated again to determine the feasibility of switching to a backward chaining method.



SECTION	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0352134096	100	98	96	94	92
0352171996	56	52	48	44	41
0352166096	100	97	95	92	89
0352166096	100	97	95	92	89
0352160796	75	73	71	69	67
0352160796	75	73	71	69	67
0352155296	75	73	71	69	67
0352155296	75	73	71	69	67
0351185696	58	54	50	46	43
0352150196	50	46	42	38	35
0352150196	50	46	42	38	35
0352144296	52	48	44	40	37
0352144296	52	48	44	40	37
0352143296	96	94	92	90	88
0291126696	29	27	25	22	20
0352126096	75	72	70	67	64
0352103096	46	43	40	37	34
0352105796	61	57	53	49	45
0291053296	34	32	30	28	26
0291053296	34	32	30	28	26

Figure 23. F-KBES PCI Output

The TS-KBES considers the three pavement types included under the F-KBES (concrete, asphalt, and composite). The knowledge-base rules are taken from the decision matrix for each pavement type are represented in the form of if-statements. Figures 24-26 show the decision matrix for the three pavement types. Each figure (24-26) shows the available treatment strategies for each pavement type (ACC, PCC, and COM) and the decision tree components for each treatment strategy. Pavement condition information such as PCI, IRI, structure, and rutting is used to determine the feasibility of each treatment. Other factors such as age, aggregate class, and thickness are also used in the decision matrix.

Figure 24 is the decision matrix for PCC pavements. Four alternatives are considered, and all but one is dependent on pavement thickness, for a total of 9 different alternatives. The cost for each alternative is factored per 2-lane mile. The total cost for each section is dependent on the length of each section. Figures 25 and 26 provide the same information for ACC and COM, respectively. For example, consider a PCC pavement section with a PCI value of 60, structure rating (ST) value of 3.0, aggregate durability class 3, and is 17 years old. From Figure 24, with a PCI of more than 50, only overlays are considered because pavement replacement is only feasible if PCI is less than 50. Next, the ST value is considered and it is found that the only alternative is a three inch bonded PCC overlay (3B1). Next, the age and the aggregate class are checked. Both meet the decision tree criteria, which means 3B1 is considered a feasible treatment strategy. The same procedure is followed for the different pavement types.

			PCI	Structure (ST)	IRI	Age_Rehab	Agg. Class	Avg. K	
Treatment	**Thickness**	**Code**	**Triggers**						**Cost**
Functional Overlay	4"	4FO1	> 10	ST < 1.76	> 2.25				$180,000
Structural Overlay	4"	4S1	> 10	1.76 < ST < 2.14				> 125	$180,000
	6"	6S1	> 10	2.14 < ST < 2.90				> 125	$270,000
	8"	8S1	> 10	2.90 < ST < 3.66				> 125	$360,000
Bonded PCC Overlay	3"	3B1	> 50	2.5 <= ST < 3.5		15	> 2		$300,000
	4"	4B1	> 50	3.5 <= ST < 4.5		15	> 2		$400,000
	5"	5B1	> 50	4.5 <= ST < 5.5		15	> 2		$500,000
	6"	6B1	> 50	5.5 <= ST < 6.5		15	> 2		$600,000
Pavement Replacement		REPL	< 50						$750,000

Figure 24. Concrete Pavement Treatments Decision Matrix

			PCI	Structure (ST)	IRI	Rutting	
Treatment	**Thickness**	**Code**	**Triggers**				**Cost**
Functional Overlay	4"	4FO4	> 10	ST < 1.76	> 1.75		$180,000
Structural Resurfacing	4"	4S4	> 10	1.76 < ST < 2.14		< 0.20	$180,000
	6"	6S4	> 10	2.14 < ST < 2.90		< 0.20	$270,000
	8"	8S4	> 10	2.90 < ST < 3.66		< 0.20	$360,000
Structrual Resurfacing and Milling	4"	4M4	> 10	2.5 < ST < 3.5		> 0.20	$280,000
	6"	6M4	> 10	3.5 < ST < 4.5		> 0.20	$450,000
	8"	8M4	> 10	4.5 < ST < 5.5		> 0.20	$540,000
Pavement Replacement		REPL	< 50				$750,000

Figure 25. Asphalt Pavement Treatments Decision Matrix

			PCI	Structure (ST)	T. Thickness	IRI	Rutting	Avg. K	
Treatment	Thickness	Code	Triggers						Cost
Functional Overlay	4"	4F3B	> 10	ST < 1.76	< = 12"	> 1.75			$180,000
Structural Resurfacing	4"	4S3B	> 10	1.76 < ST < 2.14	<= 12"		< 0.20	> 125	$180,000
	6"	6S3B	> 10	2.14 < ST < 2.90	<= 12"		< 0.20	> 125	$350,000
	8"	8S3B	> 10	2.90 < ST < 3.66	<= 12"		< 0.20	> 125	$440,000
Structrual Resurfacing and Milling	4"	4M3B	> 10	2.5 <= ST < 3.5	<= 12"		> 0.20	> 125	$280,000
	6"	6M3B	> 10	3.5 <= ST < 4.5	<= 12"		> 0.20	> 125	$450,000
	8"	8M3B	> 10	4.5 <= ST < 5.5	<= 12"		> 0.20	> 125	$540,000
Pavement Replacement		REPL	< 50						$750,000

Figure 26. Composite Pavement Treatments Decision Matrix

As shown in Figures 24-26, each pavement type has a list of treatment strategies (functional rehabilitation, structural rehabilitation, and reconstruction). An individual treatment strategy might have different thicknesses and for each thickness there are different parameter levels that trigger each treatment. A cost value (per mile) is associated with each treatment strategy. dTIMS was again used as an expert system shell to build the knowledge rules to determine the feasible treatment strategy or strategies for each pavement section. Depending on the input parameters used, multiple treatment strategies might be feasible for an individual pavement section in the same year.

dTIMS will output a list of feasible treatment strategies for each pavement section for all of the years in the planning or analysis period. The PCI and age values from the F-KBES are the initial input into the TS-KBES. Other condition variables including roughness (in terms of the International Roughness Index - IRI), rutting (inches), structure rating, total thickness, aggregate class, and average K value (subgrade reaction) are used by the KBES to determine feasible treatment alternatives based on the treatment decision matrix for each pavement type.

