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16. Abstract

The Pavement Management Information System currently implemented within TxDOT contains a simple single year ranking procedure for prioritization of projects and for conducting impact analysis. This report compares the performance of this ranking procedure with two multi-year optimization procedures, one that only permits a single treatment during the planning period; the other allows multiple treatments.

A case study of 23 sections is used to compare the three methodologies and their effectiveness is compared in terms of how the individual sections are prioritized and the overall pavement condition at the end of the planning horizon.

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COMPARING RANKING AND OPTIMIZATION PROCEDURES FOR THE TEXAS PAVEMENT MANAGEMENT INFORMATION SYSTEM

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IMPLEMENTATION STATEMENT

The current Texas DOT's PMIS system has been implemented statewide to assist with network-level fund estimation, impact analysis, and project prioritization. This version uses a simple Cost-Effectiveness Ratio approach to rank and prioritize projects. In this report, alternative optimization routines are evaluated to perform the prioritization. The time optimization system which incorporates the consequences of deferred maintenance is described in this report. The use of a time optimization system should be considered for the next update of PMIS.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Tom Scullion, P.E. #62683.

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SUMMARY

The Pavement Management Information System currently implemented within TxDOT contains a simple single year ranking procedure for prioritization of projects and for conducting impact analysis. This report compares the performance of this ranking procedure with two multi year optimization procedures. One only permits a single treatment during the planning period, and the other allows multiple treatments.

A case study of 23 sections is used to compare the three methodologies. The methodologies are evaluated in terms of the overall pavement condition at the end of the planning horizon.

CHAPTER 1
INTRODUCTION

BASIC PAVEMENT MANAGEMENT INFORMATION SYSTEM CONCEPTS

Pavement Management Information System (PMIS) is an automated system for storing, retrieving, analyzing, and reporting information designed to assist decision-makers to make cost-effective decisions concerning the maintenance and rehabilitation of pavements (TxDOT 1993).

PMIS assists decision-makers at two levels of management that are referred to as network-level and project-level. The purpose of network-level management is directed at planning and programming of Maintenance and Rehabilitation activities. This includes how much funding is needed for a given analysis period, which sections of the highway network need maintenance or rehabilitation, and the impact of various funding levels on the pavement condition. The highway sections selected by the network-level management are analyzed in detail at the project-level. Project-level management is often referred to as pavement design because it includes the detailed engineering analysis required to determine the most cost-effective design, and the maintenance treatment or rehabilitation strategy to be applied to the specific highway section.

In other words, the main differences between the network-level and the project-level management are (1) the amount and type of data required and (2) the type of decisions to be made. Since data collection is expensive, minimum data is usually collected at the network-level. However, this data collected at network-level is not adequate for making project-level decisions because more complete and detailed data on individual highway sections must be collected. Decisions at the network-level are related to the budget process, funding, and prioritization of candidate highway sections, while at project-level, the decisions are concerned with the detailed assessment of the cause of deterioration and the selection of the most cost-effective maintenance, rehabilitation, or reconstruction strategy. Otherwise, the principles involved at both network and project-level are the same.

DESCRIPTION OF THE ELEMENTS OF TxDOT PMIS

The details of PMIS are presented in detail in companion report 1989-1; the basic elements are described and summarized below:

- an inventory of pavement sections,
- pavement condition data,
- needs estimate,
- prioritization of candidate highway sections for funding, and
- impact analysis of funding decisions on current and future pavement condition.

INVENTORY

The network inventory provides basic information to pavement managers on the type and location of the pavements they are responsible for. Since the entire length of the highway network is impossible to manage as a whole, it is helpful to divide the network into sections. This process is called segmentation, and there are two general concepts in PMIS for making this segmentation. In the first concept, the highway network is divided into uniform size, 0.8 km (0.5 mile), Data Collection Sections. In the second concept, the highway network is broken into Management Sections of variable length which are defined as sections of pavements, of similar structure, that the engineer intends to maintain in a uniform manner. Minimum data required for each Data Collection or Management Section include: identification, the beginning and ending Reference Marker limits, number of traffic lanes, functional classification, area, pavement type, and traffic levels.

In the current version of PMIS, the basic Data Collection Section length is 0.8 km. The option of using variable user defined section lengths (Management Sections) is available, but, as of yet, it is largely unused.

PAVEMENT CONDITION DATA

PMIS provides the capability of collecting and storing the following four types of pavement condition data:

- visual distress data measures surface defects such as patching, rutting (shallow and deep rutting), and cracking (block, alligator, longitudinal and transverse cracking),
- ride quality data measures the pavement roughness,
- deflection data measures the overall pavement structural strength, and
- skid data measures pavement friction resistance.

The main analysis modules within PMIS primarily use the Visual and Ride Quality data. These two data items are mandatory. The deflection and skid data are less commonly available.

NEEDS ESTIMATE

Once the highway network has been defined and pavement condition data for each Data Collection Section or Management Section have been collected, PMIS identifies the sections needing maintenance and rehabilitation to help pavement managers determine how much money they need to repair deficient pavement sections to provide a desired condition. Within the system, an array of decision trees are used to relate the current condition for the type pavements to the required treatment level. Since the network-level management is more interested in the level of treatment and the amount of funds required, the PMIS Needs Estimate program predicts which one of the following general treatment levels is warranted for each highway section:

- needs nothing (NN),
- preventive maintenance (PM),
- light rehabilitation (LRhb),
- medium rehabilitation (MRhb), and
- heavy rehabilitation/reconstruction (HRhb).

The selection of the actual treatment is a project-level decision. PMIS (and other Network-Level Systems) does not contain sufficient information to make project-level decisions. The use of general treatment levels for identifying the sections needing maintenance and rehabilitation avoids the problem of pavement managers trying to use the PMIS for making project-level decisions when the program only provides network-level assistance.

PRIORITIZATION OF CANDIDATE SECTIONS

The PMIS Needs Estimate program identifies funds needed to provide the desired level of service through the maintenance and rehabilitation of the entire highway network without regard to available funds. However, the reality is that funds are limited, and there is not enough money available to repair all the highway sections in the network needing maintenance and rehabilitation treatments. Therefore, PMIS prioritization of candidate highway sections is a systematic methodology that assists pavement managers to establish priorities for the optimal allocation of available funds while the best possible highway network condition is provided. Systematic methodologies for the efficient use of available funds are usually one of two general approaches: (1) prioritization or ranking of highway sections in order of importance, and (2) optimization techniques based on operations research for selecting the optimum set of highway sections, which will be discussed in the next chapter.

Within the implemented PMIS, a single year ranking procedure, applied sequentially for the analysis period based on an effectiveness to cost ratio, has been used. The effectiveness is defined as the sum of the areas under the condition and ride utility curves generated by any particular treatment. At any point in time, the no-treatment and after-treatment change in condition and ride utility are projected over the planning period. The improvement in condition (effectiveness) is defined as the area between these curves. The life of the treatment is defined as either the time it takes for the after-treatment curve to intersect the no-treatment curve, or for the after-treatment curve to deteriorate and hit a user-supplied minimum value ("failure criterion").

Within PMIS, the following factors are involved in generating the ranking (Cost-Effectiveness Ratio):

a. the effectiveness (total area under both condition and ride curves),

b. the life of treatment, and

c. the annual equivalent treatment cost.

To provide a weighting factor for traffic, the calculated ratio is multiplied by $\log_{10}$ (VMT), where VMT is the vehicle miles traveled on the section. Further discussion of the current TxDOT procedure is given in Chapter 3.

IMPACT ANALYSIS

The PMIS Impact Analysis is used to show the effects of pavement decisions, policies, and other external factors on overall pavement condition and financial projections. Impact analysis assists pavement managers to justify obligation authority or policy changes by providing information in a number of different ways regarding the expected effects on current and future pavement condition.

GOALS OF STUDY

The prioritization process currently used within PMIS is not an optimization system; it is a simple ranking procedure. It does not have any objective function, and it does not consider any consequences of delaying treatment. For example, a section which requires a low-cost treatment in the current year may not generate a high enough benefit cost ratio for inclusion in the final program. However, if treatment is delayed, then it could move from a low-cost to a medium-cost treatment. The overall consequences of delaying this treatment will have a negative impact.

The goal of this study is to develop an efficient approach for the problem of planning and scheduling maintenance and rehabilitation activities at network-level using optimization techniques based on operations research techniques. The specific goals of this study include:

1. To measure the effectiveness of the sequential single-year ranking method used by the current Texas Department of Transportation (TxDOT) Pavement Management Information System (PMIS) with two other deterministic multi-year optimization methods: (1) a multi-year optimization method with single treatments (MYO-ST), and (2) a multi-year optimization method with multiple treatments (MYO-MT); and
2. To perform sensitivity analysis of the solution.

CHAPTER 2
PRIORITY PROGRAMMING OF MAINTENANCE AND REHABILITATION ACTIVITIES

Priority programming methods of maintenance and rehabilitation activities vary from simple subjective ranking methods that involve simple procedures to sophisticated optimization methods that use mathematical programming. A process that uses a ranking method for selecting an ordered set of highway sections is called prioritization. Prioritization is more formally defined as the process of ranking highway sections needing maintenance or rehabilitation based on a set of rules or guidelines established by the managing agency (FHWA, 1991). Usually, the set of rules used by a ranking method are simple and easy to understand, but the selection of highway sections to be maintained and rehabilitated may be far from an optimal solution. Optimization methods provide tools to ensure that either maximum benefits from the use of available funds are obtained or that minimum costs are used to achieve desired goals. Table 2.1 summarizes basic characteristics of different classes of priority programming methods (Hass et al., 1985).

RANKING METHODS

A ranking method is a set of rules that are simple and easy to understand, and it does not require much data to be implemented. The most commonly used ranking methods available are:

- Rank by distress,
- Rank by distress and traffic,
- Rank by initial cost,
- Rank by net present value,
- Rank by benefit/cost ratio or cost-effectiveness analysis.

Simple ranking procedures could be used to prioritize the sections needing maintenance and rehabilitation treatments; however, that type of procedure is limited in the number of factors which can be considered. It also ranks the pavements in the worst condition as the highest priority without regard to the return on the funds expended. For instance, ranking by distress

Table 2.1. Different Classes of Priority Programming Methods (Hass et al., 1985).

