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REHABILITATION AND MAINTENANCE SYSTEM:
THE OPTIMIZATION MODELS

BY

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Research Report Number 239-1

Pavement Rehabilitation Fund Allocation

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ABSTRACT

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Five different optimization models have been developed to analyze the pavement maintenance problem from different perspectives. The RAMS-DO-1 model deals with the solution to the maintenance problem at the district level over a one-year planning horizon. The problem is formulated as a 0-1 linear integer programming problem. The RAMS-SOFA-1 is a dynamic programming formulation which integrates the solutions from RAMS-DO-1 for various districts to maximize statewide benefit. The RAMS-SOFA-2 deals with the global state-level optimization. The program determines the optimum rehabilitation and maintenance strategies for each section of highway segments in all the districts. The RAMS-DTO-1 is a nonlinear integer programming formulation which also deals with optimization at the district level, but it considers management decisions for a planning horizon of several years, such as 10 to 15 years. The RAMS-DO-2 is similar to RAMS-SOFA-2, but deals with district optimization of fund allocation to residences in that particular district.

In fulfilling the above objectives, solution techniques have been developed to solve very large optimization problems. A typical single district optimization model might exhibit 5,000-10,000 zero-one decision variables. The solutions obtained show that scarce resources such as manpower, materials, machinery, and money (statewide budgets) can be optimally allocated within the state and in individual districts to obtain the most cost-effective Rehabilitation and Maintenance strategies over a specified planning horizon.

SUMMARY

This report gives the general summary of the Rehabilitation And Maintenance System - Optimization models. The System consists of seven computer programs. One report explains how the combined and sequential use of the computer models will enable the Texas State Department of Highways and Public Transportation to allocate money, men, machinery, and materials to the various districts in an optimal way.

The planning process begins at the district level. Selected pavement segments are inspected and the condition survey data are key punched. The validated corrected (RAMS-DCV) condition data are sent to the state authorities, who utilizing the RAMS-SCE program will determine the approximate rehabilitation and maintenance selection and the schedule for the next pavement inspection for each and every district. The lower and upper limits on the district budgets are determined by the state and the information is sent back to the appropriate districts. Using the RAMS-DO-1 program, each district determines the optimal rehabilitation and maintenance strategies for one year and the benefits for different budget levels between the lower and upper limits on the budget specified by the state. However, constraints on resource availability and pavement rating requirements may be too binding to obtain a feasible solution. When this is the case, a management decision is required to increase the availability of specific types of resources, e.g., material, equipment days, district budget and betterment budget; and/or decrease the rating requirement of specific highway segments. After the reformulation of the resource availability and/or pavement rating requirement constraints, the appropriate solution method is applied to the revised mathematical model. The problem feasibility is checked again. When infeasible, the procedure

mentioned above is iterated until a feasible solution is reached. The computed results must be examined carefully by the maintenance engineer and top management. If unacceptable, it is necessary to go back to Task I of the strategic planning to reevaluate and readjust the problem analysis and data collection. When every district determines an optimal solution, the benefits for various budget levels in each district are sent back to the state from all the districts. Using this information, the state determines (RAMS-SOFA-1) the optimum budget level at each district which maximizes the state-level benefit with the available state budget. The RAMS-SOFA-2 will aid the state in determining the statewide strategy and fund allocation on Interstate and spine networks district by district. The above information is transferred back to the districts which in turn utilizes RAMS-DO-2 program to determine the fund allocation to the residences. Utilizing the RAMS-DTO-1 program individual districts may determine the funds required for every year of a finite (5, 10, or 15 years) planning horizons, maintain the road segments at a certain pavement quality.

IMPLEMENTATION STATEMENT

This report summarizes the Texas Rehabilitation And Maintenance System (RAMS) optimization models which have been developed for use by the engineers and management of the Texas State Department of Highways and Public Transportation. The purpose of this report is to bring forward the ideas and advantages of using optimization models in allocating pavement rehabilitation and maintenance funds to achieve the best possible highway system in the State of Texas. The report describes five different optimization models which deal with the various aspects of the complex highway maintenance problems.

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 views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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CHAPTER I

INTRODUCTION

The Texas Transportation Institute has been engaged for the past few years in developing a Rehabilitation And Maintenance System (RAMS) for the state of Texas. Planning models are needed on a yearly basis by the Texas State Department of Highways and Public Transportation. The system which has been developed contains a set of mathematical models and a family of computer programs which can be used as tools in helping the management to make better decisions in rehabilitation and maintenance of Texas state highways.

The RAMS family consists of seven programs which are listed in Table I. The RAMS-DCV (16) is a data check and validation program; it checks for errors in the input data of the district pavement condition survey. A flow chart is shown in Figure 1. The RAMS-SCE(7) is the state cost estimating program which determines the approximate maintenance strategy for the highway segments. The input data requirements are shown in Figure 2. The other five programs are RAMS-DO-1, RAMS-SOFA-1, RAMS-SOFA-2, RAMS-DTO-1, and RAMS-DO-2. The flow charts of these optimization models are shown in Figures 3, 4, 5, 6, and 7 respectively. The combined and sequential use (Figure 8) of these seven programs will facilitate planning, cost estimation, and fund allocation for the pavement maintenance management.

This report deals with a descriptive analysis of each optimization model and the corresponding solution algorithms that are contained in these programs. The general objective of the RAMS programs is to maximize the total effectiveness of all rehabilitation and maintenance activities scheduled for the entire highway network in the state of Texas in each year of a predetermined planning period while remaining within the available

TABLE I

RAMS Programs

Rehabilitation And Maintenance System

RAMS - DCV
RAMS - SCE
RAMS- DO-1
RAMS - DTO-1
RAMS - SOFA-1
RAMS-DO-2
RAMS - SOFA-2

1st Letter

D stands for District
S stands for State

2nd Letter(s)

O stands for Optimization
TO stands for Time Optimization
CE stands for Cost Estimating
CV stands for Check and Validation

3rd Letter(s)