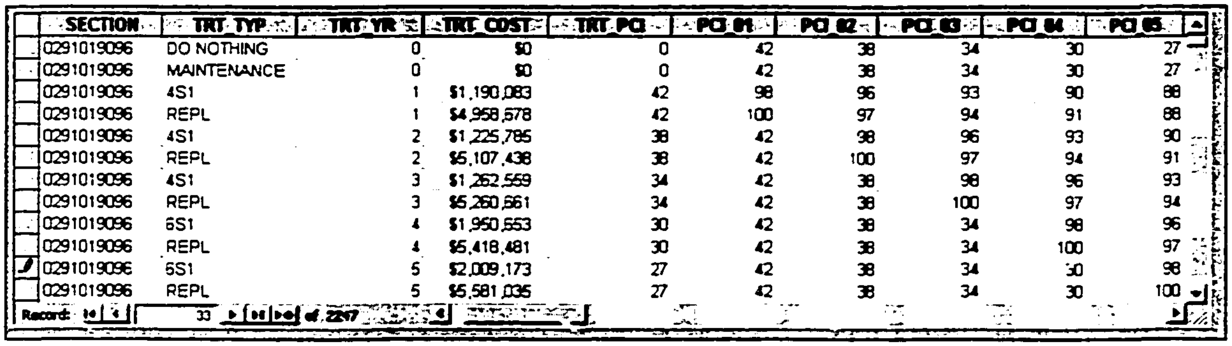
Each feasible treatment strategy has a cost and a resulting PCI associated with it. The resulting PCI value is based on the PCI value that was calculated by the F-KBES before the treatment strategy is applied and the improvement resulting from the application of a treatment strategy. Table 5 shows an example of improvement in PCI and other factors (IRI and rutting) as a result of the application of a reconstruction strategy. As a treatment strategy is implemented, the pavement condition improves. Table 5 shows the improved pavement condition values due to the implementation of a reconstruction strategy. Several tables are developed for the remaining treatment alternatives. These improvement values are determined using historical information (construction records and the Iowa DOT pavement management information system). The TS-KBES considers the resulting PCI and determines a set of feasible treatment strategies considering the PCI value for the remaining years in the analysis period.

Table 5. Improvements in Pavement Condition After Reconstruction

Pavement Type	**Resulting Parameter Values**			
	PCI	**IRI**	**Rutting**	**Age**
Concrete	100	1.5	0	0
Asphalt	100	1.2	0	0
Composite	100	1.3	0	0

The same process is repeated for the other treatment strategies for each pavement type and similar tables are used in the knowledge-base to determine the improvement in pavement condition after the application of a specific treatment strategy. dTIMS outputs a list of the pavement sections with their associated feasible treatment alternatives, PCI values, and other parameters necessary as input to the dynamic program.

dTIMS is capable of running the KBES program for a maximum of a 20-year analysis period, generating strategies for each pavement section for each year. For purposes of this research, however, only 5 years are used as the analysis period because this is a project selection level pavement management system. Figure 27 is an example of dTIMS output for an individual pavement section. As it can be seen from Figure 27, individual sections might have multiple feasible treatment strategies selected for the same year depending on the condition (PCI, IRI, structure, and rutting) and the other parameters in the decision matrix. In the example shown in Figure 27, a four inch overlay (4S1) and pavement replacement (REPL) were both feasible in years 1, 2, and 3 of the analysis period. Figure 27 shows one section on interstate 29 with 12 feasible alternatives for the 5 year analysis period. Each alternative has a cost, an application year, and resulting PCI values associated with it. It can be seen from Figure 27 that as the pavement condition deteriorates, different treatment strategies become feasible. The output from TS-KBES is formatted for use in the dynamic program which is discussed in the next section. See Appendix II for complete results from the TS-KBES for all of the Iowa DOT interstate sections.



SECTION	TRT_TYP	TRT_YR	TRT_COST	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0291019096	DO NOTHING	0	$0	0	42	38	34	30	27
0291019096	MAINTENANCE	0	$0	0	42	38	34	30	27
0291019096	4S1	1	$1,190,083	42	98	96	93	90	88
0291019096	REPL	1	$4,958,578	42	100	97	94	91	88
0291019096	4S1	2	$1,225,785	38	42	98	96	93	90
0291019096	REPL	2	$5,107,438	38	42	100	97	94	91
0291019096	4S1	3	$1,262,559	34	42	38	98	96	93
0291019096	REPL	3	$5,260,661	34	42	38	100	97	94
0291019096	6S1	4	$1,950,553	30	42	38	34	98	96
0291019096	REPL	4	$5,418,481	30	42	38	34	100	97
0291019096	6S1	5	$2,009,173	27	42	38	34	30	98
0291019096	REPL	5	$5,581,035	27	42	38	34	30	100

Figure 27. TS-KBES Example Output

Dynamic Programming Model

Deterministic dynamic programming is used for the project selection and resource allocation module in the pavement management system. The dynamic program is used to determine which pavement sections will be selected for inclusion in the maintenance and rehabilitation program. The DP will then determine the type of treatment strategy, time (year in the analysis period), and the estimated cost for each selected section. The dynamic program utilizes the output from the TS-KBES and builds the decision process network for all pavement sections considered in the analysis period. The deterministic part means that the condition (state) at the next stage (year) of each pavement section is completely defined by the state and the decision policy at the current stage.

The objective function of the dynamic program can be formulated to minimize total cost subject to performance constraints, maximization of benefits (area under the performance curve) subject to budget constraints, or maximization of asset value subject to budget constraints and user costs. The following is the description of the different formulations of the three dynamic program objectives. Depending on agency objectives, operating procedures, and required results (construction program, short or long range planing, and/or funding impacts), one or more approaches can be selected to run the dynamic program and produce the list of selected pavement management sections for maintenance and rehabilitation projects.

Dynamic Program Objective Functions

1. Minimize **C**, **C** = Total Cost

$$Total\_Cost = \sum_{y_1^p}\sum_{i_1^n}\sum_{j_1^o}\sum_{K_1^m}(L_i)*(T_{kij})*(A_{kij})$$

where;

y = number of stages (years in the analysis period) from 1 to p,

i = number of pavement sections from 1 to n,

j = number of states (depends on the PCI) from 1 to o,

k = number of treatments from 1 to m,

L_i = length of section **i**,

T_{kij} = cost of applying treatment **k** to section **i** at state **j**, and

A_{kij} = 0, if treatment **k** is not feasible for section **i** at state **j** and
1, if treatment **k** is feasible for section **i** at state **j**.

The objective function is constrained by performance criteria in terms of overall pavement condition (PCI). With this formulation, the dynamic program calculates the minimum budget needed to maintain an average pavement condition according to the performance constraint. Other constraints such as number of miles in each state, number of miles for each treatment strategy, construction time frame, and human resources can also be included in the dynamic program.