CLASS OF METHOD	ADVANTAGES AND DISADVANTAGES
Simple subjective ranking of projects based on judgment	Quick, simple; subject to bias and inconsistency; may be far from optimal
Ranking based on parameters, such as serviceability, deflection, etc.	Simple and easy to use; may be far from optimal
Ranking based on parameters with economic analysis	Reasonably simple; should be closer to optimal
Optimization by mathematical programming model for year-by-year basis	Less simple; may be close to optimal; effects of timing not considered
Near optimization using heuristics and marginal cost-effectiveness	Reasonably simple; can be used in a microcomputer environment; close to optimal results
Comprehensive optimization by mathematical programming model taking into account the effects of project timing	Most complex; can give optimal program (maximization of benefits or minimization of costs)

ranks the pavement sections with the greatest quantity of distress, or other measures such as percent alligator cracking, average rut depth, and average faulting, as the first to be repaired. Similarly, pavements can be ranked by least first cost, by least net present cost, or least equivalent uniform annual costs. However, these prioritization procedures do not consider the costs or benefits of the users.

A better approach is ranking the sections by benefit/cost ratio or by cost-effectiveness. The benefit-cost analysis calculates the net benefits, such as reduced vehicle operating cost, by the pavement user over the selected analysis period in monetary terms. The costs are normally the total costs over the same selected analysis period incurred by the government agency responsible for the pavement section. The costs include construction costs, maintenance costs, and future rehabilitation costs. The cost-effectiveness analysis, which is used by TxDOT PMIS, is basically the same as the benefit-cost analysis except that a surrogate is used in place of

monetary benefits. Detailed descriptions of the above ranking methods may be found in FHWA 1991 and FHWA 1994.

OPTIMIZATION METHODS

Operations research seeks the determination of the best or optimum course of action of a decision problem under the restriction of limited resources. The term operations research is usually associated with the use of mathematical techniques to model and analyze decision problems, and it helps management to determine its policy and actions scientifically (Taha, 1987). However, the purpose of operations research is to support management in policy and decision making, not to make decisions for the manager.

An optimization model is a mathematical formulation of the decision making process in which constraints are identified, and an objective function is maximized or minimized. Comparing optimization to ranking, optimization uses decision variables in place of decision alternatives, constraints in place of limited resources available (money, equipment, materials, time), and optimizes an objective function (maximizing benefits or minimizing costs), which is the goal of the optimization process. In pavement management systems, objective functions fall into one of the following categories (Lytton, 1985):

- minimization of costs; i.e., the objective function calculates the minimum cost for maintaining the highway system above a user-supplied minimum condition level, or
- maximization of benefits; i.e., the maximum benefit objective function makes sure that the use of available funding achieves the maximum benefit.

The objective function and constraints in the model are expressed mathematically in the form of equalities or inequalities to allow computers to assist managers in the complicated task of searching for the best set of alternatives.

Optimization models are classified as deterministic and stochastic. This classification refers to the model variables. Deterministic models ignore the influence of random or unpredictable factors, and the variable values are stated with certainty. Stochastic models

capture the important random components of the system, and the variables must be defined by an appropriate probability function. Among the major deterministic and stochastic methods are (Lytton, 1985):

Deterministic methods:

- Linear programming,
- Non-linear programming,
- Integer programming,
- Dynamic programming, and
- Goal programming.

Stochastic methods:

- Monte Carlo simulation, and
- Markov decision approach.

The remainder of this report is concerned with deterministic optimization modeling using integer linear programming techniques. For more information and details regarding the other optimization methods, good introductory texts on operations research are Taha 1987 and Ravindran et al. 1987.

RANKING METHODS VS. OPTIMIZATION METHODS

It is clear that the goal of any priority programming method, ranking, or optimization, is to obtain an ordered set of highway sections, making an efficient use of the available funds while providing the best possible highway network condition, or to reduce the costs of the user to an acceptable minimum, or both (Lytton, 1985). However, any systematic methodology of priority programming should help the pavement manager answer the following three questions (Haas et al., 1985):

- Which highway sections should be maintained or rehabilitated?
- What type of maintenance or rehabilitation treatment level should be applied?
- When should the maintenance or rehabilitation treatment be applied?

The advantage of ranking methods over optimization methods is that they are simpler to use and understand, require less data to implement, and always yield feasible solutions (Liebman et al., 1985). However, because of their simplicity, they deal only with the first or the first two questions shown above and do not guarantee optimal allocation of available funds. In addition, ranking methods do not guarantee the optimum solution to any particular problem, and they are limited in their ability to determine the best time to apply a treatment.

Optimization methods provide tools that are capable of allocating available funds over time in the most efficient way. They can give better solutions than the ranking procedures, and it has been claimed by the Arizona DOT that this solution results in substantial savings. Optimization methods can include future budget limitations and pavement conditions to provide optimal answers to long-term planning so that consequences of immediate decisions can be more accurately assessed, and better engineering solutions are provided. However, time optimization models are more complex and difficult to understand, and the best length of time for a planning horizon is not clear. Furthermore, for highway networks with a large number of sections, or maintenance and rehabilitation alternatives, or a long-term planning horizon, optimization models can become impractical because they may be computationally expensive, or require the use of sophisticated computer equipment and software.

In summary, despite their disadvantages, ranking methods may still be useful and adequate for many highway agencies, and the choice to use them will depend upon the size and complexity of the highway network, the staff and funds available to collect and manage the data, and the expected savings that will result in the use of optimization methods. On the other hand, the boundary line to justify a ranking method over an optimization method has not been identified yet, and the funds to be saved by using optimization instead of ranking may be substantial and should always be considered seriously (Lytton, 1985). The overall goal is to use the existing pavement condition information to generate the best set of candidate sections with their appropriate treatment level for each year in the analysis period. This is network-level information to be used for district engineers when selecting the work program for the next period. When additional information becomes available, the priorities may change, and project-level evaluation must be made prior to defining the work program.

SINGLE-YEAR AND MULTI-YEAR OPTIMIZATION METHODS

Optimization methods can be either single-year optimization methods or multi-year optimization methods.

SINGLE-YEAR MODELS

The basic analysis to identify candidate sections for preventive maintenance and rehabilitation begins with the current year. Each year, highway agencies face the problem of developing a single-year program which optimizes expenditure of available funds for that year. The effect of each feasible treatment is calculated for each candidate section, and those which give the greatest effectiveness for the available funds are identified. The purpose of a single-year optimization model is to select in any single-year the treatment for each pavement section in the highway network so that the maximum benefit or effectiveness over the analysis for the budget available for that year can be achieved. The following information is needed for the formulation of the optimization model:

- number of sections in the highway network,
- set of feasible treatments (NN, PM, LRhb, MRhb, HRhb) for each section, and
- cost and effectiveness (or benefit) associated with each treatment

As mentioned previously, there exist two basic scenarios for any optimization method: (1) effectiveness maximization and (2) cost minimization.

(1) Effectiveness Maximization Case

The model is structured as:

MAXIMIZE: Total Network Effectiveness

The objective function of the model maximizes the overall effectiveness resulting from a set of budget-feasible section treatments.

SUBJECT TO: Total Cost of Program ≤ Budget

This constraint ensures that the total budget available is not exceeded. The mathematical model is formulated as follows:

$$\textit{Maximize } Z = \sum_{i=1}^{N} \sum_{j \in S_i} E_{ij} X_{ij}$$

subject to

$$\sum_{j \in S_i} X_{ij} = 1 \quad \textit{for each } i$$

$$\sum_{i=1}^{N} \sum_{j \in S_i} C_{ij} X_{ij} \leq B$$

$$X_{ij} = \{0, 1\} \textit{ for all } i \textit{ and } j$$

where the following notation is used:

- N = total number of sections,
- S_i = set of treatments (including the NN alternative) for section "i,"
- E_{ij} = effectiveness associated with the selection of treatment "j" for section "i,"
- C_{ij} = cost of choosing treatment "j" for section "i,"
- B = available budget for the current year,
- X_{ij} = 1 if treatment "j" is chosen for section "i;" 0 otherwise.

The first set of constraints allows only one treatment to be selected for each section.

(2) Cost Minimization Case

In this case, the basic model is formulated as a minimization problem where it is desired to find the most cost-effective way to achieve a specified cumulative level of effectiveness from the selected highway sections.

The model is structured as:

MINIMIZE:	Total Annual Budget
SUBJECT TO:	Performance of Network ≥ Target Level

and the mathematical model is formulated as follows:

$$Minimize\ Z = \sum_{i=1}^{N} \sum_{j \in S_i} C_{ij} X_{ij}$$

subject to

$$\sum_{j \in S_i} X_{ij} = 1 \quad for\ each\ i$$

$$\sum_{i=1}^{N} \sum_{j \in S_i} E_{ij} X_{ij} \geq R$$

$$X_{ij} = \{0, 1\}\ for\ each\ i\ and\ j$$

where R is a specified minimum effectiveness level of the pavement section to be achieved in the most cost-effective manner.

These two mathematical models are classified as 0-1 Integer Linear Programming (ILP) models since the decision variables X_{ij} can take only values of 0 or 1. If X_{ij} is equal to 1, this means that section "i" for treatment "j" was selected. On the other hand, if X_{ij} is equal to 0, this means that section "i" for treatment "j" was not selected.

Experience has shown that ranking methods classified as incremental benefit-cost ratio or marginal cost-effectiveness analysis are very effective and fast for solving large scale single-year 0-1 ILP optimization problems to optimality or near to optimality (McFarland and Rolling, 1985; Haas et al., 1985; and Stukhart et al., 1991). However, with single-year optimization, no attempt is made to determine the best timing for initiating a treatment action. Instead, the emphasis of this type of optimization is to choose the set of pavement sections to be considered for a treatment in the current year, and consequences of immediate decisions cannot be assessed in the future. Thus, decisions for each year are made independently of any decisions for other years in the analysis period.

MULTI-YEAR MODELS

Multi-year optimization methods generate several long-term maintenance and rehabilitation strategies for each section in the network. As mentioned before, multi-year optimization methods are capable of answering the following three critical questions to assist pavement managers:

- Which highway sections should be selected?
- What type of treatment level should be applied?
- When should the treatment be applied?

Single-year optimization methods are able to answer only the first two questions. This report is concerned with the effectiveness maximization case, and only this case will be analyzed for the remainder of this report.

Effectiveness Maximization Case

A basic multi-year optimization model is structured as:

MAXIMIZE: Total Network Effectiveness During the Planning Horizon

The objective function of the model maximizes the overall effectiveness resulting from a set of budget-feasible section alternatives for each year in the planning horizon.