FA stands for Fund Allocation

Numbers

1 - stands for the 1st in the series
2 - stands for the 2nd in the series

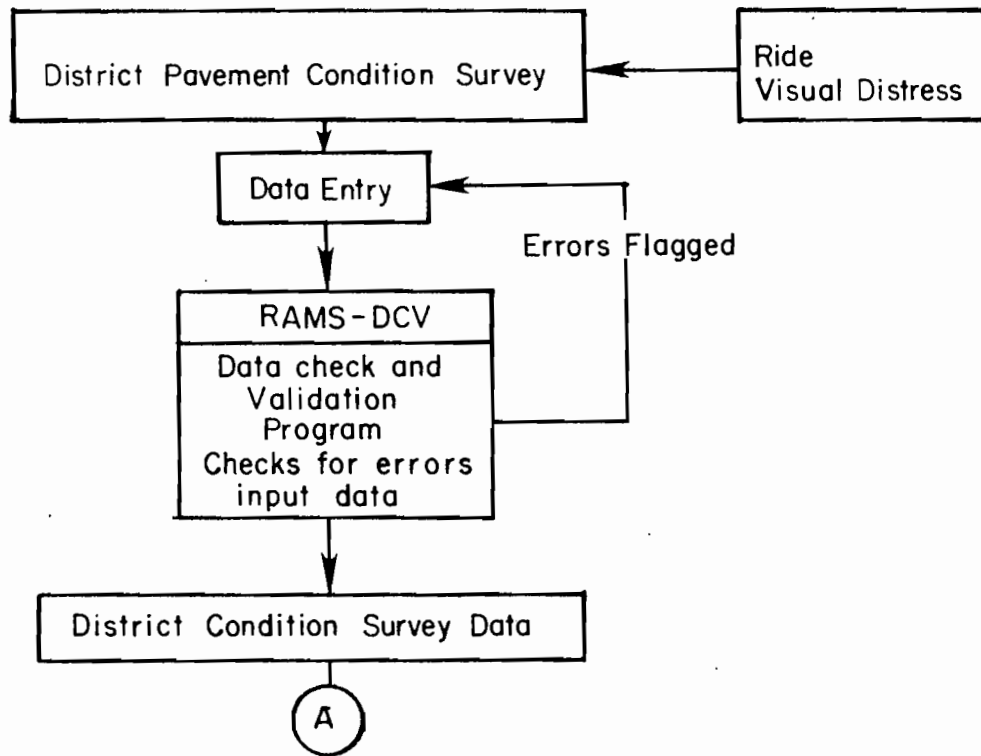


FIGURE 1. - RAMS-DCV FLOW CHART

District Condition Survey Data

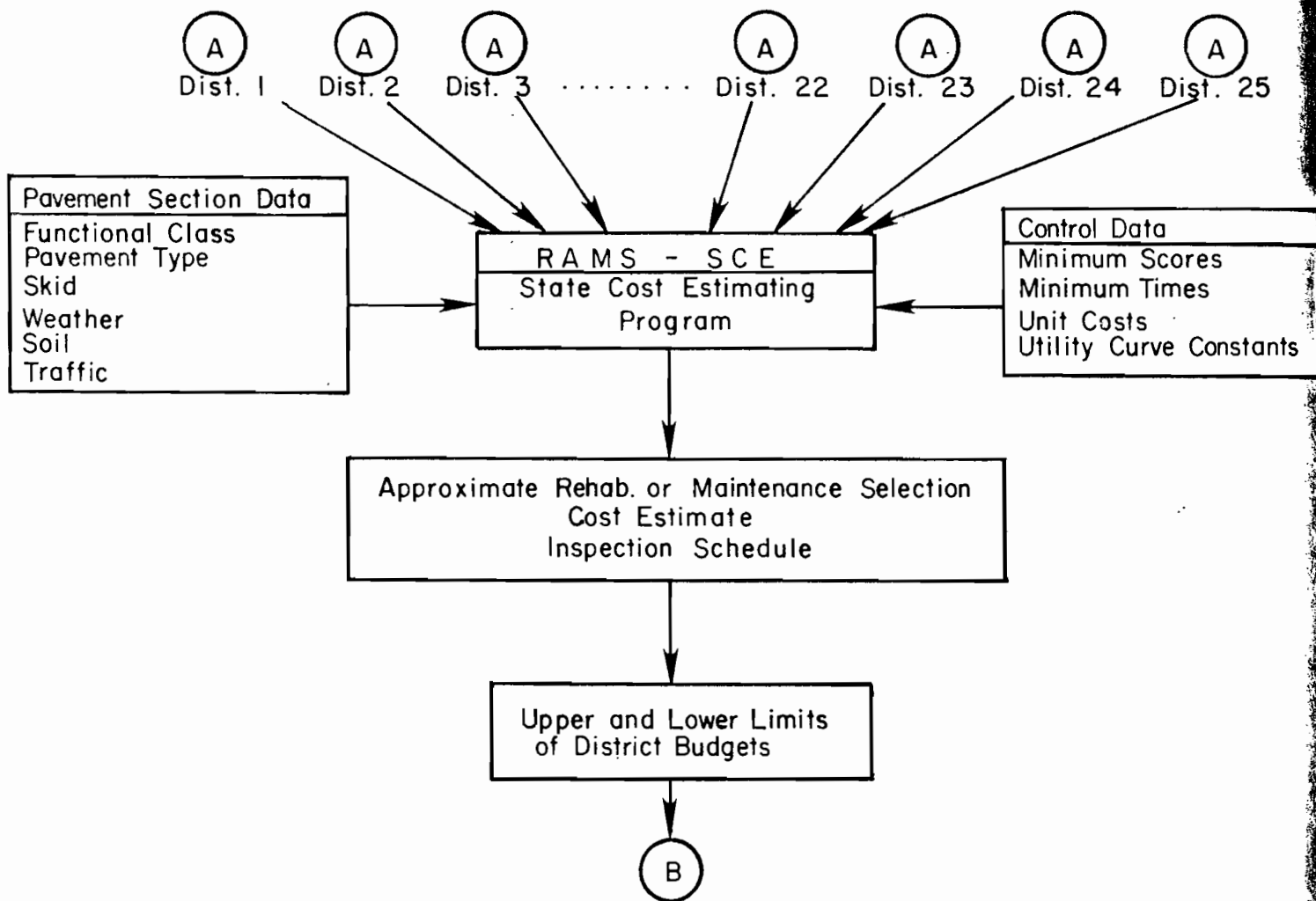


FIGURE 2. - RAMS-SCE FLOW CHART

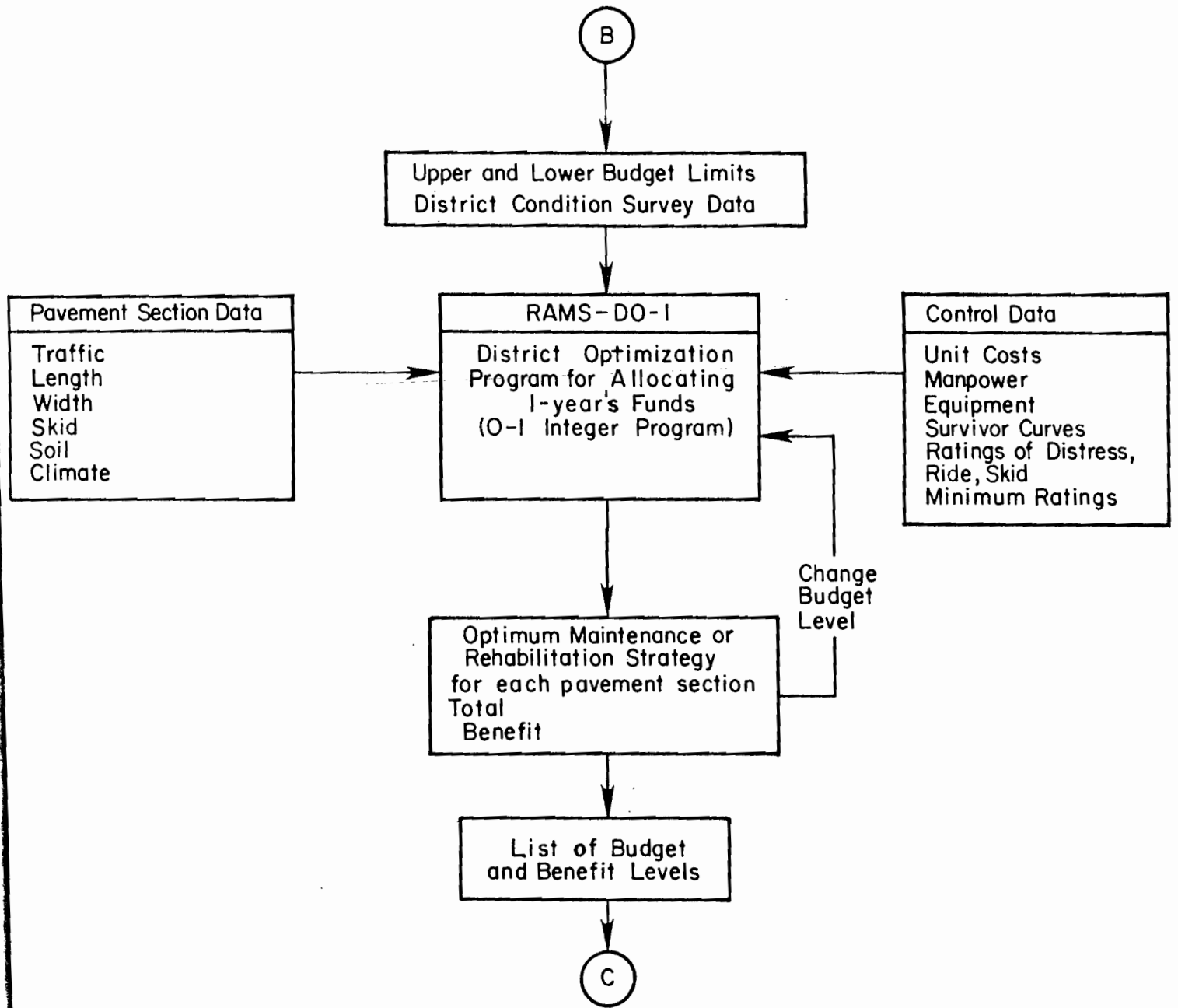