2. Maximize **B**, **B** = Benefits

$$Benefits = \sum_{y_1}^{p}\sum_{i_1}^{n}\sum_{j_1}^{o}\sum_{K_1}^{m}(L_i)*(PCI_{kij})*(A_{kij})$$

where;

y = number of stages (years in the analysis period) from 1 to p,

i = number of pavement sections from 1 to n,

j = number of states (depends on the PCI) from 1 to o,

k = number of treatments from 1 to m,

L_i = length of section **i**,

PCI_{kij} = PCI resulting from applying treatment **k** to section **i** at state **j**, and

A_{kij} = 0, if treatment **k** is not feasible for section **i** at state **j** and 1, if treatment **k** is feasible for section **i** at state **j**.

The objective function (to maximize benefits) is constrained by annual budget numbers for each year in the planning or analysis period considered. Other constraints such as number of miles in each state, number of miles for each treatment strategy, construction time frame, and human resources can be also included in the dynamic program if the information is available and can be expressed in a mathematical format.

3. Maximize **A**, **A** = Asset Value

$$Asset\_Value = \sum_{y=1}\sum_{i=1}\sum_{j=1}\sum_{K=1}(L_i)*(V_{kij})*(A_{kij})$$

where;

y = number of stages (years in the analysis period) from 1 to p,

i = number of pavement sections from 1 to n,

j = number of states (depends on the PCI) from 1 to o,

k = number of treatments from 1 to m,

L_i = length of section **i**,

V_{kij} = asset value resulting from applying treatment **k** to section **i** at state **j**, and

A_{kij} = 0, if treatment **k** is not feasible for section **i** at state **j** and
1, if treatment **k** is feasible for section **i** at state **j**.

The objective function is constrained by annual budget numbers for each year in the planning or analysis period considered. Other constraints such as number of miles in each state, number of miles for each treatment strategy, construction time frame, and human resources can be also included in the dynamic program given that the information is available and easy to express in a mathematical format. The asset value is based on pavement condition and can be obtained from an asset management system if such a system has been implemented. The dynamic program is capable of maximizing the asset value of the entire pavement system or maximize the increase in the asset value. Determining the asset value is a subject for future research.

The dynamic program decision process network is developed for each section for all the years in the planning or analysis period. Information regarding condition (PCI) and the feasible treatment strategies for each section is provided from the TS-KBES output. The resulting PCI and cost numbers are also included. The FORTRAN program builds the network and selects projects and treatment strategies associated with them based on the system constraint (budget or performance).

The output from the dynamic program gives the user a listing of all the pavement sections and the type of work selected (treatment strategy), the timing (which year in the planning or analysis period), and the estimated cost. Appendix III contains a sample of the dynamic program output.

RESULTS

This chapter presents the results from comparing the outcome from the KBES pavement management optimization system and what the Iowa DOT currently uses as their pavement management system (MYP using dTIMS). The interstate system data were used to compare the results from the two system.

The interstate system consists of 450 individual pavement management sections covering all of the interstate system in the state in both directions covering approximately 1560 miles. The Iowa DOT has been using dTIMS as their pavement management system software since 1995. The Iowa DOT 5-year interstate construction program has been developed using output from dTIMS since 1998. The results from the Iowa DOT system (MYP using dTIMS) for the years 2002 to 2006 were compared to those from the KBES pavement management optimization (using DP) for the same time period. The following discussion provide a general overview of the comparison and the results.

The comparison was conducted using the resulting PCI values for each year in the analysis period using the same budget for the two systems. Table 6 shows the Iowa DOT interstate budget for the 5 years included in the analysis period.

Table 6. Iowa DOT Budget by Year

Year	Budget (Millions)
2002	$78
2003	$23
2004	$14
2005	$52
2006	$40

The PCI values resulting from each system were compared. Figure 28 shows the result of that comparison. As can been seen from Figure 28, using KBES pavement management system using dynamic programming (KBES_DP) resulted in a higher PCI average after 5 years. The value of the average PCI after 5 years using KBES_DP was 83.18 compared to an average PCI of 80.8 resulting from using the multi-year prioritization technique (MYP) in dTIMS. That is an improvement of three percent on the overall PCI for the entire interstate system. The total budget used to run the two systems for the 5-year period is $207 million.

To determine the financial impact of improving the PCI by three percent, the MYP approach was used to conduct a "what-if-analysis". Figure 29 shows the results from the "what-if-analysis". As can be seen from Figure 29, it is going to take $266 million over the 5-year period using the MYP system to achieve the same PCI (83.18) that resulted from the KBES_DP. That is an increase of $59 million over 5 years to achieve the same PCI level. Using the KBES_DP pavement management system resulted in better allocation of resources which is translated to an improvement in the overall pavement condition (3 percent).