SUBJECT TO: Total Cost of Program for year "t" ≤ Budget for year "t"

This constraint ensures that the total budget available for each year "t" is not exceeded. The mathematical model is formulated as follows:

$$\textit{Maximize } Z = \sum_{i=1}^{N} \sum_{j \in S_i} \sum_{t=1}^{T} E_{ijt} X_{ijt}$$

subject to

$$\sum_{j \in S_i} X_{ijt} = 1 \quad \textit{for each } i \textit{ and } t$$

$$\sum_{i=1}^{N} \sum_{j \in S_i} C_{ijt} X_{ijt} \leq B_t \quad \textit{for each } t$$

$$X_{ijt} = \{0, 1\} \textit{ for each } i, j, \textit{ and } t$$

where the following notation is used:

N = total number of sections,
S_i = set of treatments (including the NN alternative) for section "i,"
E_{ijt} = effectiveness for treatment "j" at year "t" if section "i" is selected,
C_{ijt} = cost of choosing treatment "j" for section "i" at year "t,"
B_t = available budget for year "t,"
X_{ijt} = 1 if treatment "j" is chosen for section "i" at year "t;" 0 otherwise,

and the first set of constraints allows only one treatment to be selected for each section. The basic multi-year maximization optimization model described above can be found imbedded in

the optimization models used in the following references: Phillips et al. 1981, Armstrong et al. 1981, Colucci-Rios and Sinha 1985, and Fwa et al. 1994. Minimization case examples can be found in Cook 1984, Davis and Van Dine 1988, and Grivas et al. 1993. This type of model considers pavement maintenance and rehabilitation timing trade-offs, and their timings are selected by finding the best combination of sections, alternative treatments, and time of application such that the overall effectiveness is maximized. One critical component which must be available to achieve the best combination is performance prediction or deterioration models for existing highway sections and for the treatment alternatives being considered by the model. Multi-year optimization models are more complex than single-year optimization models, and they are solved using advanced operations research techniques such as linear programming, non-linear programming, integer programming, dynamic programming, and goal programming. In addition, the single-year and multi-year formulations discussed in this report do not consider manpower, equipment, and materials as major requirements since work can always be contracted out if funds are available.

MULTI-YEAR RANKING METHODS (SEQUENTIAL YEAR RANKING METHODS)

Since multi-year optimization models are complex, at times these models cannot be solved in a reasonable amount of time because of their computational complexity. Consequently, they use heuristic solution methods such as the incremental benefit-cost ratio, the marginal cost-effectiveness analysis, and the effective gradient to obtain a near-optimal solution. These heuristic methods are an extension of single-year ranking methods because they perform a sequence of successive single-year ranking problems considering one-year periods. Therefore, they are classified as sequential year ranking methods.

In a sequential year ranking method, all the one-year periods of the planning horizon are sequentially and independently considered one year at the time in their chronological order. After each one-year period, the highway sections are deteriorated or upgraded as appropriate. If a section was not selected for a treatment in the first year, the condition of the section is deteriorated for one year and reconsidered as a candidate for the next year. On the other hand, if the section was selected for a treatment, then its condition is upgraded based on the type of

treatment level performed. Finally, a new list of candidate sections is generated after updating their condition, effectiveness, and costs, and the method is repeated again. Even though this methodology allows the selection of one section to be treated more than once during the planning horizon, it does not consider the interrelation that exists among years from the point of view of the timing of each section (James et al., 1993).

CHAPTER 3
DETAIL OF OPTIMIZATION SCHEMES

PMIS uses a sequential year ranking of cost-effectiveness to identify candidate highway sections. This ranking method belongs to the family of sequential year ranking methods described in the previous section, and from now on it will be referred as PMIS. This section describes the schemes of two multi-year optimization methods that compared the effectiveness of PMIS. The first method is a multi-year optimization method that allows only a single treatment to a highway section during the planning horizon; the second is a multi-year optimization method that allows multiple treatments to the highway sections during the same planning period. A 10-year planning horizon was chosen to compare the performance of the three models because PMIS performance prediction models can only be run up to 10 years in the future at this time.

PMIS ranks the sections in order of decreasing "Cost-Effectiveness Ratio," and then identifies sections as candidates for funding. The Cost-Effectiveness Ratio (CERatio) is defined as follows:

$$CERatio = 10000 \left\lfloor \frac{LM * E}{EffLife * UACost} \right\rfloor \log_{10} VMT$$

where:

CERatio = Cost-Effectiveness Ratio,

LM = Lane Miles,

E = Effectiveness for distress and ride quality,

EffLife = Effective Life of the Needs Estimate treatment, in years,

UACost = Uniform Annual Cost of the Needs Estimate Treatment, in dollars,

VMT = Vehicle Miles Traveled.

The 10000 term in the equation converts the CERatio values into one-to-four integers (instead of small decimal values).

Sorting the sections in order of decreasing CERatio by PMIS implies some type of maximization. Therefore, the two multi-year optimization models developed for this study used a maximization objective function for the analysis. The CERatio was selected as the parameter to be maximized in the objective function of the optimization models so they could be evaluated with respect to the solution of PMIS under the same budget conditions.

MULTI-YEAR OPTIMIZATION WITH A SINGLE TREATMENT (MYO-ST)

This discrete multi-year optimization model allows only a single treatment to a highway section during the planning horizon. In other words, this model assumes that once a section has been selected for a treatment, that section cannot be selected for another treatment during the planning horizon.

The mathematical model is structured as follows:

FORMULATION MYO-ST

$$Maximize\ Z = \sum_{i=1}^{N} \sum_{t=1}^{T} E_{it} X_{it}$$

subject to

$$\sum_{t=1}^{T} X_{it} \leq 1 \quad for\ each\ i$$

$$\sum_{i=1}^{N} C_{it} X_{it} \leq B_t \quad for\ t = 1$$

$$X_{it} = \{0, 1\}\ for\ each\ i\ and\ t$$

where the following notation is used:

N = total number of sections,

E_{it} = effectiveness associated with the treatment given to section "i" at year "t,"

C_{it} = cost associated with the treatment given to section "i" at year "t,"

B_t = available budget for year t,

X_{it} = 1 if section "i" is selected at year "t" for a treatment; 0 otherwise.

Formulation of this problem is similar to a basic single-year optimization model described in Chapter 2. However, the main advantage of this formulation over a basic multi-year optimization model is that it does not include the set of treatment alternatives for every section "i" in the model. The justification of this approach is that within PMIS, only one treatment level is considered by the model; i.e., if the decision trees specify that section "i" requires a HRhb treatment to upgrade the distress utility or ride utility to a utility level of 1.0, the model does not consider the effectiveness that may be achieved by selecting a PM, LRhb, or MRhb treatment; or if section "i" requires only a PM treatment, none of the rehabilitation treatments is considered. Thus, there are only two alternatives considered for every section "i" in any year "t:" (1) if section "i" is selected at year "t," $X_{it} = 1$, this section will receive the right treatment, and (2) if section "i" is not selected at year "t," $X_{it} = 0$, this implies that the NN alternative has been chosen. The required treatment level for each section is selected using a decision tree based on the distress and ride condition of the section. These decision trees were generated by experienced TxDOT engineers. If the section needs a treatment as defined by the decision trees but insufficient funds are available, then this section is placed in the "stop-gap" category. This simplification reduces the computational complexity of the problem by avoiding the calculations required by inappropriate treatment levels (less number of decision variables). For example, a basic multi-year optimization model with 23 sections, four treatment levels, and a 10-year planning horizon will have 920 0-1 integer variables, while **FORMULATION MYO-ST** will have only 230 0-1 variables.

Data for 23 sample highway sections from a Texas District and a 10-year planning horizon were used to test the model. Cost and CERatio information for section 2 used in this case study is shown in Table 3.1. This table contains all the basic information needed for making decisions at network-level : Cost, CERatio, and the required treatment level at any year during the 10-year planning horizon.

Table 3.1. Cost and CERatio Information for Sample Section 2.

First Time Maintenance and Rehabilitation Information			
Year	Cost ($ x 1000)	Cost-Effectiveness Ratio (CBRatio)	Treatment Level
1	90	294.67	MRhb
2	94	310.45	MRhb
3	99	328.19	MRhb
4	104	346.84	MRhb
5	109	364.65	MRhb
6	325	207.01	HRhb
7	342	152.50	HRhb
8	359	153.11	HRhb
9	377	152.19	HRhb
10	396	150.11	HRhb

The information for every sample section at any year in the planning horizon was obtained using PMIS deterioration models for those sections. It can be noticed that if this section does not receive a MRhb treatment during the first five years, it will need a more expensive HRhb treatment later. In addition, the least expensive cost to rehabilitate the section is during year 1, $90,000 with a CERatio of 294.67. However, if the section is rehabilitated in year 5, it will cost $14,000 more ($104,000), but a greater CERatio will be achieved (364.65). A **FORMULATION MYO-ST** with 23-sample sections and a 10-year planning horizon will have 230 0-1 integer variables that, along with yearly limited budgets constraints, will make the problem of analyzing timing trade-offs for every section more complex.

Finally, another difference from the basic single-year optimization model is provided with the first set of constraints, namely:

$$\sum_{t=1}^{T} X_{it} \leq 1 \quad \textit{for each } i$$

This set of constraints implies that each section "i" in the network will receive, at most, one treatment during the planning horizon T. Notice that the right-hand side of the constraint may be 0 or 1. Figure 3.1 shows a schematic representation for the $\sum X_{it} = 0$ case and a 10-year planning horizon (the NN alternative is chosen for 10 years).