FIGURE 3. - RAMS-DO-1 FLOW CHART

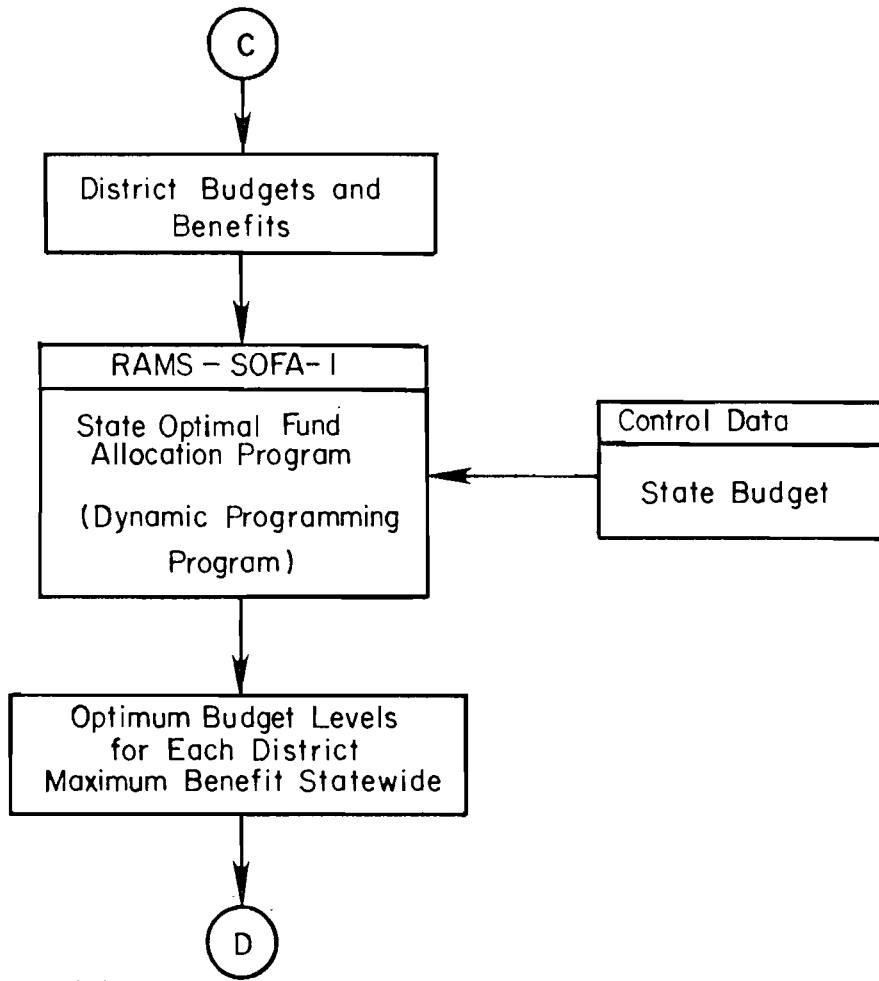


FIGURE 4. - RAMS-SOFA-1 FLOW CHART

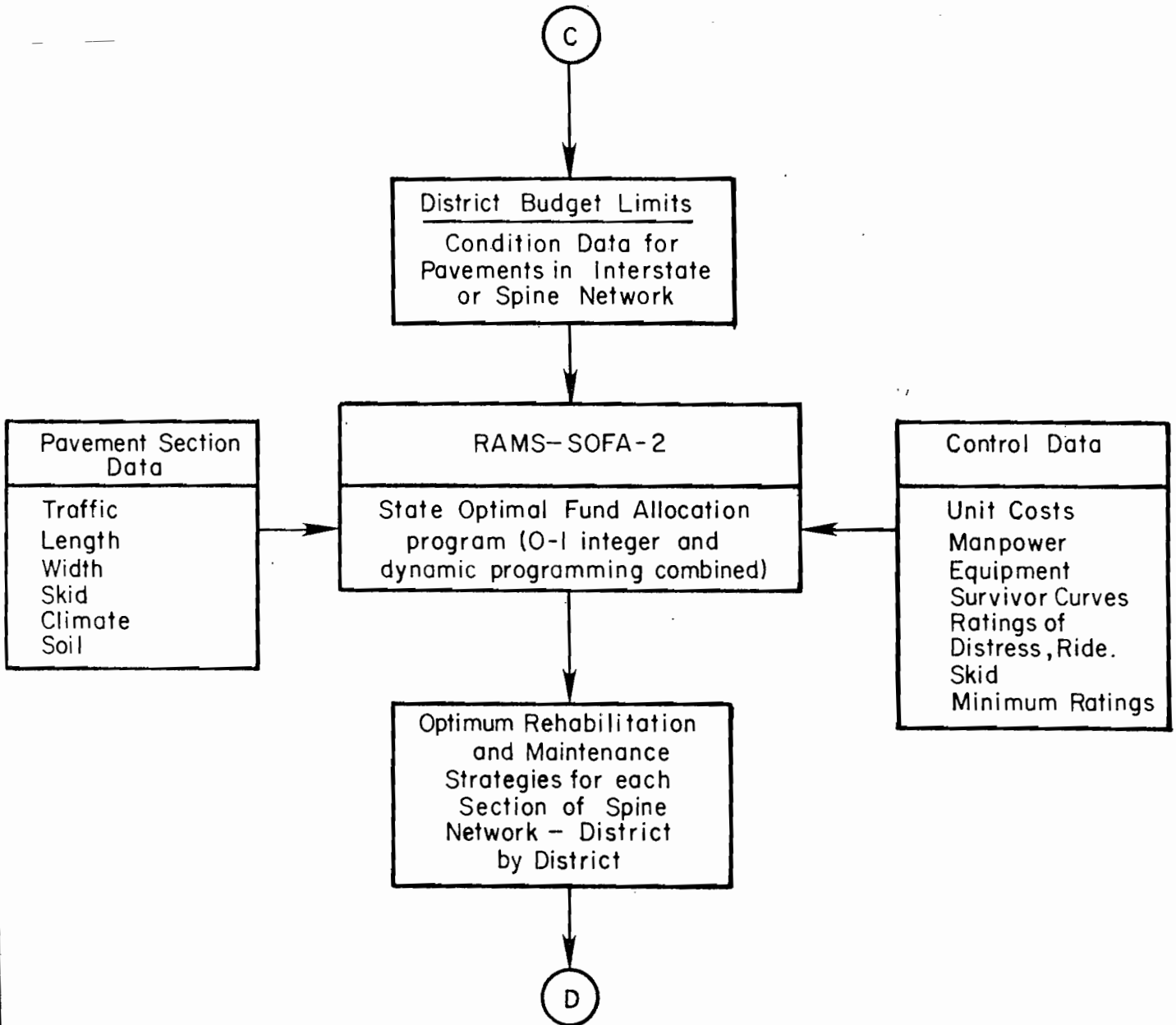


FIGURE 5. - RAMS-SOFA-2 FLOW CHART

OPTIMAL TIME-STAGING OF PROJECTS

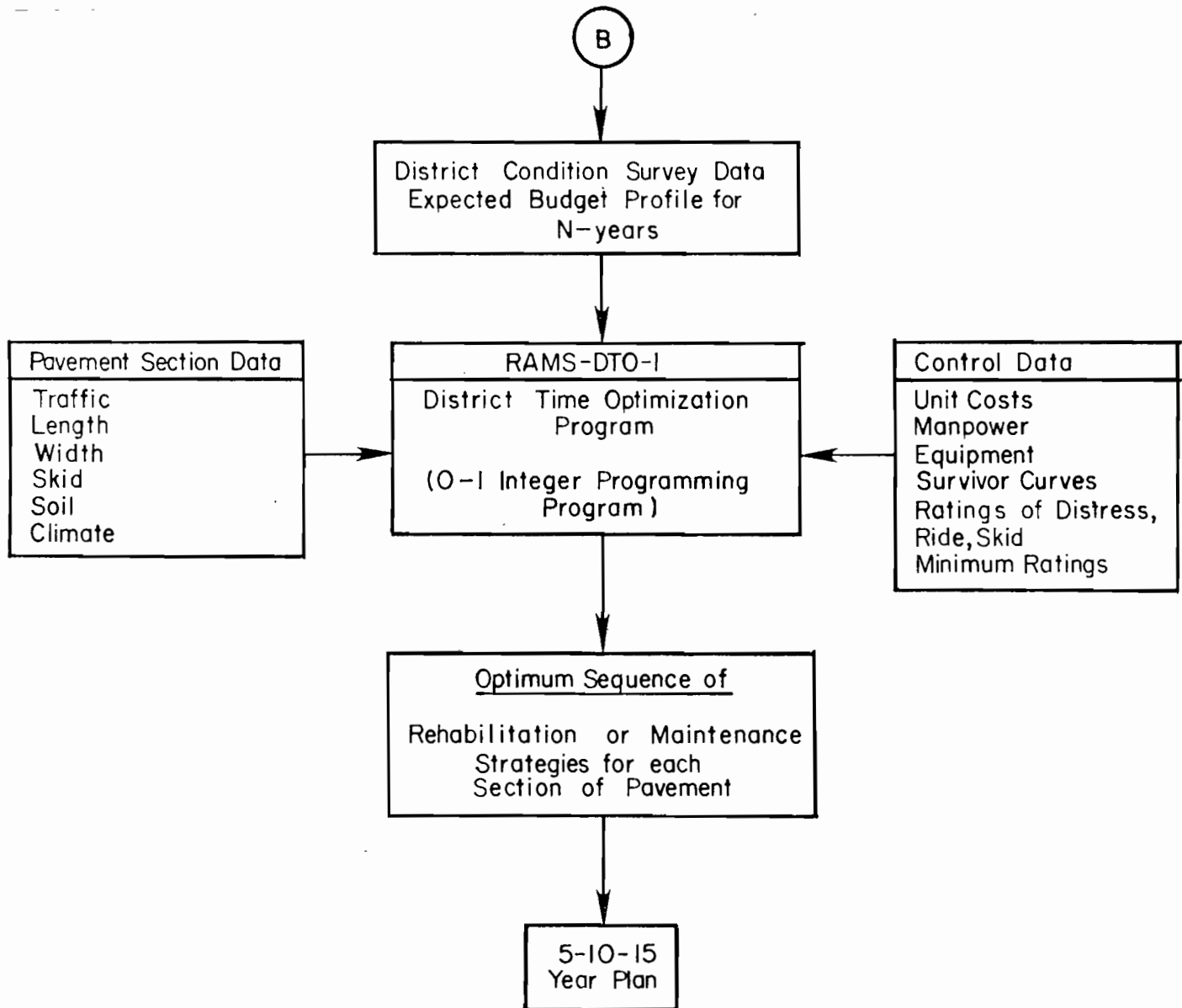


FIGURE 6. - RAMS-DTO-1 FLOW CHART

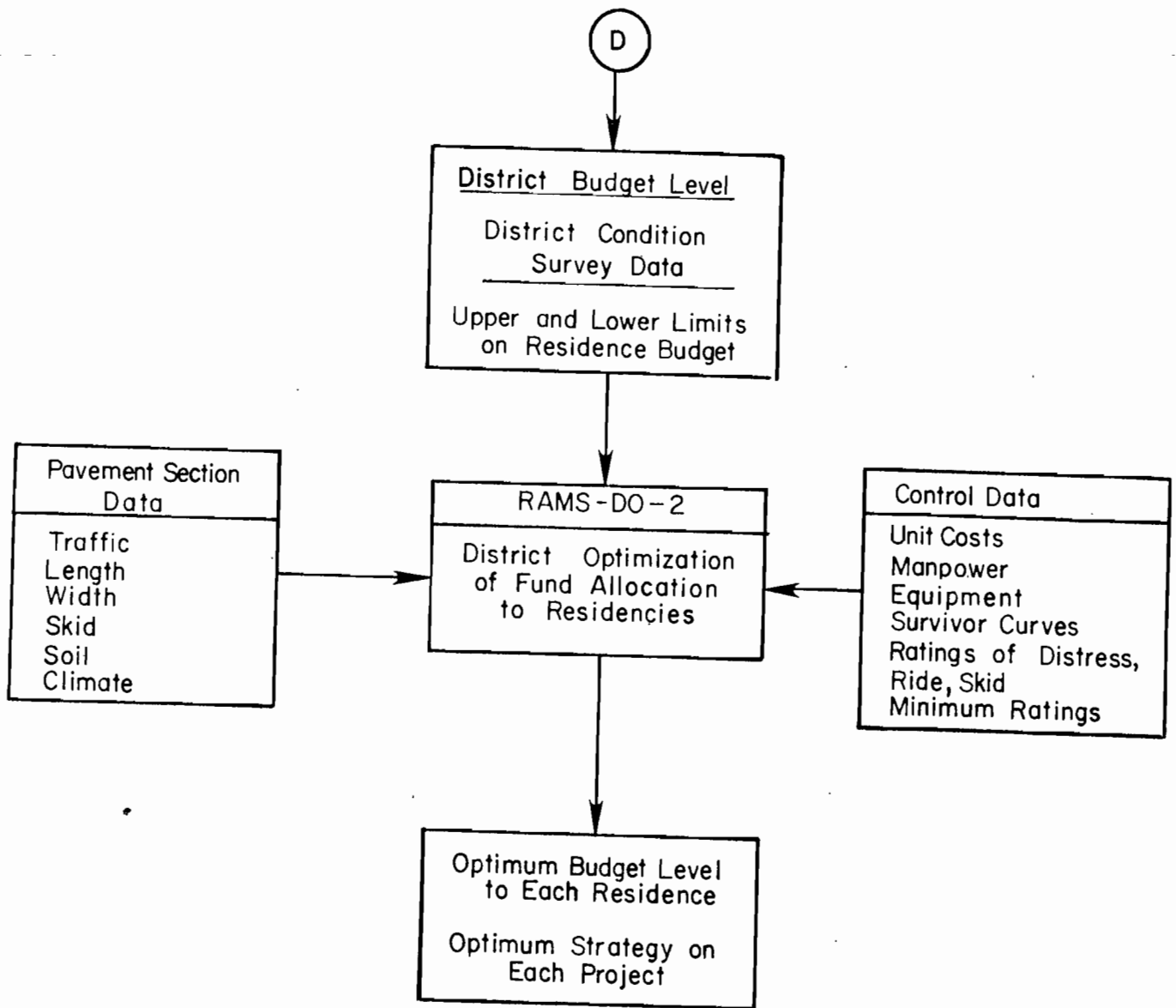