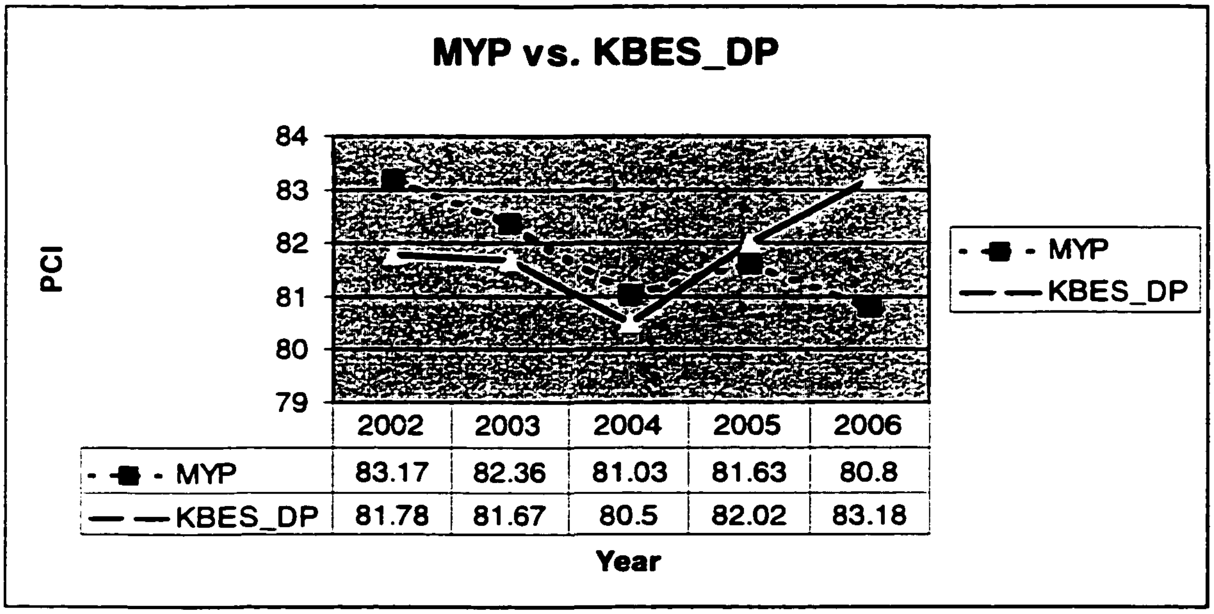


Figure 28. MYP vs. KBES_DB PMS Results

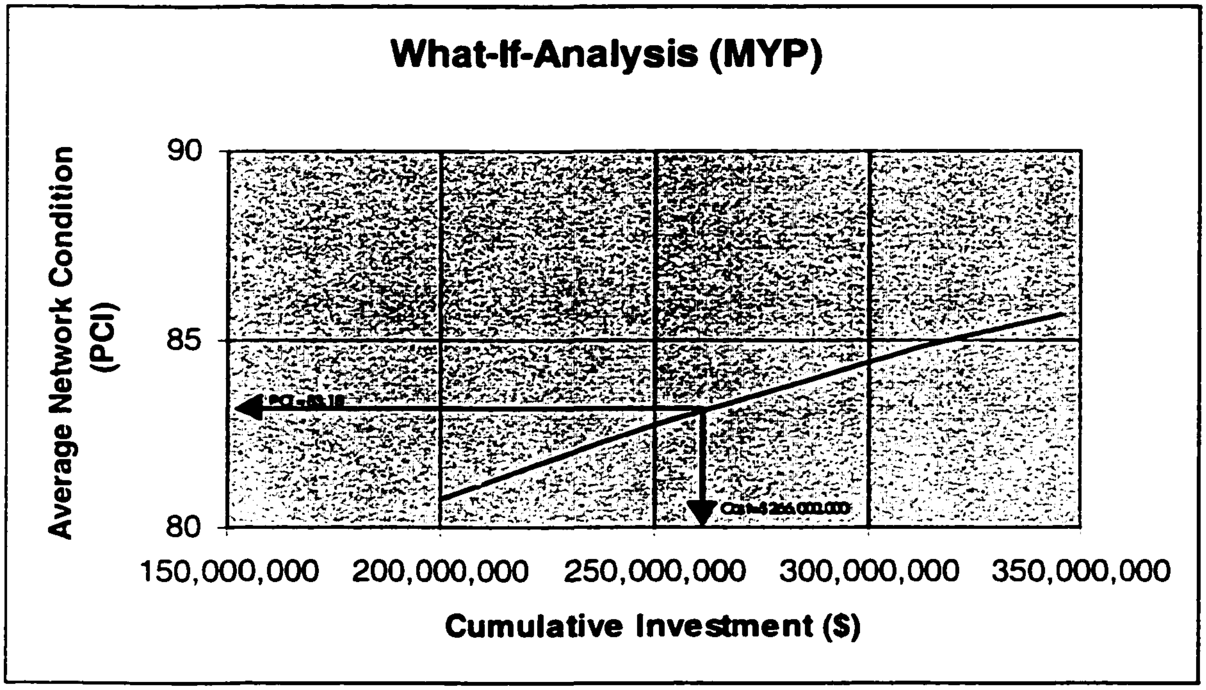


Figure 29. MYP "What-If-Analysis"

DISCUSSION AND CONCLUSIONS

Knowledge-based expert systems and dynamic programming were used to develop a comprehensive pavement management system covering condition forecasting, treatment strategy selection, and project selection and resource allocation aspects. The objective of this research was to use knowledge-based expert systems as part of a pavement management system instead of a stand-alone project level tool. Knowledge-based expert systems have been used, as shown in the literature review, to perform specific tasks related to the pavement management process, primarily, for diagnosis applications (treatment strategy selection). The results of this research showed the feasibility of using knowledge-based expert systems as a component in the pavement management system.

Two KBES modules have been developed to perform pavement condition forecasting (F-KBES) and treatment strategy selection (TS-KBES). The F-KBES was used in conjunction with deterministic performance curves, developed using historical data and regression analysis. The use of KBES proved to be feasible and provided added advantages because of the flexibility in adding new parameters that affect pavement condition without the need to modify original performance curves. F-KBES utilized a forward chaining approach inference engine to run the knowledge-base rules and facts to determine the impact of different parameters on overall pavement condition. As more parameters are added, another evaluation of the inference engine approach will be required to ensure that the KBES is operating in an efficient manner.

One of the advantages of using F-KBES for forecasting pavement condition is the ability of the system to learn from cases it investigated and in turn, adjust the pavement condition accordingly. This was used to determine a calculated age (based on the condition index (PCI) value and the age-based performance curves) for each pavement section considered in the analysis. Using the calculated age provides added flexibility when the data are used in the other pavement management system components.

TS-KBES was used to represent the knowledge in accordance with a treatment decision matrix for the selection of feasible treatment strategies for different pavement types. Each set of treatment decision matrix was represented in the knowledge-base rules and facts to enable the KBES to select feasible treatment strategies for different pavement sections included in the analysis. The use of KBES for diagnosis purposes have been documented in the literature and has been proven to be a feasible and efficient tool. The use of TS-KBES in this research followed the examples in the literature with one difference and that is that the output from the KBES was used as input into a resource allocation procedure for project selection. Also, TS-KBES selected feasible treatment strategies for each pavement section for all of the years in the planning or analysis period. In addition, TS-KBES considered the resulting pavement condition resulting from the application of a specific treatment strategy and calculated associated costs. This proved to be beneficial in building the input for the dynamic program. It simplified the initial setup of the dynamic program and streamlined its operation.

Future research in this area should focus on the development of an explanation facility. This should be added to make TS-KBES more user interactive and provide the user with an opportunity to modify the outcome from the KBES.

Dynamic programming has traditionally been used as a resource allocation tool for network level pavement management systems utilizing probabilistic performance prediction tools. In this research, deterministic dynamic programming was used as project selection and resource allocation tool for a project selection level pavement management system. The feasibility of using dynamic programming has been established in earlier research by this author (3). The use of dynamic programming reduces the pavement management problem size and results in a more flexible approach to solve the resource allocation problem. The dynamic program used the TS-KBES output (treatment strategies, cost, and associated pavement condition values) in addition to pavement inventory information. The dynamic program objective function can take on different forms to meet the different needs of the transportation agency using the pavement management system.

In conclusion, the use of knowledge-based expert systems in pavement management have proven feasible and advantageous. The use of dynamic programming for project selection and resource allocation adds decision support capabilities to the pavement management process. Future research in this area should focus on the use of asset management principles to the infrastructure management process including not only pavements and bridges, but other physical infrastructure managed by highway agencies.