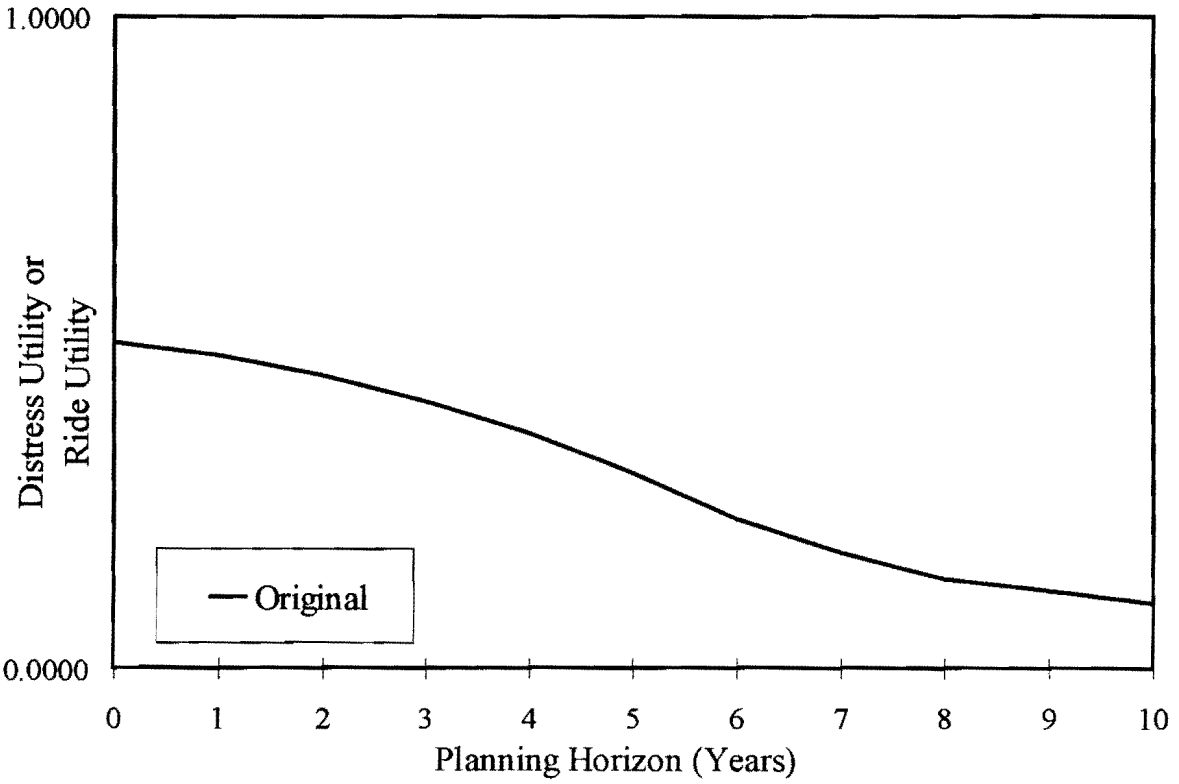

Figure 3.1. Schematic Representation for the Needs-Nothing (NN) Alternative.

On the other hand, Figure 3.2 shows the schematic representation for the $\sum X_{it} = 1$ case where the section is a candidate for receiving a treatment every year that **FORMULATION MYO-ST** needs to take into consideration (treatments for years 4-10 were omitted), but only one of these treatments may be selected. Figure 3.3 shows the case in which a treatment from Figure 3.2 was selected at year 1.

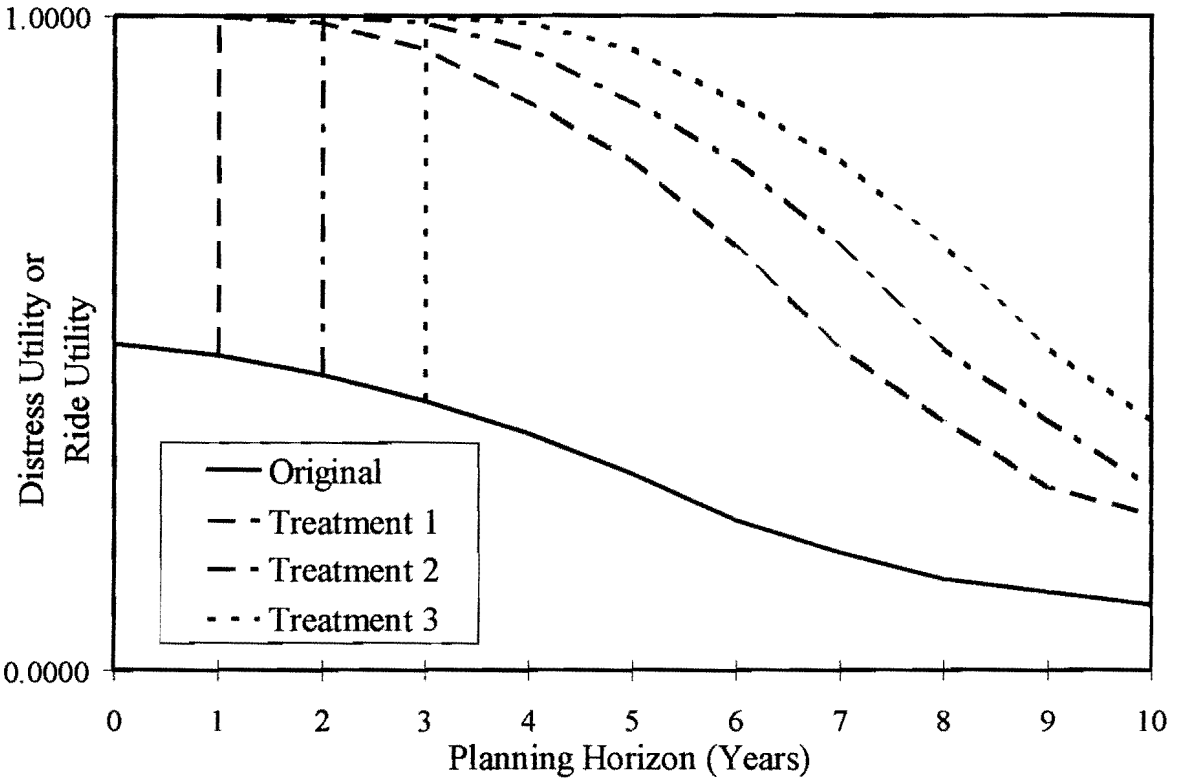

Figure 3.2. Schematic Representation of Selecting a Single Treatment.

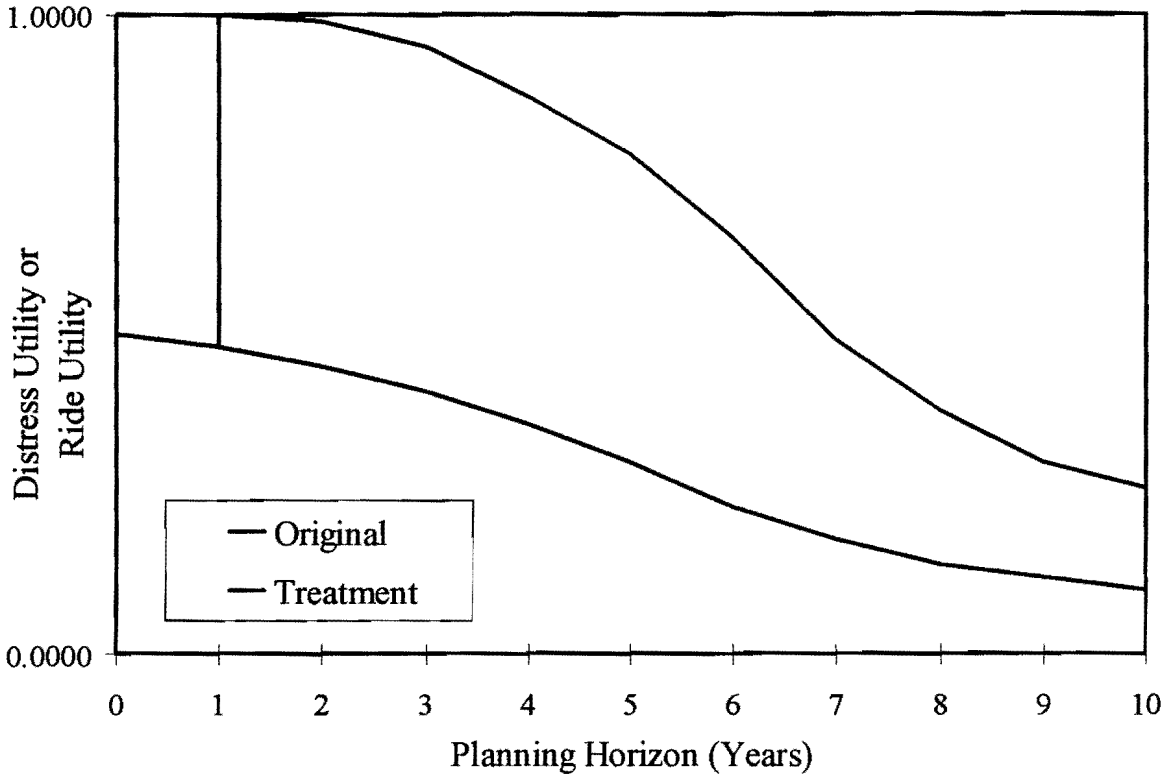

Figure 3.3. Schematic Representation for Selecting a Treatment at Year 1.

MULTI-YEAR OPTIMIZATION WITH MULTIPLE TREATMENTS (MYO-MT)

In a multi-year optimization method with multiple maintenance and rehabilitation treatments, a section that is selected once for a treatment can be considered again for later treatments during the planning horizon. The mathematical model for this type of optimization is more complex than the model with single treatments. However, their structures are similar, and the multi-year optimization model with multiple treatments may be viewed as an extension of the multi-year optimization model with single treatments. Formulation of the multi-year optimization problem with multiple treatments (**FORMULATION MYO-MT**) is given as follows:

FORMULATION MYO-MT:

$$\text{Maximize } Z = \sum_{i=1}^{N}\sum_{t=1}^{T} E_{it}X_{it} + \sum_{i=1}^{N}\sum_{t=2}^{T} F_{ist}Y_{ist}$$

subject to

$$\sum_{i=1}^{N} C_{it}X_{it} \le B_t \text{ for } t=1$$

$$\sum_{i=1}^{N} C_{it}X_{it} + \sum_{i=1}^{N} D_{ist}Y_{ist} \le B_t \text{ for each } t;\ t=\{2,\cdots,T\}$$

$$\sum_{t=1}^{T} X_{it} \le 1 \text{ for each } i$$

$$\sum_{t_2=t_1+1}^{T} Y_{ist_2} \le X_{it_1} \text{ for each } i, \text{ and } t_1;\ t_1=\{1,\cdots,T-1\}$$

$$\sum_{t_2=t_1+1}^{T} Y_{ist_2} \le Y_{iRt_1} \text{ for each } i, \text{ and } t_1;\ t_1=\{2,\cdots,T-1\}$$

$$X_{it} = \{0, 1\} \text{ for each } i \text{ and } t$$

$$Y_{ist} = \{0, 1\} \text{ for each } i \text{ and } t;\ t>1$$

where

N = total number of sections,

T = number of years in the planning horizon,

S, R = sets of years at which section "i" has received previous treatments, $R \subset S$,

E_{it} = effectiveness associated with section "i" if a treatment is given at year "t,"

F_{iSt} = effectiveness associated with section "i" if a treatment is given at year "t" given that it was treated at least once,

C_{it} = cost associated with section "i" if a treatment is given at year "t,"

D_{iSt} = cost associated with section "i" if a treatment is given at year "t" given that it was treated at least once,

B_t = available budget at year "t,"

X_{it} = 1 if section "i" is a candidate for receiving a treatment in year "t;" 0 otherwise,

Y_{iSt} = 1 if section "i" is a candidate for receiving a new treatment in year "t" given that it was treated at least once; 0 otherwise.