FIGURE 7. - RAMS-DO-2 FLOW CHART

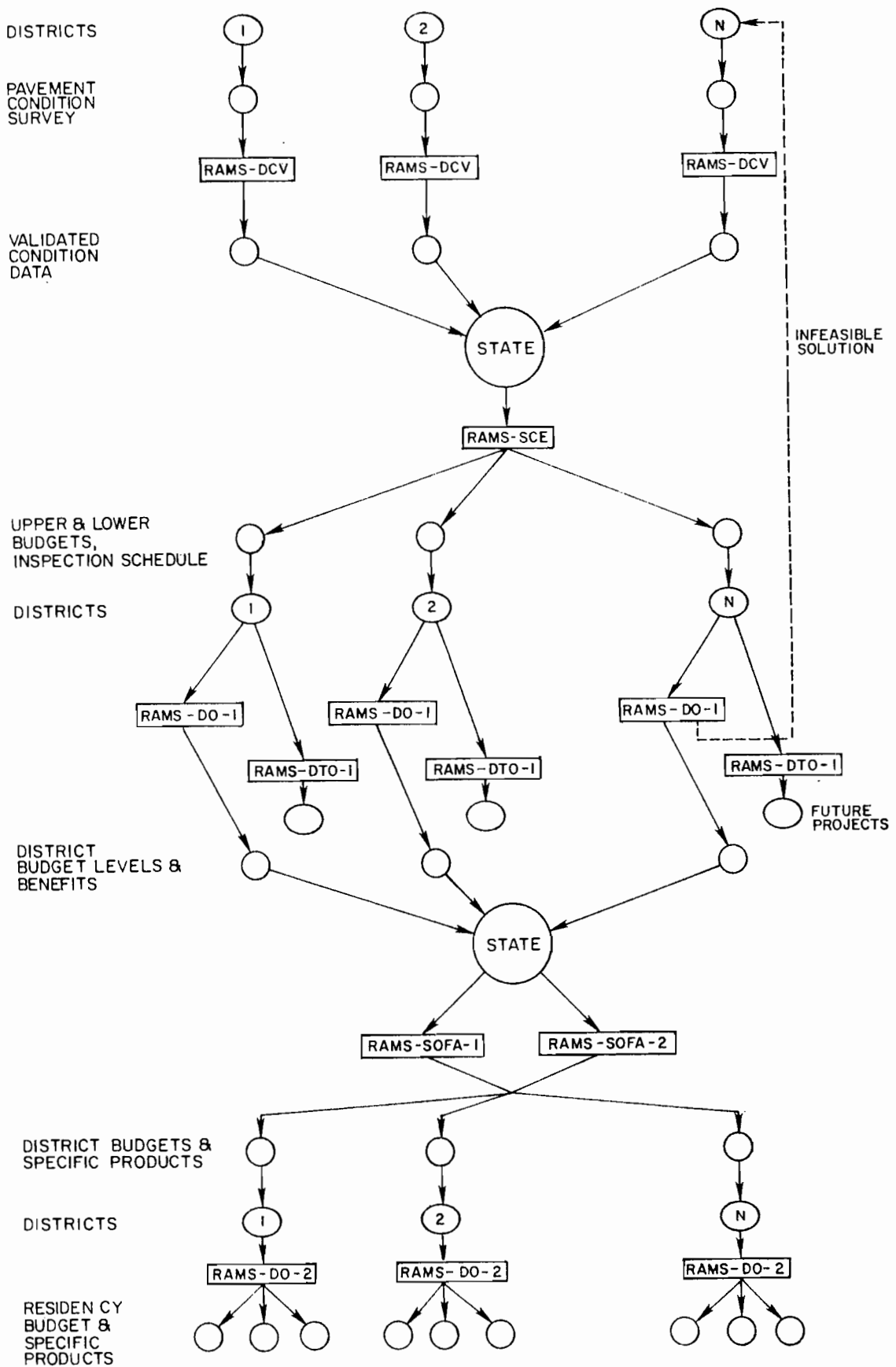


FIGURE 8. - REHABILITATION AND MAINTENANCE SYSTEM
FLOW CHART

budget. This is achieved by the optimal selection of a maintenance ; policy for all highway segments in a specified network. The mathematical representation of this problem proved to be too large for the existing, efficient optimization techniques to produce a solution within reasonable time and money. Research at Texas A&M University conducted by the Texas Transportation Institute, has resulted in a state-of-art solution methodologies capable of deriving realistic rehabilitation and maintenance policies.