APPENDIX I : F-KBES OUTPUT

SECTION	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0291000098	64	62	60	58	56
0291008998	61	59	57	55	53
0291019098	42	38	34	30	27
0291025498	40	36	32	28	25
0291032198	34	30	26	22	19
0291032798	55	52	50	47	44
0291033498	34	30	26	22	19
0291034898	48	45	43	40	37
0291035798	33	29	25	21	18
0291037298	57	54	52	49	46
0291037798	36	32	28	24	21
0291038598	82	79	77	74	71
0291039298	85	82	80	77	74
0291040298	86	83	81	78	75
0291041898	84	81	79	76	73
0291043698	71	68	66	63	60
0291046898	46	43	41	38	35
0291051598	38	34	30	26	23
0291052198	34	30	26	22	19
0291052798	39	35	31	27	24
0291053298	34	32	30	28	26
0291054598	47	44	41	38	35
0291056398	100	97	94	91	88
0291057798	95	92	89	86	83
0291072498	95	92	89	86	83
0291077698	64	61	59	56	53
0291081798	53	50	48	45	42
0291083998	63	60	58	55	52
0291090598	94	91	89	86	83
0291094898	99	96	94	91	88
0291098098	100	97	95	92	89
0291100898	100	97	95	92	89
0291105898	100	97	95	92	89
0291112398	49	46	43	40	37

SECTION	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0291120298	45	42	39	36	33
0291126698	29	27	25	22	20
0291127498	41	39	37	34	32
0291128698	47	45	43	40	38
0291132898	43	41	39	36	34
0291133798	49	47	45	42	40
0291134398	54	52	50	47	45
0291135298	52	50	48	45	43
0291136098	37	35	33	30	28
0291137598	41	39	37	34	32
0291140698	48	46	44	41	39
0291145198	57	55	53	50	48
0291148298	59	57	55	52	50
0291149198	55	53	51	48	46
0291150698	54	52	50	47	45
0292000098	69	67	65	63	61
0292008998	70	68	66	64	62
0292019098	42	38	34	30	27
0292025498	42	39	37	34	31
0292026998	40	36	32	28	25
0292032198	36	32	28	24	21
0292032898	54	51	49	46	43
0292033498	36	32	28	24	21
0292034798	50	47	45	42	39
0292036198	34	30	26	22	19
0292038598	84	81	79	76	73
0292040298	89	86	84	81	78
0292041398	85	82	80	77	74
0292041898	81	78	76	73	70
0292043698	74	71	69	66	63
0292046898	54	51	49	46	43
0292051598	36	32	28	24	21
0292052198	34	30	26	22	19
0292052798	39	35	31	27	24

SECTION	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0292053298	43	41	39	37	35
0292054598	42	39	36	33	30
0292056398	100	97	94	91	88
0292057798	98	95	92	89	86
0292060898	100	97	94	91	88
0292065598	99	96	93	90	87
0292070898	100	97	94	91	88
0292072498	100	97	94	91	88
0292076598	42	38	34	30	26
0292077698	69	66	64	61	58
0292079798	78	75	73	70	67
0292083298	71	68	66	63	60
0292086598	68	65	63	60	57
0292087998	67	64	62	59	56
0292089798	51	49	47	45	43
0292094898	99	96	94	91	88
0292097298	100	97	95	92	89
0292100898	97	94	92	89	86
0292105898	71	68	66	63	60
0292112398	51	48	45	42	39
0292120298	45	42	39	36	33
0292126698	30	28	26	23	21
0292128098	47	45	43	40	38
0292129798	29	27	25	22	20
0292131798	48	46	44	41	39
0292133998	47	45	43	40	38
0292136298	39	37	35	32	30
0292141098	51	49	47	44	42
0292141898	46	44	42	39	37
0292145198	62	60	58	55	53
0292148298	58	56	54	51	49
0292149198	55	53	51	48	46
0292150698	57	55	53	50	48
0351000098	83	80	78	75	72

SECTION	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0351001498	87	84	82	79	76
0351002398	92	89	87	84	81
0351003798	91	88	86	83	80
0351004798	88	85	83	80	77
0351005298	87	84	82	79	76
0351007298	95	92	90	87	84
0351008898	90	87	85	82	79
0351009498	96	93	91	88	85
0351010198	96	93	91	88	85
0351011198	94	91	89	86	83
0351012398	98	95	93	90	87
0351013898	94	91	89	86	83
0351014998	86	83	81	78	75
0351016098	97	94	92	89	86
0351016898	90	87	85	82	79
0351018298	100	97	95	92	89
0351019498	94	91	89	86	83
0351020798	100	97	95	92	89
0351022098	92	89	87	84	81
0351022798	100	97	95	92	89
0351024298	85	82	80	77	74
0351026098	100	97	95	92	89
0351028398	90	87	85	82	79
0351029198	100	97	95	92	89
0351031698	86	83	81	78	75
0351033098	75	72	69	66	63
0351038098	70	67	64	61	58
0351042898	67	65	63	60	58
0351044598	57	55	53	50	48
0351045598	68	66	64	61	59
0351054498	53	51	49	46	44
0351056798	43	41	39	36	34
0351059898	57	55	53	50	48
0351062298	48	46	44	41	39

APPENDIX II : TS-KBES OUTPUT

SECTION	TRT_TYP	TRT_YR	TRT_COS	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0291019098	DO NOTHING	0			42	38	34	30	27
0291019098	4S1	1	$1,190,083	42	98	96	93	90	88
0291019098	REPL	1	$4,958,678	42	100	97	94	91	88
0291019098	4S1	2	$1,225,785	38	42	98	96	93	90
0291019098	REPL	2	$5,107,438	38	42	100	97	94	91
0291019098	4S1	3	$1,262,559	34	42	38	98	96	93
0291019098	REPL	3	$5,260,661	34	42	38	100	97	94
0291019098	6S1	4	$1,950,653	30	42	38	34	98	96
0291019098	REPL	4	$5,418,481	30	42	38	34	100	97
0291019098	6S1	5	$2,009,173	27	42	38	34	30	98
0291019098	REPL	5	$5,581,035	27	42	38	34	30	100
0291032798	DO NOTHING	0			55	52	50	47	44
0291032798	6S3B	1	$237,570	55	98	96	93	90	88
0291032798	6S3B	2	$244,697	52	55	98	96	93	90
0291032798	8S3B	3	$316,847	50	55	52	98	96	93
0291032798	REPL	3	$540,080	50	55	52	100	97	94
0291032798	8M3B	4	$400,524	47	55	52	50	91	89
0291032798	REPL	4	$556,283	47	55	52	50	100	97
0291032798	8M3B	5	$412,539	44	55	52	50	47	91
0291032798	REPL	5	$572,971	44	55	52	50	47	100
0291034898	DO NOTHING	0			48	45	43	40	37
0291034898	REPL	1	$686,752	48	100	97	94	91	88
0291034898	REPL	2	$707,355	45	48	100	97	94	91
0291034898	REPL	3	$728,576	43	48	45	100	97	94
0291034898	REPL	4	$750,433	40	48	45	43	100	97
0291034898	REPL	5	$772,946	37	48	45	43	40	100
0291037298	DO NOTHING	0			57	54	52	49	46
0291037298	4M3B	2	$144,070	54	57	91	89	86	83
0291037298	4M3B	3	$148,392	52	57	54	91	89	86
0291037298	6M3B	4	$245,642	49	57	54	52	91	89
0291037298	REPL	4	$409,404	49	57	54	52	100	97
0291037298	6M3B	5	$253,012	46	57	54	52	49	91
0291037298	REPL	5	$421,686	46	57	54	52	49	100
0291040298	DO NOTHING	0			86	83	81	78	75
0291040298	6S3B	1	$593,744	86	98	96	93	90	88
0291040298	6S3B	2	$611,556	83	86	98	96	93	90
0291040298	6M3B	3	$809,875	81	86	83	91	89	86
0291040298	6M3B	4	$834,171	78	86	83	81	91	89
0291040298	6M3B	5	$859,196	75	86	83	81	78	91