The first term in the objective function

$$\textbf{Maximize } Z = \sum_{i=1}^{N}\sum_{t=1}^{T} E_{it}X_{it} + \sum_{i=1}^{N}\sum_{t=2}^{T} F_{iSt}Y_{iSt}$$

represents the options for selecting a single treatment discussed in **FORMULATION MYO-ST** and shown in Figure 3.2. Let's assume that a section received a treatment at year 1 (see Figure 3.3). Then, the question is when the next treatment should be given to that section, and it is illustrated in Figure 3.4. The second term in the objective function represents the treatments a highway section may receive after it has been treated once.

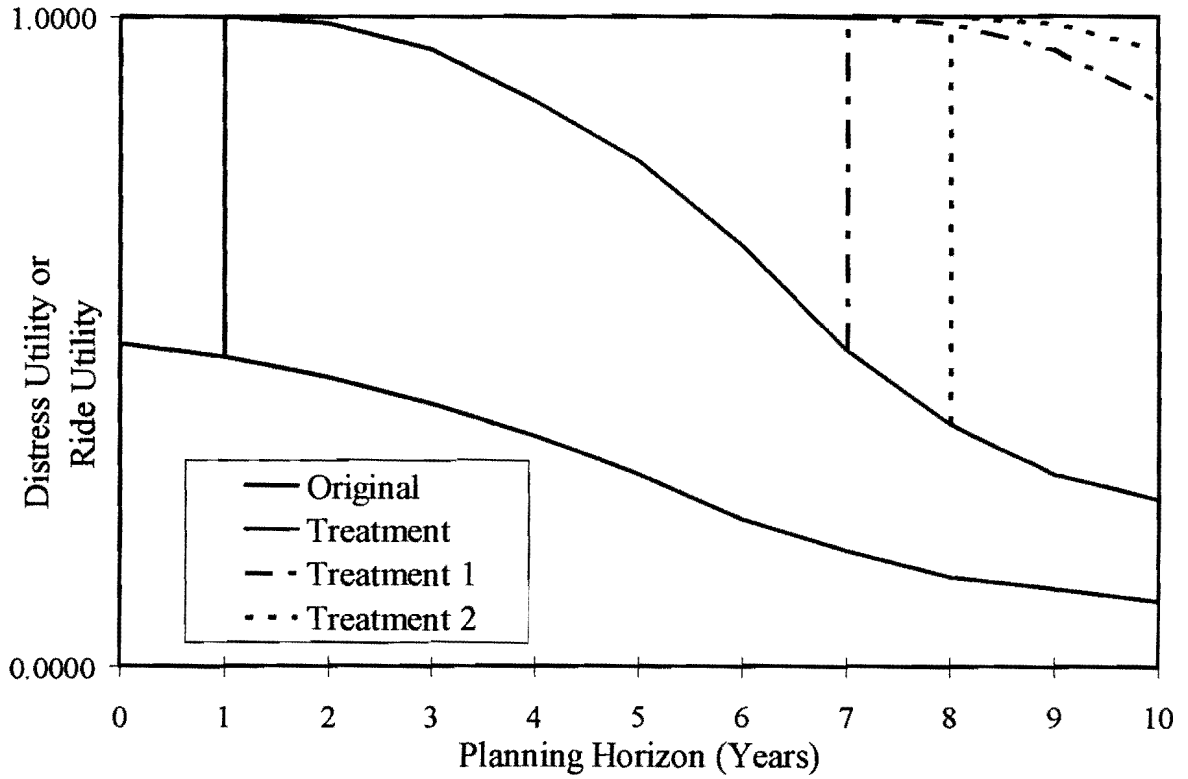

Figure 3.4. Schematic Representation for Selecting a Treatment at Year 1 and then at Year 7 or 8.

Table 3.1 shows first-time maintenance and rehabilitation information for sample section 2 in this case study. Table 3.2 shows cost and CERatio information for sample section 2 if a treatment is given at year 1. If a MRhb treatment is given at year 1, section 2 will need a PM treatment at year 8, or MRhb treatments at years 9 or 10. Similarly, Tables 3.3 and 3.4 show cost and CERatio information for sample section 2 if treatments were given at years 2 and 3, respectively. Figure 3.5 displays the case where a section received the first treatment at year 1, and the second one at year 8. For any decision variable in formulation MYO-MT, the first digit indicates the section number and the last digit indicates the year that section is candidate for a treatment. Variable X2-1 means section 2 is candidate for a first time treatment at year 1 (belongs to the first term of the objective function). Variable Y2_1_8 belongs to the second term of the objective function and means that section 2 received a treatment at year 1 and is candidate for a second time treatment at year 8. Since set "S" keeps track of the years at which previous treatments are given, then, set S = {1} in this case.

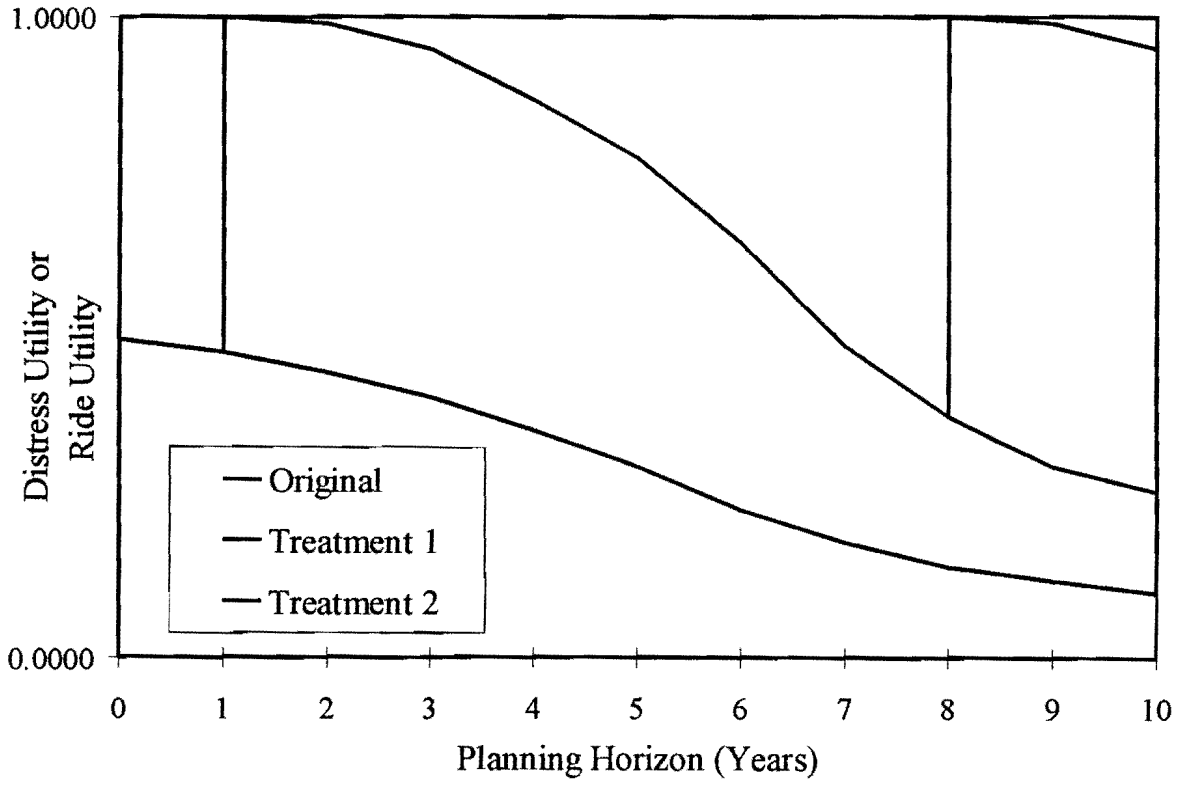

Figure 3.5. Schematic Representation for Selecting a Treatment at Year 1 and 8.

Table 3.2. Cost and CERatio Information for Sample Section 2 if a Treatment was Given in Year 1.

Second Time Maintenance and Rehabilitation Information if First Treatment was Given in Year 1			
Year	Cost ($ x 1000)	Cost-Effectiveness Ratio (CBRatio)	Treatment Level
8	19	722.51	PM
9	133	177.47	MRhb
10	140	184.49	MRhb

Table 3.3. Cost and CERatio Information for Sample Section 2 if a Treatment was Given in Year 2.

Second Time Maintenance and Rehabilitation Information if First Treatment was Given in Year 2			
Year	Cost ($ x 1000)	Cost-Effectiveness Ratio (CBRatio)	Treatment Level
9	20	688.10	PM
10	140	517.54	MRhb

Table 3.4. Cost and CERatio Information for Sample Section 2 if a Treatment was Given in Year 3.

Second Time Maintenance and Rehabilitation Information if First Treatment was Given in Year 3			
Year	Cost ($ x 1000)	Cost-Effectiveness Ratio (CBRatio)	Treatment Level
10	21	655.34	PM

The first set of constraints in **FORMULATION MYO-MT** are the budget constraints:

$$\sum_{i=1}^{N} C_{it} X_{it} \leq B_t \quad for\ t=1$$

$$\sum_{i=1}^{N} C_{it} X_{it} + \sum_{i=1}^{N} D_{ist} Y_{ist} \leq B_t \quad for\ each\ t;\ t=\{2,\cdots,T\}$$

The first constraint is the budget constraint for year one and there is no cost for later treatments involved at this year. The effects of later treatments begin after year one, t > 1, and are included in the second term of the second budget constraint. The next set of constraints are related both to the selection of, at most, one treatment during a planning period or sub-period, and to the precedence of treatments:

$$\sum_{t=1}^{T} X_{it} \leq 1 \quad for\ each\ i$$

$$\sum_{t_2 = t_1+1}^{T} Y_{ist_2} \leq X_{it_1} \quad for\ each\ i,\ and\ t_1;\ t_1=\{1,\cdots,T-1\}$$

$$\sum_{t_2 = t_1+1}^{T} Y_{ist_2} \leq Y_{iRt_1} \quad for\ each\ i,\ and\ t_1;\ t_1=\{2,\cdots,T-1\}$$

The first constraint is related to the decision of when to give the first time treatment, and it was explained in formulation MYO-ST. The planning period for this constraint is "T" and is shown in Figure 3.2. The second and third constraints deal with later treatments for planning sub-periods of T. For example, if the first time treatment for a section was given at year 1, then the second treatment may be given between years 2 and 10, and this is considered as a planning sub-period. Tables 3.1, 3.2, 3.3, and 3.4 are represented in a precedence network diagram shown in Figure 3.6.