Planning is required at two distinct levels of planning: the District level and the State level. The objective at the District level is to maximize the total effectiveness of all maintenance and rehabilitation activities scheduled for the next year while reamining within the available budget. This planning process is represented by the single period district optimization model (RAMS-DO-1). RAMS-DO-1 can be expanded to consider the effects of future scarce resource supplies and pavement quality requirements on future (greater than one year) maintenance schedules. This multiperiod model is termed as RAMS-DTO-1. The third model, RAMS-SOFA-1 is the state optimal fund allocation model. The fourth model deals with integrating the individual district schedules at the state level to optimize the overall effectiveness of the total system. This State Planning Program (RAMS-SOFA-2) is capable of optimally allocating rehabilitation and maintenance funds for the next funding period throughout the state districts, and allocating other (local) resources within each district. This global model is also capable of optimally

allocating funds over a finite time (planning) horizon for a single district. When it is used within a district, this program is called RAMS-DO-2.

RAMS-DO-1 is a 0 - 1 integer linear programming model. An algorithm developed by Ahmed (1), and Phillips and Lytton (11) uses the concept of an effective gradient utilizing a basic Toyoda (17) algorithm to solve this single period problem. RAMS-DTO-1 is formulated as a 0 - 1 integer non-linear programming problem. A network decomposition procedure proposed by Sathaye (15) and Phillips is used to solve this multiperiod highway maintenance problem. RAMS-SOFA-1 (12) is modeled as a dynamic programming problem. RAMS-SOFA-2 is also modeled as a dynamic programming problem. Tari (4) and Phillips has developed a hybrid dynamic programming algorithm, capable of handling multiple constraints. This technique will be used to solve the global State optimization problem.

The formulation of these resource allocation methods for strategic planning of maintenance and rehabilitation provides a basic framework within which management decisions can be made and altered while fully recognizing the effect those decisions will have upon the quality of pavements within a highway network.

Development of a practical planning model for pavement maintenance and rehabilitation management involves the following interrelated tasks: (1) problem analysis and data collection, (2) formulation of the mathematical model, (3) optimization and (4) analysis of the solution. Each of these four tasks are described in some detail in Chapters II, III, IV and V.

CHAPTER II

TASK I: PROBLEM ANALYSIS AND DATA COLLECTION

Task 1 of the strategic planning for a pavement rehabilitation and maintenance management system is problem analysis and data collection which is categorized into four tasks: (1) management decision, (2) roadway description, (3) pavement condition and (4) resource information.

(1) Management Decision

Management decisions determine the number of highway segments that will be considered in a highway network, the number of maintenance strategies that will be employed, the number of distress types to be included in determining the current condition of all highway segments and the analysis period for planning and control. "Forced" or "Politically motivated" mandates are also a part of this decision process.

(a) Highway Segment. One highway segment can be a portion of a highway section or a combination of several sections such that a segment can be treated as a unity in the study. The traffic condition and environmental factors which affect the effectiveness of maintenance and rehabilitation activities within the units should be very similar. The strategic planning system will select an optimal maintenance strategy for each unit, that is, each highway segment specified by the decision-maker. Highway sections which are expected to provide acceptable service and require no maintenance during the next year, or is not cost effective, need not be included in the scope of the management decision process.

(b) Maintenance Strategies. Undoubtedly, numerous practical applications of maintenance strategies can be listed. However, the more strategies

included in a given analysis, the more effort is required in assembling maintenance effectiveness data and in the solution of the resulting mathematical programming problem. Consequently, the current list of strategies has been restricted to eleven rehabilitation and maintenance alternatives: (1) strip seal, (2) fog seal, (3) chip seal, (4) light patching and chip seal, (5) extensive patching and chip seal, (6) chip seal and planned thin overlay, (7) plant mix seal or open graded friction course, (8) thin overlay with less than 2 inches of asphalt concrete, (9) moderately heavy overlay with 2 to 3 inches of asphalt concrete, (10) heavy overlay with 3 to 6 inches of asphalt concrete and (11) reconstruction. These strategies are listed in order of increasing unit cost. Usually, strategies (1) - (4) are funded from the state maintenance budget. Funding for strategies (5) - (8) is either from the State maintenance budget or from the federal funds. Strategies (9) - (11) are funded from the betterment budget as contract work.

(c) Pavement Distress. Usually, pavement distress manifestations can be categorized into the following nine types (1) rutting, (2) reeling, (3) flushing, (4) corrugations, (5) roughness, (6) alligator cracking, (7) longitudinal cracking, (8) transverse cracking and (9) patching. This classification has been used in several visual rating systems for evaluating pavements (3, 6, 8).

(d) Analysis Period. A heavy overlay will, undoubtedly last longer than seal coats when applied to the same highway pavement. In order to calculate the overall effectiveness of all maintenance activities, it may be necessary to analyze the pavement survival rates over a specified time period. A planning horizon should be selected to be longer than any

maintenance or rehabilitation method, including reconstruction, is expected to last without requiring additional maintenance work. A period of ten years is recommended for analysis. This does not mean that maintenance decisions and budgeting for the next ten years will be studied in the single period programs. Instead, only the next year's maintenance strategies and budgeting will be determined, but their choice will be based upon the effectiveness of each maintenance strategy within the given analysis period. The multiple year planning program (RAMS-DTO-1) investigates maintenance and budgeting decisions over several years.

(2) Roadway Description

Once the number of highway segments to be considered in a resource allocation scheme is determined by management decisions, the pavement type, length, width, traffic and environmental conditions of each segment can be established. The roadway data collected on each highway segment can be organized into a roadway inventory matrix for computer processing. This data base is currently being constructed by the Texas Transportation Institute. Traffic, soil, and environmental indices are characterized by multiplying factors which increase with traffic, subgrade, and climate conditions that accelerate the impact of various forms of distress. The formulation of these three indices will be discussed subsequently.

(3) Pavement Condition

Pavement condition can be characterized in the following manner:

- (1) the current pavement condition rating of each segment, for each distress type;
- (2) the potential gains of rating of each segment for each maintenance strategy and distress type;
- (3) the pavement survival rate of each main-

tenance strategy (for each distress type and time period on each type of pavement); (4) the minimum rating requirement of each segment (for each distress type and time period); and (5) the rating requirement of each segment and time period.

(a) Potential Gain of Rating. The potential gain of rating is defined as the net expected increase of pavement rating of each segment, for each type of distress and maintenance strategy. The potential gain of rating for a given type of distress cannot exceed the amount of rating that is lost by that form of distress. A gain-of-rating matrix has been devised for an arbitrary highway segment. When the number of segments becomes large, the task of composing this collection of matrices can be done most efficiently by computer. It is possible that some maintenance strategies do not improve, but instead reduce the pavement ratings of certain distress types. As an example, seal coating does not improve rutting, and a fog seal may accentuate flushing. In these cases, a zero or negative gain-or-rating can result.