SECTION	TRT_TYP	TRT_YR	TRT_COS	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0291041898	DO NOTHING	0			84	81	79	76	73
0291041898	4S3B	4	$362,639	76	84	81	79	98	96
0291041898	4S3B	5	$373,518	73	84	81	79	76	98
0291043698	DO NOTHING	0			71	68	66	63	60
0291043698	4S3B	1	$596,803	71	98	96	93	90	88
0291043698	4S3B	2	$614,707	68	71	98	96	93	90
0291043698	4S3B	3	$633,148	66	71	68	98	96	93
0291043698	6S3B	4	$1,268,055	63	71	68	66	98	96
0291043698	6S3B	5	$1,306,096	60	71	68	66	63	98
0291056398	DO NOTHING	0			100	97	94	91	88
0291057798	DO NOTHING	0			95	92	89	86	83
0291072498	DO NOTHING	0			95	92	89	86	83
0292077698	DO NOTHING	0			69	66	64	61	58
0292077698	8S3B	1	$932,232	69	98	96	93	90	88
0292077698	8M3B	2	$1,178,427	66	69	91	89	86	83
0292077698	8M3B	3	$1,213,779	64	69	66	91	89	86
0292077698	8M3B	4	$1,250,193	61	69	66	64	91	89
0292077698	8M3B	5	$1,287,698	58	69	66	64	61	91
0351000098	DO NOTHING	0			83	80	78	75	72
0351000098	6S3B	1	$512,992	83	98	96	93	90	88
0351000098	6S3B	2	$528,381	80	83	98	96	93	90
0351000098	6S3B	3	$544,233	78	83	80	98	96	93
0351000098	6S3B	4	$560,560	75	83	80	78	98	96
0351001498	DO NOTHING	0			87	84	82	79	76
0351001498	4F3B	1	$161,298	87	98	96	93	90	88
0351001498	4F3B	2	$166,137	84	87	98	96	93	90
0351001498	4F3B	3	$171,121	82	87	84	98	96	93
0351001498	4M3B	4	$274,174	79	87	84	82	91	89
0351001498	4M3B	5	$282,399	76	87	84	82	79	91
0351002398	DO NOTHING	0			92	89	87	84	81
0351002398	4M3B	2	$424,487	89	92	91	89	86	83
0351002398	4M3B	3	$437,222	87	92	89	91	89	86
0351002398	6M3B	4	$723,758	84	92	89	87	91	89
0351002398	6M3B	5	$745,471	81	92	89	87	84	91
0351003798	DO NOTHING	0			91	88	86	83	80
0351003798	4F3B	1	$186,698	91	98	96	93	90	88
0351003798	4F3B	2	$192,299	88	91	98	96	93	90
0351003798	4F3B	3	$198,068	86	91	88	98	96	93
0351003798	4F3B	4	$204,010	83	91	88	86	98	96

SECTION	TRT_TYP	TRT_YR	TRT_COS	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0351003798	4F3B	5	$210,130	80	91	88	86	83	98
0351004798	DO NOTHING	0			88	85	83	80	77
0351004798	4F3B	2	$96,054	85	88	98	96	93	90
0351004798	4F3B	3	$98,936	83	88	85	98	96	93
0351004798	4F3B	4	$101,904	80	88	85	83	98	96
0351004798	4S3B	5	$104,961	77	88	85	83	80	98
0351005298	DO NOTHING	0			87	84	82	79	76
0351005298	4F3B	1	$383,593	87	98	96	93	90	88
0351005298	4M3B	2	$614,601	84	87	91	89	86	83
0351005298	4M3B	3	$633,039	82	87	84	91	89	86
0351005298	4M3B	4	$652,030	79	87	84	82	91	89
0351005298	6M3B	5	$1,079,342	76	87	84	82	79	91
0351007298	DO NOTHING	0			95	92	90	87	84
0351007298	4S3B	3	$300,740	90	95	92	98	96	93
0351007298	4S3B	4	$309,763	87	95	92	90	98	96
0351007298	4S3B	5	$319,055	84	95	92	90	87	98
0351008898	DO NOTHING	0			90	87	85	82	79
0351008898	4F3B	1	$118,656	90	98	96	93	90	88
0351008898	4F3B	2	$122,216	87	90	98	96	93	90
0351008898	4F3B	3	$125,882	85	90	87	98	96	93
0351008898	4F3B	4	$129,659	82	90	87	85	98	96
0351008898	4M3B	5	$207,742	79	90	87	85	82	91
0351009498	DO NOTHING	0			96	93	91	88	85
0351010198	DO NOTHING	0			96	93	91	88	85
0351010198	4F3B	1	$191,147	96	98	96	93	90	88
0351010198	4F3B	2	$196,882	93	96	98	96	93	90
0351010198	4F3B	3	$202,788	91	96	93	98	96	93
0351010198	4F3B	4	$208,872	88	96	93	91	98	96
0351010198	4F3B	5	$215,138	85	96	93	91	88	98
0351011198	DO NOTHING	0			94	91	89	86	83
0351011198	4S3B	1	$211,912	94	98	96	93	90	88
0351011198	4S3B	2	$218,270	91	94	98	96	93	90
0351011198	4S3B	3	$224,818	89	94	91	98	96	93
0351011198	6S3B	4	$450,260	86	94	91	89	98	96
0351011198	6S3B	5	$463,768	83	94	91	89	86	98
0351012398	DO NOTHING	0			98	95	93	90	87
0351013898	DO NOTHING	0			94	91	89	86	83
0351013898	4S3B	4	$229,131	86	94	91	89	98	96
0351013898	4S3B	5	$236,005	83	94	91	89	86	98