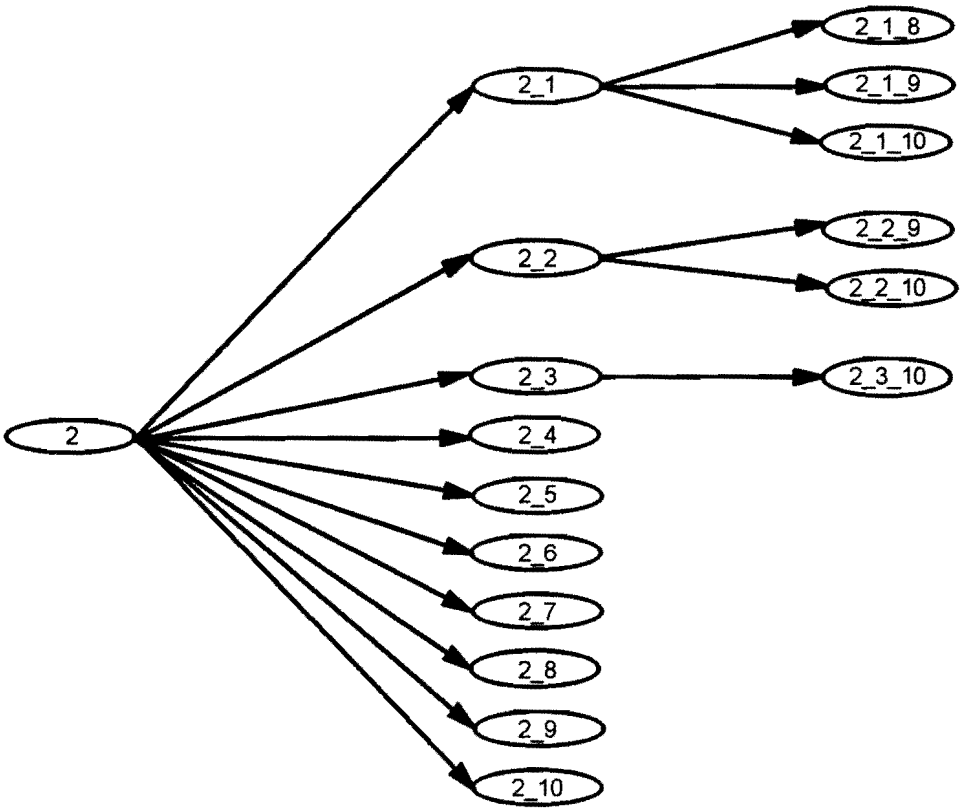

Figure 3.6. Precedence Diagram for Sample Section 2.

The nodes represent the decision variables in the problem, and the constraint for a first time treatment will be written as:

$$X2\_1 + X2\_2 + X2\_3 + X2\_4 + X2\_5 + X2\_6 + X2\_7 + X2\_8 + X2\_9 + X2\_10 \leq 1,$$

and the constraints for the second time treatments will be:

$Y2\_1\_8 + Y2\_1\_9 + Y2\_1\_10 \leq X2\_1$ if first time treatment was given at year 1,

$Y2\_2\_9 + Y2\_2\_10 \leq X2\_2$ if first time treatment was given at year 2, and

$Y2\_3\_10 \leq X2\_3$ if first time treatment was given at year 3.

The basic idea behind these last three constraints is that a second treatment cannot be given to a section if it has not been treated before. For example, from Figure 3.6, it can be seen that section 2 cannot be a candidate for a treatment in years 8, 9, and 10 (Y2_1_8, Y2_1_9, and Y2_1_10) if the treatment at year 1 (X2_1) has not been given (precedence relationship between treatments). An illustration for constraint

$$\sum_{t_2 = t_1+1}^{T} Y_{iSt_2} \leq Y_{iRt_1} \quad \textit{for each } i, \textit{ and } t_1;\ t_1 = \{2, \cdots, T-1\}$$

may be the following: let's assume that section 8 may be selected to receive treatments at years 1 and 4, and the next treatment may be given at years 7, 8, 9, or 10. This constraint will be written as:

$$Y8\_1\_4\_7 + Y8\_1\_4\_8 + Y8\_1\_4\_9 + Y8\_1\_4\_10 \leq Y8\_1\_4$$

where R = {1} and S = {1, 4}. Using this notation, it can be seen that $\mathbf{R} \subset \mathbf{S}$ for every case.

The last set of constraints are related to the integrality nature of the decision variables, that is, all decision variables can take only integer values of either 0 or 1:

$$X_{it} = \{0, 1\} \textit{ for each } i \textit{ and } t$$

$$Y_{ist} = \{0, 1\} \textit{ for each } i \textit{ and } t;\ t>1$$

CHAPTER 4

OPTIMIZATION SOFTWARE

DESCRIPTION OF SOFTWARE

Formulations MYO-ST and MYO-MT were tested on a 486 IBM compatible PC environment (33 MHZ) with 16 megabytes of random access memory (RAM) and were solved using CPlex Optimization software version 3.0 (CPLEX, 1994). CPlex is a general purpose, commercial integer programming package for solving large-scale linear programming problems that usually involve the allocation of scarce resources in leading businesses such as energy, chemicals, manufacturing, transportation, banking, finance, communication, electronics, defense, health and public services, and natural resources. CPlex has no problem size limitation and is available on a wide range of computer platforms, from a 386 IBM-compatible PC to all the latest high-performance Cray and Covex supercomputers.

The CPlex software is based on three main modules: (1) the CPlex Linear Optimizer that solves linear programming models containing continuous variables with three state-of-the-art algorithms: a modified-simplex algorithm, a dual-simplex algorithm, and a networks algorithm, (2) the CPlex Mixed Integer Optimizer which is an extended version of the Linear Optimizer that adds the capability to solve problems with integer variables as well as continuous variables, and (3) a CPlex Callable Library with linear optimization routines that provide flexibility and offers efficient integration into user-written programs developed in C, Fortran, or other languages. CPlex solvers require less than 1 megabyte of hard disk space. RAM requirements vary according to problem size, and mixed-integer problems require significantly more RAM than similarly-sized problems with all continuous variables. The commercial pricing list for specific CPlex operating systems supported for each computer type are listed below:

	--Base System--	----Algorithmic Options--		-Format Option-
	Linear Optimizer	Barrier	Mixed Integer	Callable Library
I Mainframe	$23,600	+10,600	+5,300	+10,600
II Midrange	$11,000	+ 5,000	+2,500	+ 5,000
III UNIX	$ 5,400	+ 2,400	+1,200	+ 2,400
IV PC DOS/Windows	$ 3,000	+ 1,800	+ 900	+ 1,800

The CPlex Barrier Option is specially designed for users with large problems (millions of variables and constraints). It allows them to integrate problem reduction pre-processing sub-routines and to solve mixed-integer programming sub-problems. CPlex version 3.0 used in this report included the CPlex Linear Optimizer and the CPlex Mixed Integer and Barrier Solvers. All the results discussed in the next chapter used the default CPlex settings, except for the Strategy Covers where cover cuts were not generated.

INPUT FOR ANALYSIS

Data for 23 sample highway sections from a Texas District and a 10-year planning horizon were used to test and compare formulations MYO-ST and MYO-MT with TxDOT PMIS that uses a Cost-Effectiveness-Ratio ranking method. Ride and distress condition, and cost and cost-effectiveness-ratio (CERatio) information for the 23 sections were obtained from PMIS. Table 4.1 shows sample data used for the first year analysis, and similar tables were available for each year in the planning horizon. The ride value is the Present Serviceability Index as measured using TxDOT Siometer on a scale 0-5, with 5 being perfect. The Ride and Distress Utility values range from 0 to 100, with 100 being perfect. The Distress Utility is a composite index combining all of the utility values for each individual distress. The Treatment Level is the type of maintenance and rehabilitation required as defined by TxDOT decision trees. The utility values and decision trees are described in companion report 1989-1. The Years Effective is the number of years that the applied treatment will generate benefit, and the CERatio is the cost-effectiveness ratio of the applied treatment as described in Chapter 3.

As explained in Chapter 3, not all the information in these tables was used by the optimization models; only cost and CERatio data, summarized as in Table 3.1 for each sample section, are needed for making decisions at the network-level. In addition, only first-time maintenance and rehabilitation decisions were allowed with data gathered in tables such as that in Table 4.1. Therefore, PMIS performance and deterioration models for the existing 23 sections were used to obtain the information needed for future treatments. This was summarized and is shown in Tables 3.2, 3.3, and 3.4.

Finally, PMIS and formulations MYO-ST and MYO-MT were tested using different budget levels that ranged from $200,000 to $750,000 per year, with increments of $50,000. In this analysis, the applied budget level was a constant in each year of the analysis period.

Table 4.1 Initial Condition, Cost, and CERatio Data for 23 Sample Sections.

Condition, Cost, and CERatio Information at Year 1								
Section Number	Length Km (Miles)	Ride	Ride Utility	Distress Utility	Treatment Level	Cost (K)	Year Effective	CERatio
1	2.40 (1.5)	1.3	5.0	60.5	HRhb	285	11	264
2	2.40 (1.5)	4.0	100.0	36.7	MRhb	90	7	219
3	3.20 (2.0)	1.9	29.4	2.1	HRhb	340	9	268
4	2.40 (1.5)	4.0	100.0	27.2	PM	15	6	840
5	3.20 (2.0)	1.4	5.0	76.7	HRhb	380	10	210
6	1.60 (1.0)	4.6	100.0	69.8	NN	0	0	0
7	4.00 (2.5)	1.6	18.7	65.8	HRhb	475	8	198
8	1.60 (1.0)	2.8	77.7	54.9	LRhb	45	9	552
9	4.80 (3.0)	1.9	29.4	79.5	HRhb	510	13	277
10	4.80 (3.0)	4.8	100.0	53.7	MRhb	225	7	129
11	2.40 (1.5)	2.4	53.1	53.3	HRhb	255	9	231
12	3.20 (2.0)	5.0	100.0	2.2	MRhb	100	7	210
13	1.92 (1.2)	2.7	100.0	62.8	PM	11	9	1038
14	4.00 (2.5)	0.7	5.0	85.4	HRhb	425	13	264
15	1.60 (1.0)	4.5	100.0	75.3	MRhb	60	10	124
16	4.80 (3.0)	4.6	100.0	1.1	MRhb	180	7	179
17	1.60 (1.0)	1.9	52.6	79.7	MRhb	60	10	411
18	1.60 (1.0)	3.1	95.2	55.2	MRhb	60	10	464
19	4.80 (3.0)	2.0	58.4	10.2	LRhb	120	6	517
20	4.00 (2.5)	2.8	77.7	24.7	HRhb	475	8	164
21	0.96 (0.6)	3.6	100.0	27.0	PM	6	7	1067
22	1.92 (1.2)	1.6	18.7	53.9	HRhb	204	13	305
23	0.64 (0.4)	1.5	15.6	36.6	HRhb	76	9	218

CHAPTER 5
RESULTS

The major purpose of this research was to identify appropriate multi-year optimization methods for use in TxDOT PMIS: one that allows only single treatments during the planning horizon, formulation MYO-ST, and another that allows multiple treatments, formulation MYO-MT, and to compare their effectiveness with respect to PMIS that uses a sequential single-year ranking method (PMIS). Formulations MYO-ST and MYO-MT are 0-1 integer linear programming models that are used for solving large-scale discrete problems for planning and scheduling of maintenance and rehabilitation activities in a network-level pavement management system.