(b) Pavement Survival Rate. In order to assess the effects of maintenance and rehabilitation policies over a chosen planning period, a pavement survival matrix which contains the survival probability of each segment, for each distress type and maintenance strategy, has been developed. Where maintenance and rehabilitation are concerned, the term "survival" indicates that the pavement condition is still expected to be rated high enough not to require additional maintenance or rehabilitation work at some future point in time. For instance, for a specific highway segment i , maintenance strategy j and distress type k at t years after maintenance work has been performed, a typical survival rate, P_{ijkt} , may be as follows:

$$\begin{aligned}
P_{ijkt} &= 1.00 && \text{if } t = 0 \text{ yr} \\
&= 0.90 && \text{if } t = 1 \text{ yr} \\
&= 0.70 && \text{if } t = 2 \text{ yr} \\
&= 0.40 && \text{if } t = 3 \text{ yr} \\
&= 0 && \text{if } t \geq 4 \text{ yr}
\end{aligned}$$

The maintenance effectiveness when strategy j is applied per unit surface area of highway segment i when distress type k is present is defined as:

$$\sum_{t=1}^{N_T} d_{ijk} P_{ijkt}$$

where

d_{ijk} = potential gains of pavement rating of highway segment i , for maintenance strategy j and distress type k :

P_{ijkt} = pavement survival probability of highway segment i , for maintenance strategy j and distress type k , and time t ; and

N_T = number of years in the analysis period.

Estimation of the potential gains of rating for each highway segment can be a time-consuming process for highway engineers. For instance, if 100 highway segments are considered in the analysis framework, the data for 100 gain-of-rating matrices must be assembled. This problem can be simplified by categorizing the existing pavements into several major types, such as (1) surface treatment pavement, (2) hot mixed asphaltic concrete (HMAC) pavement without overlay, and (3) HMAC overlaid pavement.

The gain-of-rating of the three pavement types at typical traffic and environment conditions can thus be used to compose three basic matrices. The gain-of-rating of each individual highway segment can now be derived by multiplying a traffic adjustment index to the basic matrix. The maintenance effectiveness can be rewritten as:

$$\sum_{t=1}^{N_T} D_{njk} \cdot \left[\text{Max } 1 - a_i b_i c_i (1 - P_{ijkt}), 0 \right]$$

where

D_{njk} = potential gains of pavement rating of maintenance strategy j and distress type k , if highway segment i is pavement type n ;

a_i = traffic adjustment index of highway segment i ; and

b_i = environment adjustment index of highway segment i .

c_i = subgrade soil adjustment index of highway segment, i .

The master matrix of probabilities of pavement survival, P_{ijtk} , represents characteristic survival curves which may be modified by different traffic volumes and environmental effects. The characteristic curves should be the highest expected probabilities within a given district so that the adjustment factors, a_i , b_i , and c_i , will always be 1 or greater. Thus, an increase in a_i , b_i , or c_i will represent increasingly heavier traffic loading, more plastic subgrade soil, or more severe environmental conditions and will reduce the probability of survival.

(c) Definition of Benefit. When a rehabilitation and maintenance strategy is applied to a segment of highway section, the rating of the particular

segment is improved. This increase in the rating is seen in all the distress types that the particular roadway segment is subjected to. If we assume that the maximum possible rating of a distress type for a given strategy, occurs as soon as the strategy is applied ($t = 0$), then maintenance effectiveness for segment i of unit area (mile - ft) from application of strategy j , for a particular distress type k is:

$$\sum_{t=1}^{N_T} D_{njk} \cdot \text{Max} \left\{ \left[1 - a_i b_i c_i (1 - P_{ijkt}) \right] \cdot R_{\text{max}(k)}, 0 \right\}$$

where

$R_{\text{max}(k)}$ is the maximum possible rating for distress type k .

The total benefit will be the sum of benefits for all distress types.

i.e.,

The total benefit for segments from application of strategy j is:

$$\sum_{k=1}^{N_D} \sum_{t=1}^{N_T} D_{njk} \cdot \text{Max} \left\{ \left[1 - a_i b_i c_i (1 - P_{ijkt}) \right] \cdot R_{\text{max}(k)}, 0 \right\}$$

The above quantity represents the total benefit for a mile-ft of pavement area; for a segment of length L_1 mile and width L_2 feet, the total benefit is calculated as the product of L_1 , L_2 and benefit for unit area.

(4) Resource Information

The resource allocation schemes which will be described are primarily directed to annual budgeting and management. However, a substantial degree

of flexibility for decision-making has been retained. For instance, seasonal (or even monthly) reviews of the selected maintenance strategies are strongly encouraged so that inflated costs and the scarcity of resources as well as the need for changing pavement rating score requirements can all be included in the management analysis framework to alter or justify previous maintenance decisions.

Resources for pavement maintenance and rehabilitation can be categorized into the following groups: (1) material and supply, (2) equipment, (3) man-power, (4) district overhead cost, (5) betterment budget for contract work, and (6) state and federal available funds. First of all, the number of material types, equipment types, and manpower types must be identified. In light of the availability of the resources and the design engineer's preference, the types of materials, equipment, and manpower adopted and utilized for maintenance and rehabilitation in one district are not necessarily the same as those adopted and utilized in another district. The resource requirements per unit surfacing area (one-mile long and one-foot wide) of each resource type, maintenance strategy, and highway segment are represented in the form of resource matrices. These are updated and changed each time the planning model is used.

CHAPTER III

TASK II: FORMULATION OF MATHEMATICAL MODELS

The mathematical models for each of the solution procedures surveyed in this report are formulated as follows.

A: RAMS-DO-1

The objective of this resource allocation model for highway maintenance is to maximize the overall effectiveness of the maintenance activities, subject to constraints such as limited resources and minimum requirements on pavement quality and service life. mathematically, the problem as formulated by Lu and Lytton (8) is as follows:

$$\text{maximize } \sum_{i=1}^{N_H} \sum_{j=1}^{N_H} \sum_{k=1}^{N_D} \sum_{t=1}^{N_T} L_{1i} L_{2i} d_{ijk} P_{ijkt} x_{ij} \quad (1)$$

subject to

multiple choice decision variable constraints,

$$\sum_{j=1}^{N_S} s_{ij} \leq 1 \quad i = 1, 2, 3, \dots, N_H \quad (2)$$

material availability constraints,

$$\sum_{i=1}^{N_H} \sum_{j=1}^{N_S} s_{ijq} L_{1i} L_{2i} x_{ij} \leq S_g \quad g = 1, 2, \dots, N_G \quad (3)$$

equipment availability constraints,

$$\sum_{i=1}^{N_H} \sum_{j=1}^{N_S} e_{ijf} L_{1i} L_{2i} x_{ij} \leq E_f \quad f = 1, 2, \dots, N_F \quad (4)$$

manpower availability constraints,

$$\sum_{i=1}^{N_H} \sum_{j=1}^{N_S} h_{ijq} L_{1i} L_{2i} x_{ij} \leq H_q \quad q = 1, 2, \dots, N_Q \quad (5)$$