SECTION	TRT_TYP	TRT_YR	TRT_COS	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0351016098	DO NOTHING	0			97	94	92	89	86
0351016898	DO NOTHING	0			90	87	85	82	79
0351216698	DO NOTHING	0			81	78	76	73	70
0351216698	4S3B	2	$382,115	78	81	98	96	93	90
0351216698	4S3B	3	$393,578	76	81	78	98	96	93
0351216698	4S3B	4	$405,386	73	81	78	76	98	96
0351216698	6S3B	5	$811,898	70	81	78	76	73	98
0352000098	DO NOTHING	0			93	90	88	85	82
0352000098	4M3B	5	$409,316	82	93	90	88	85	91
0352001298	DO NOTHING	0			95	92	90	87	84
0352002098	DO NOTHING	0			95	92	90	87	84
0352002098	4M3B	3	$986,732	90	95	92	91	89	86
0352002098	4M3B	4	$1,016,334	87	95	92	90	91	89
0352002098	4M3B	5	$1,046,824	84	95	92	90	87	91
0352005298	DO NOTHING	0			90	87	85	82	79
0352005298	4F3B	2	$192,299	87	90	98	96	93	90
0352005298	4F3B	3	$198,068	85	90	87	98	96	93
0352005298	4F3B	4	$204,010	82	90	87	85	98	96
0352005298	4F3B	5	$210,130	79	90	87	85	82	98
0741000098	DO NOTHING	0			100	97	95	92	89
0741002498	DO NOTHING	0			100	97	95	92	89
0741003498	DO NOTHING	0			100	97	95	92	89
0742000098	DO NOTHING	0			100	97	95	92	89
0742002498	DO NOTHING	0			100	97	95	92	89
0742003498	DO NOTHING	0			100	97	95	92	89
0801018798	DO NOTHING	0			89	86	84	81	78
0801018798	6M3B	1	$1,008,112	89	91	89	86	83	81
0801018798	6M3B	2	$1,038,356	86	89	91	89	86	83
0801020998	DO NOTHING	0			79	76	74	71	68
0801020998	4F3B	1	$771,820	79	98	96	93	90	88
0801020998	4M3B	2	$1,236,627	76	79	91	89	86	83
0801020998	4M3B	3	$1,273,726	74	79	76	91	89	86
0801020998	4M3B	4	$1,311,938	71	79	76	74	91	89
0801020998	6M3B	5	$2,171,726	68	79	76	74	71	91
0801025198	DO NOTHING	0			61	58	56	53	50
0801025198	8S3B	1	$411,052	61	98	96	93	90	88
0801025198	8S3B	2	$423,384	58	61	98	96	93	90
0801026098	DO NOTHING	0			61	58	56	53	50
0801026098	8S3B	1	$912,292	61	98	96	93	90	88

SECTION	TRT_TYP	TRT_YR	TRT_COS	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0801026098	8M3B	2	$1,153,220	58	61	91	89	86	83
0801026098	8M3B	3	$1,187,816	56	61	58	91	89	86
0801073398	DO NOTHING	0			49	46	43	40	37
0801073398	REPL	1	$5,097,728	49	100	97	94	91	88
0801073398	REPL	2	$5,250,659	46	49	100	97	94	91
0801073398	REPL	3	$5,408,179	43	49	46	100	97	94
0801073398	REPL	4	$5,570,424	40	49	46	43	100	97
0801073398	REPL	5	$5,737,537	37	49	46	43	40	100
0801079998	DO NOTHING	0			48	45	42	39	36
0801079998	REPL	1	$4,512,172	48	100	97	94	91	88
0801079998	REPL	2	$4,647,538	45	48	100	97	94	91
0801079998	REPL	3	$4,786,964	42	48	45	100	97	94
0801079998	REPL	4	$4,930,573	39	48	45	42	100	97
0801079998	REPL	5	$5,078,490	36	48	45	42	39	100
0801085798	DO NOTHING	0			43	40	37	34	31
0801085798	REPL	1	$8,885,295	43	100	97	94	91	88
0801085798	REPL	2	$9,151,854	40	43	100	97	94	91
0801085798	REPL	3	$9,426,409	37	43	40	100	97	94
0801085798	REPL	4	$9,709,202	34	43	40	37	100	97
0801085798	REPL	5	$10,000,478	31	43	40	37	34	100
0801097298	DO NOTHING	0			41	38	35	32	29
0801097298	REPL	1	$1,531,095	41	100	97	94	91	88
0801097298	REPL	2	$1,577,028	38	41	100	97	94	91
0801097298	REPL	3	$1,624,339	35	41	38	100	97	94
0801097298	REPL	4	$1,673,069	32	41	38	35	100	97
0801097298	REPL	5	$1,723,261	29	41	38	35	32	100
6801013198	DO NOTHING	0			71	68	66	63	60
6801013198	6S3B	1	$1,456,060	71	98	96	93	90	88
6801013198	8M3B	2	$2,313,887	68	71	91	89	86	83
6801013198	8M3B	3	$2,383,303	66	71	68	91	89	86
6801013198	8M3B	4	$2,454,802	63	71	68	66	91	89
6801013198	8M3B	5	$2,528,446	60	71	68	66	63	91
6801017198	DO NOTHING	0			62	59	57	54	51
6801017198	8S3B	1	$3,041,425	62	98	96	93	90	88
6801017198	8S3B	2	$3,132,668	59	62	98	96	93	90
6801023998	DO NOTHING	0			94	91	89	86	83
6801026698	DO NOTHING	0			94	91	89	86	83
6801027698	DO NOTHING	0			94	91	89	86	83