For this case study, formulation MYO-ST had 230 0-1 integer decision variables, while formulation MYO-MT had 429 0-1 integer decision variables. Ideally, the way that formulation MYO-MT was formulated in Chapter 3 should have a total of 1,265 0-1 integer decision variables for 23 sample sections and a 10-year planning horizon, i.e., 23 x 10 = 230 variables for first-year treatments, and 23 x (9+8+7+6+5+4+3+2+1) = 23 x 45 = 1,035 for later treatments in later years. However, most of the decision variables were zero (about 66%) because in reality, when a treatment is applied to a highway section, it is predicted to take several years for that section to be considered as a candidate for the next treatment. For example, if a MRhb treatment is applied in year 1 to sample section 2 (see Table 3.1), it is expected that the next treatment (PM, from Table 3.2) will be required in year 8. Then, all decision variables from Y2_1_2 to Y2_1_7, and any other decision variable that may be related to them in the future such as Y2_1_2_3, Y2_1_2_3_4, Y2_1_2_3_4_5, etc., will be zero.

Of the 23 sample sections in the unlimited-fund scenario, 19 of the sections required two treatments to reach the 10-year planning horizon. Typically, a MRhb or HRhb treatment in year 1, with a PM treatment in year 8 or 9 was required. Three other sections (sections 4, 6, and 21 from Table 4.1) had three treatments, and only one section (section 8) had four treatments (variable Y8_1_4_7_10), this being repeated preventive maintenance. Therefore, it is expected that, in reality, a section will not receive more than four treatments in a 10-year planning

horizon. The high percentage of variables equal to zero (no treatment in analysis year) and the small number of treatments allowed in any planning horizon are critical issues for the computational complexity of formulation MYO-MT to be used for large-scale highway networks involving thousands of sections. This is possible because the model considers only a single treatment at any time based on the predicted level of distress and ride on the section. This treatment is defined by the decision trees, which relate level of distress to required treatment.

Figure 5.1 shows the accumulated CERatio at the end of the 10-year planning horizon for different funding levels using PMIS and formulations MYO-ST and MYO-MT. Formulation MYO-MT was the best cost-effective method for allocating funds, followed by PMIS, and finally, formulation MYO-ST was the worst method. From Figure 5.1, PMIS seems to give a good approximation for maximizing the accumulated CERatio obtained by the MYO-MT formulation, especially for low to medium budget levels. For a $200,000 annual budget, the accumulated CERatio obtained by PMIS was 17,113 units compared to 18,188 units by the MYO-MT formulation, a difference of 1,075 CERatio units. However, because a difference of 1,075 CERatio units (5.9%) does not clearly indicate how much better formulation MYO-MT is over the PMIS method, the backlog mileage requiring MRhb or HRhb treatment at the end of the analysis period was used in order to make a better evaluation of the effectiveness of the three methods.

Figure 5.2 shows the mileage requiring MRhb or HRhb treatment for each budget level at the end of the 10-year planning period. Formulation MYO-MT needed a $650,000 annual budget for repairing all the sections requiring MRhb or HRhb treatment, while PMIS required a $750,000 annual budget. This difference is equivalent to $1 million in a 10-year planning period ($100,000 per year). Formulation MYO-ST did not decrease the backlog mileage to zero with any of the budget levels analyzed.

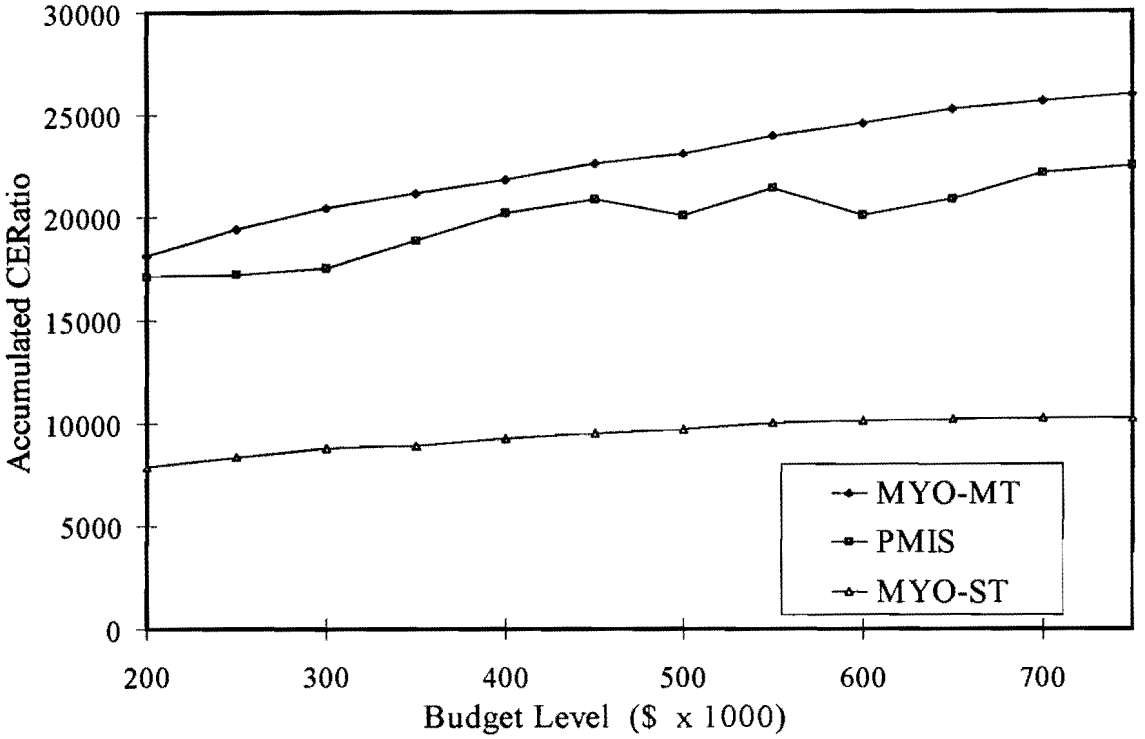

Figure 5.1. Accumulated CERatio at the End of the 10th Year.

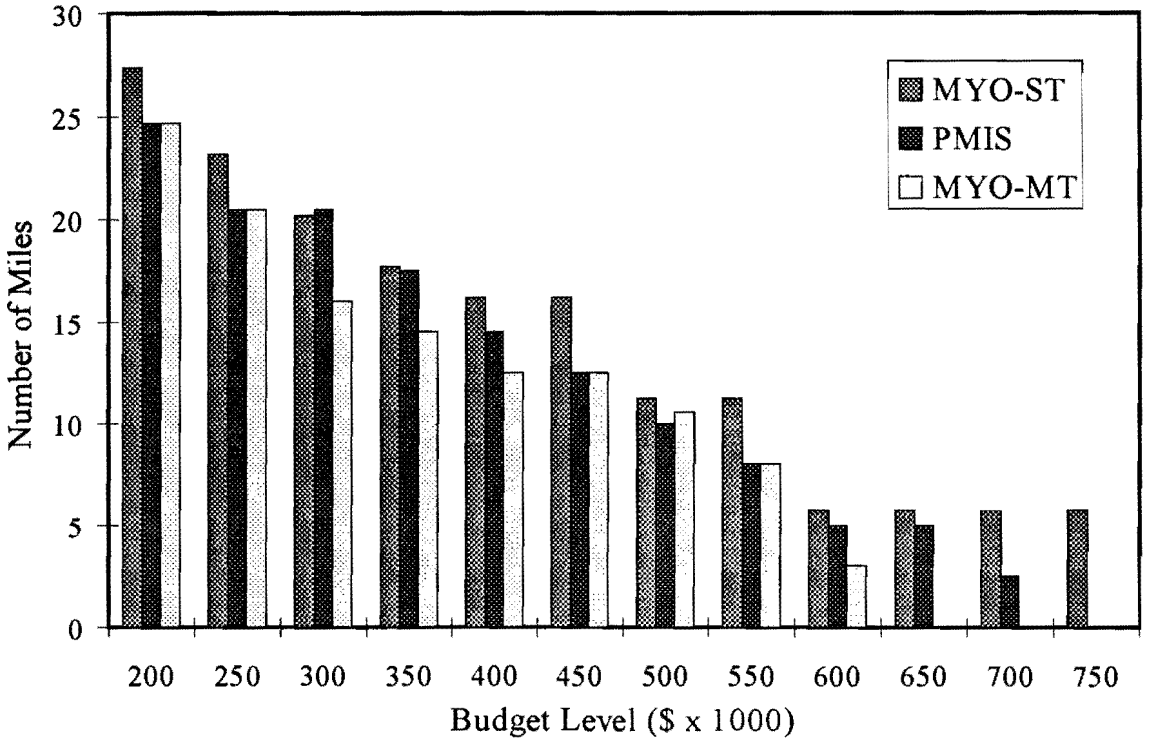

Figure 5.2. Backlog Mileage Requiring MRhb or HRhb Treatment at the End of Analysis Period (10 Years).

The main reasons why formulation MYO-ST is inefficient for maximizing the accumulated CERatio and reducing the backlog mileage to zero in long-term planning periods is the assumption that once a section has been selected for a treatment, that section cannot be selected for another treatment during the planning period. This assumption does not allow any PM or LRhb treatment for the sections treated at the beginning of the planning period to keep them in good condition in the future so that by the end of the planning period those sections are in bad condition again.

It is clear from Figure 5.2 that formulation MYO-MT was more efficient for selecting sections needing MRhb or HRhb treatment than PMIS at $300 K, $350 K, $400 K, $600 K, $650 K, and $700 K budget levels. Table 5.1 shows the sections selected at each year by the three methods for a $650,000 annual budget, and Table 5.2 shows the annual expenditures due to the treatments needed by those sections. The main advantage of formulation MYO-MT method over PMIS was its ability to defer treatments and use the budget more wisely. PMIS uses a sequential single-year analysis which does not consider the consequences of deferring treatments. Some of the treatments can be deferred for several years before the highway section deteriorates into a higher-cost treatment. The MYO-MT formulation appears to defer treatments on non-critical sections, that is, sections that are not close to moving into a higher treatment level. In some instances, this permits the application of more expensive treatments to other sections in early years. It can also be seen from Table 5.1 that the sections selected in the first year by PMIS and formulation MYO-MT were similar. This was expected because the ranked cost effectiveness analysis used by PMIS is effective for solving single-year optimization problems near to optimality. However, after the first year, the sections selected by PMIS and formulation MYO-MT were different not only at the $650,000 budget level, but also for every budget level used in this study. The selection of sections in worse condition and the consequence of using a time optimization procedure by the MYO-MT formulation made the impact on the accumulated CERatio shown in Figure 5.1. The total benefits resulting from applying the different methodologies to the highway network at the end of the planning horizon clearly shows that at each budget level the MYO-MT formulation generates higher benefits.

At the other budget levels ($200 K, $250 K, $450 K, $500 K, and $550 K from Figure 5.2), PMIS and formulation MYO-MT selected the same sections, but in different order. The advantage of the MYO-MT formulation was the deferral of treatments so that (1) the overall CERatio from Figure 5.1 was maximized, (2) the backlog was reduced as shown in Figure 5.2, and (3) as shown in Table 5.2, annual expenses were more homogeneous in every year of analysis. At $500 K budget level, PMIS and formulation MYO-MT selected the same sections (in different order, too), except that PMIS selected section 14 with a 4.0-km (2.5-mile) length and the MYO-MT formulation selected section 5 with a 3.2 -km (2.0-mile) length for a treatment so that PMIS had 0.5 backlog miles less than the MYO-MT formulation at the end of the 10-year planning horizon. However, from Figure 5.1, it can be seen that the decision made by the MYO-MT formulation had a much better impact on the accumulated CERatio.

Finally, Table 5.2 shows that none of the three methods selected the sections so that each year exactly $650,000 were spent. Therefore, the original $650,000 annual budgets were adjusted to the annual budgets displayed on Table 5.2 for PMIS and MYO-MT methods only, and programs were run again to compare the ability of both methods to adjust their initial budgets to the optimal ones. In other words, instead of using $650,000 per year for PMIS, a $611,000 budget was used for the first year, $608,000 for the second year, $579,000 for the third year, and so on. This adjustment was made to every original budget level from $200,000 to $750,000. After adjusting the annual budgets, the results showed that the same optimal solution and selection of sections each year as in each original budget level solution were obtained by formulation MYO-MT, while PMIS always found a different solution than the previous one (see Table 5.3 for the $650,000 budget level case). This shows that PMIS is not reliable in the selection of candidate sections after making simple adjustments in the annual budget levels.

Figure 5.3 shows the computational running times (in seconds) required by the MYO-MT formulation for every budget level. Notice that the model is very sensitive to different budget levels.

Table 5.1. Sections Selected by PMIS and Formulations MYO-ST and MYO-MT with a $650,000 Annual Budget.

Annual Selection of Sections to be Rehabilitated			
Year	PMIS	MYO-ST	MYO-MT
1	2,4,8,13,17,18,19,21,22	8,12,17,19,22,23	4,8,15,17,18,19,21,22,23
2	6,9,15	1,11,13	6,10,11,12,13
3	12,14	9,18	2,20
4	3,8,16	7,21	7,8
5	1,4,13,21,23	2,14	9
6	6,11,19	4,20	4,6,14,21
7	5,8	3,6	3,8,13
8	2,10,17,18,22	5,15	1,11,19,20
9	4,15,21	NONE	5,18
10	3,6,8,9,12	10,16	2,4,6,7,8,10,12,15,16,17,21,22,23

Table 5.2. Annual Expenses for Treatments Needed by the Sections Selected in Table 5.1.

Annual Expenses			
Year	PMIS	MYO-ST	MYO-MT
1	$611,000	$610,000	$646,000
2	$608,000	$578,000	$630,000
3	$579,000	$628,000	$623,000
4	$612,000	$644,000	$560,000
5	$529,000	$626,000	$620,000
6	$491,000	$625,000	$582,000
7	$521,000	$466,000	$540,000
8	$377,000	$619,000	$597,000
9	$ 44,000	0	$574,000
10	$122,000	$628,000	$519,000
Total	$4,494,000	$5,424,000	$5,891,000

Table 5.3. Sections Selected by PMIS after the $650,000 Annual Budgets were Adjusted by Those Shown in Table 5.1.

Annual Selection of Sections by PMIS		
Year	$650 K per year	Annual Budget Level from Table 5.2
1	2,4,8,13,17,18,19,21,22	2,4,8,13,17,18,19,21,22
2	6,9,15	6,9
3	12,14	14,15
4	3,8,16	8,12,16,23
5	1,4,13,21,23	3,4,13,21
6	6,11,19	6,10,19
7	5,8	1,8
8	2,10,17,18,22	2,17,18,22
9	4,15,21	4,6,21
10	3,6,8,9,12	6,8,9,15,23

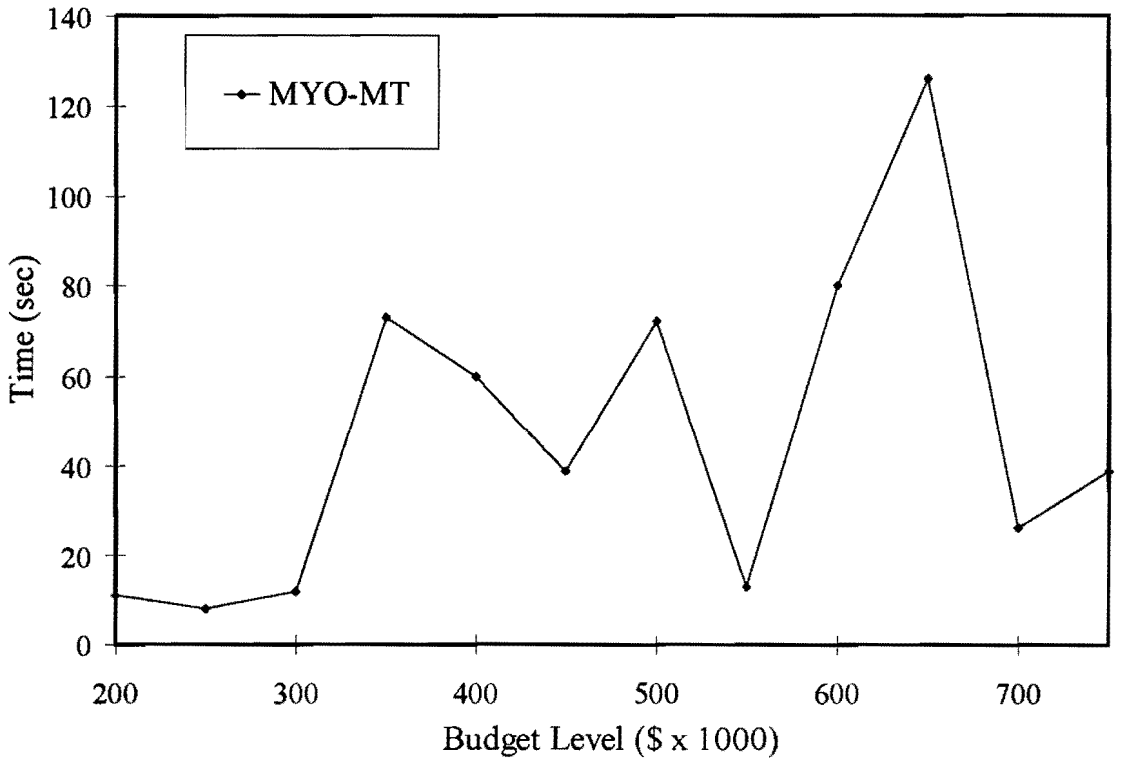

Figure 5.3. Computer Running Time for Formulation MYO-MT.

CHAPTER 6
RECOMMENDATIONS

DIFFERENT OPTIMIZATION SOLUTION TECHNIQUES

In the last decade, great progress in the ability to solve large scale integer programs has been achieved (Boyd et al., 1994). Interestingly, much of the progress has not been from new theoretical ideas but rather from a better appreciation of how existing ideas, many of which are quite rudimentary, can be exploited. Areas which had an impact on recent breakthroughs in integer programming include preprocessing, cutting planes, and even branch and bound. For example, Boyd et al. (1994) obtained results with an algorithm for the management of national air traffic involving over one million binary variables (0-1 integer decision variables) that can be solved to probable optimality in real time. Problems involving 10274, 27300, 112594, and 1015456 binary decision variables were solved in less than 1 sec, less than 1 sec, 4 sec, and 2 min and 33 sec, respectively, on an IBM RISC 350 workstation with 96-Mb RAM using the CPlex Callable Library version 2.1.

This report shows the results obtained from a small case study involving 23 sections and a 10-year planning horizon. It is suggested that a large-scale case study for the TxDOT District with the largest number of management sections should be addressed using the CPlex optimization software with the PC Linear Optimizer, Barrier, Mixed Integer, and Callable Library options. Four solution approaches are suggested for solving the MYO-MT model used in this report: (1) a network-based solution technique because of the precedence constraints in the model, (2) a cutting-plane approach, (3) a Lagrangian decomposition approach, and (4) a more robust multi-year prioritization method than the current PMIS sequential-year ranking method.

TIE INTO CURRENT TXDOT PMIS SYSTEM

Any of the four solution approaches suggested above may be used with TxDOT PMIS. PMIS analysis programs are written in SAS. If SAS can write a file as output or communicate with a C program directly, the first three approaches may be implemented using the CPlex

software with the Callable Library. Input data may be generated using the current deterioration models and saved in a file by PMIS for a given planning horizon; then the input data file may be transferred or coded to the optimization model using the CPlex Callable Library. The CPlex optimization subroutines will solve the MYO-MT model, and finally, the CPlex Callable Library will be used again to decode the output solution file for PMIS.

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