APPENDIX III : DYNAMIC PROGRAM OUTPUT

SECTION	TRT_TYP	TRT_YR	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0291037296	4M3B	3	52	57	54	91	89	86
0291056396		0	0	100	97	94	91	88
0291057796		0	0	95	92	89	86	83
0291081796	6M3B	3	48	53	50	91	89	86
0291100896		0	0	100	97	95	92	89
0291105896		0	0	100	97	95	92	89
0292025496	REPL	4	34	42	39	37	100	97
0292032896	6S3B	2	51	54	98	96	93	90
0292033496	REPL	1	36	100	97	94	91	88
0292034796	8S3B	5	39	50	47	45	42	98
0292038596	6S3B	3	79	84	81	98	96	93
0292040296	6S3B	4	81	89	86	84	98	96
0292041396	4S3B	1	85	98	96	93	90	88
0292041896	4S3B	1	81	98	96	93	90	88
0292043696	4S3B	5	63	74	71	69	66	98
0292046896	8S3B	5	43	54	51	49	46	98
0292076596	REPL	1	42	100	97	94	91	88
0292077696	8S3B	1	69	98	96	93	90	88
0292086596		0	0	68	65	63	60	57
0292087996	6M3B	2	64	67	91	89	86	83
0292089796		0	0	51	49	47	45	43
0292094896		0	0	99	96	94	91	88
0292097296		0	0	100	97	95	92	89
0292100896		0	0	97	94	92	89	86
0292105896	6S3B	2	68	71	98	96	93	90
0292112396		0	0	51	48	45	42	39
0292120296		0	0	45	42	39	36	33
0351000096	6S3B	4	75	83	80	78	98	96
0351001496	4F3B	3	82	87	84	98	96	93
0351002396	4M3B	3	87	92	89	91	89	86
0351003796	4F3B	5	80	91	88	86	83	98
0351004796	4S3B	5	77	88	85	83	80	98
0351007296	4S3B	5	84	95	92	90	87	98
0351009496		0	0	96	93	91	88	85
0351012396		0	0	98	95	93	90	87
0351016096		0	0	97	94	92	89	86
0351018296		0	0	100	97	95	92	89

SECTION	TRT_TYP	TRT_YR	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0351020796		0	0	100	97	95	92	89
0351022796		0	0	100	97	95	92	89
0351026096		0	0	100	97	95	92	89
0351029196		0	0	100	97	95	92	89
0351062296	REPL	4	41	48	46	44	100	97
0351067096	REPL	4	47	54	52	50	100	97
0351101796	REPL	4	47	59	55	51	100	97
0351102596	REPL	1	47	100	97	94	91	88
0352012396	4M3B	3	86	91	88	91	89	86
0352013396	4S3B	5	87	98	95	93	90	98
0352018196	4F3B	5	84	95	92	90	87	98
0352018896	4F3B	5	77	88	85	83	80	98
0352021596	4F3B	5	78	89	86	84	81	98
0352023496	4F3B	5	76	87	84	82	79	98
0352024296	4F3B	5	75	86	83	81	78	98
0352026796	4F3B	5	88	99	96	94	91	98
0352027796	4F3B	5	80	91	88	86	83	98
0352061496	REPL	2	46	48	100	97	94	91
0352086996	REPL	2	34	37	100	97	94	91
0352101796	REPL	3	39	45	42	100	97	94
0352116996	8S3B	1	63	98	96	93	90	88
0352126096	4S3B	2	72	75	98	96	93	90
0352129096	8S3B	4	58	66	63	61	98	96
0352134096		0	0	100	98	96	94	92
0352140196		0	0	100	98	96	94	92
0352142096		0	0	93	90	87	84	81
0352143296		0	0	96	94	92	90	88
0352166096		0	0	100	97	95	92	89
0352192796		0	0	99	96	94	91	88
0352194896		0	0	100	97	95	92	89
0352197196		0	0	94	91	89	86	83
0352201796		0	0	94	91	89	86	83
0352202696	4S3B	1	79	98	96	93	90	88
0352204696		0	0	96	93	91	88	85
0352216696	4S3B	4	72	80	77	75	98	96
0741000096		0	0	100	97	95	92	89
0741002496		0	0	100	97	95	92	89

SECTION	TRT_TYP	TRT_YR	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0741003496		0	0	100	97	95	92	89
0742000096		0	0	100	97	95	92	89
0742002496		0	0	100	97	95	92	89
0742003496		0	0	100	97	95	92	89
0801002896		0	0	55	52	50	47	44
0801018796	6M3B	2	86	89	91	89	86	83
0801020996	4F3B	1	79	98	96	93	90	88
0801025196	8S3B	2	58	61	98	96	93	90
0801026096	8S3B	1	61	98	96	93	90	88
0801055396		0	0	92	89	86	83	80
0801059996		0	0	86	83	80	77	74
0801079996	REPL	4	39	48	45	42	100	97
0801085796	REPL	2	40	43	100	97	94	91
0801097296	REPL	2	38	41	100	97	94	91
0801128296		0	0	98	95	92	89	86
0801131496	REPL	3	5	11	8	100	97	94
0801137096		0	0	62	60	58	55	53
0801137896		0	0	98	95	92	89	86
0801142196		0	0	85	82	79	76	73
0801149896		0	0	85	82	79	76	73
0801151496		0	0	95	92	89	86	83
0801156296		0	0	97	94	91	88	85
0801160396		0	0	100	97	94	91	88
0801165196		0	0	97	94	91	88	85
0802018796	6S3B	3	95	100	97	98	96	93
0802019296	6M3B	3	86	91	88	91	89	86
0802022496	8S3B	5	52	63	60	58	55	98
0802024796	8S3B	4	55	63	60	58	98	96
0802204896		0	0	94	91	88	85	82
0802209696		0	0	82	79	76	73	70
0802219996	REPL	1	23	100	97	94	91	88
0802221396		0	0	100	97	94	91	88
0802225996		0	0	79	76	73	70	67
0802228996		0	0	79	76	73	70	67
0802247996		0	0	95	92	89	86	83
0802253596		0	0	95	92	89	86	83
0802257696		0	0	87	84	81	78	75

SECTION	TRT_TYP	TRT_YR	TRT_PCI	PCI_01	PCI_02	PCI_03	PCI_04	PCI_05
0802278196	REPL	1	9	100	97	94	91	88
0802290996		0	0	97	94	91	88	85
0802294696	REPL	4	0	7	4	1	100	97
0802298696		0	0	100	97	94	91	88
0802302896	REPL	4	37	46	43	40	100	97
2351000096	REPL	2	49	52	100	97	94	91
2351010496	REPL	4	44	53	50	47	100	97
2352010496	REPL	4	41	50	47	44	100	97
2801000096		0	0	71	68	65	62	59
2802006396		0	0	70	67	64	61	58
2802008396		0	0	91	88	85	82	79
3801000096		0	0	97	94	92	89	86
3801004696		0	0	100	97	95	92	89
3801011896		0	0	97	94	92	89	86
3801017396		0	0	64	61	58	55	52
3802030296		0	0	80	77	74	71	68
3802037196		0	0	80	77	74	71	68
3802039496		0	0	81	78	75	72	69
3802043596		0	0	82	79	76	73	70
3802048696		0	0	83	80	77	74	71
6801013196	6S3B	1	71	98	96	93	90	88
6801017196	8S3B	2	59	62	98	96	93	90
6801026696		0	0	94	91	89	86	83
6801027696		0	0	94	91	89	86	83
6802000096		0	0	71	68	65	62	59
6802013196	6S3B	2	65	68	98	96	93	90
6802017196		0	0	67	64	62	59	56
6802023996		0	0	94	91	89	86	83

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