available overhead constraints,

$$\sum_{i=1}^{N_H} \sum_{j=1}^{N_S} OC_{ij} L_{1i} L_{2i} x_{ij} \leq CC \quad (6)$$

minimum rating requirement constraints,

$$cr_{ik} + \sum_{j=1}^{N_S} d_{ijk} P_{ijkt} x_{ij} \geq R_{ikt} \quad \begin{array}{l} i = 1, 2, \dots, N_H \\ k = 1, 2, \dots, N_D \\ t = 0, 1, \dots, N_T \end{array}$$

overall pavement rating requirement constraints,

$$\sum_{k=1}^{N_D} (cr_{ik} + \sum_{j=1}^{N_S} d_{ijk} P_{ijkt} x_{ij}) \geq W_{it} \quad \begin{array}{l} i = 1, 2, \dots, N_H \\ t = 0, 1, \dots, N_T \end{array} \quad (8)$$

where

N_H = number of highway segments in analysis,

N_S = number of maintenance strategies,

N_D = number of distress types,

N_T = number of years in analysis period,

L_{1i} = pavement length in mile of highway segment i ,

L_{2i} = pavement width in feet of highway segment i ,

d_{ijk} = potential gains of pavement rating of highway segment i , maintenance strategy j , and distress type k ,

P_{ijkt} = pavement survival probability of highway segment i , maintenance strategy j and distress type k , at time t ,

- x_{ij} = a decision variable which will be 1 if maintenance strategy j is selected for highway segment i , and 0 otherwise,
- S_{ijg} = amount of material (or supply) type g per unit surface area (one mile long and one foot wide) required for highway segment i , if maintenance strategy j is selected.
- S_g = total amount of material (or supply) type g available,
- N_G = number of material or supply types,
- e_{ijf} = amount of equipment type f (in equipment-days per unit one mile long and one foot wide surface area) required for highway segment i , if maintenance strategy j is selected,
- E_f = total amount of equipment type f (in equipment-days) available,
- N_F = number of equipment types,
- h_{ijq} = amount of manpower type q (in man-days per unit, one mile long and one foot wide surface area) required in highway segment i , if maintenance strategy j is applied,
- H_q = total amount of manpower type q (in man-days) available,
- N_Q = number of manpower types,
- OC_{ij} = overhead cost (in dollars per unit one mile long and one foot wide surface area) required for highway segment i , if maintenance strategy j is selected,
- CC = total overhead budget (in dollars) available,
- cr_{ik} = current pavement condition rating of highway segment i , and distress type k ,
- R_{ikt} = minimum required pavement rating of highway segment i and distress type k at time t , and,
- W_{it} = minimum required pavement rating of highway segment i of all distress types, at time t .

Magnitude of the District Optimization Problem

A convenient way to apply this formulation to a state the size of Texas is to divide the entire State highway system into several smaller subsystems. The existing highway districts may be considered as a suitable subsystem, or in some cases a subsystem may be formed by the combination of several highway districts. It should be noted that this sort of apportionment may not be optimal state-wide. However, most of the highway rehabilitation and maintenance operations are planned by highway districts rather than the entire state as a single unit, and funds are allocated to individual districts.

In an average subsystem the number of highway segments may be 300 and on the average there are about 15 strategies per segment. Hence there are typically around $300 \times 15 = 4500$, 0 - 1 decision variables. The number of material availability constraints is roughly 20, and the number of equipment and manpower availability constraints are roughly the same. There may also be additional budget requirement constraints. In addition, there are approximately 300 multiple-choice constraints to specify maintenance options, one for each highway segment. The number of minimum rating requirement constraints ($N_H \times N_D \times N_T$) and the overall rating requirement constraints ($N_h \times N_T$) may run into several hundreds. The minimum and overall rating requirement constraints are used to specify the feasible strategies for each highway segment and for an overall system (subsystem) efficiency. Assume that there are 8 distress types. Hence, an average size problem may consist of 4500 0 - 1 variables, 60 resource constraints, 300 multiple-choice constraints, 24,000 minimum rating constraints and 3,000 overall pavement rating constraints. For the current state of art

in 0 - 1 integer linear programming, the above problem is considered to be very large and for all practical purposes unsolvable.

B: RAMS-SOFA-1

The RAMS-SOFA-1(12) is a mathematical model capable of selecting the most promising set of budget levels for the districts under a fixed statewide budget. The mathematical formulation is in the form of nonlinear knapsack model. The model is as follows:

$$\text{Maximize} \quad \sum_{j=1}^N B_j (d_j)$$

subject to:

$$\sum_{j=1}^N C_j (d_j) \leq C$$

d_j is contained in S_j

where

$$S_j = \{1, 2, \dots, K_j\}$$

and

$$MI_j \leq C_j (d_j) \leq MX_j$$

where

- d_j = budget levels in district j ;
- B_j = benefit obtained by using budget level d_j in district j ;
- K_j = number of district funding levels for district j ;
- S_j = set of budget levels for district j ;
- = 1, 2, ... K_j

- C_j = amount of budget at level d_j for district j ;
 C = total amount of rehabilitation funds available for the state;
 MX_j = upper level of available funds for district j .

The problem can also be formulated as an integer linear programming problem. With 25 districts and 25 different budget levels for each district, the integer programming model will result in 625 major 0 - 1 decision variables. The Nonlinear Knapsack formulation reduces the number of decision variables to 25. An exact optimal solution is obtained to the problem by employing dynamic programming techniques.

C: RAMS-DTO-1

The mathematical model that can be used to generate a multi-period resource effective highway maintenance schedule for a district highway maintenance system can be stated as follows:

$$\text{Max } Z = \sum_{i=1}^N \sum_{j=1}^S \sum_{t=1}^T B_{ij,t}(X_{i,1,1}, \dots, X_{i,S,t-1}, X_{i,j,t}) \cdot X_{i,j,t} \quad (9)$$

subject to

$$\sum_{j=1}^S X_{i,j,t} = 1, \quad \text{for } i = 1, 2, \dots, N_H \quad (10)$$

$$t = 1, 2, \dots, T$$

$$\sum_{i=1}^N \sum_{j=1}^S CR_{i,j,t} \cdot X_{i,j,t} \leq C_t, \quad \text{for } t = 1, 2, \dots, T \quad (11)$$

$$\sum_{i=1}^N \sum_{j=1}^S MR_{i,j,t,m} \cdot X_{i,j,t} \leq AM_{t,m}, \quad \text{for } t = 1, 2, \dots, T \quad (12)$$

$$m = 1, 2, \dots, M$$

$$\sum_{i=1}^N \sum_{j=1}^S ER_{ijte} \cdot X_{ijt} \leq AE_{te}, \quad \text{for } t = 1, 2, \dots, T \quad (13)$$

$$e = 1, 2, \dots, E$$

$$\sum_{i=1}^N \sum_{j=1}^S RM_{ijto} \cdot X_{ijt} \leq MA_{to}, \quad \text{for } t = 1, 2, \dots, T \quad (14)$$

$$\text{for } o = 1, 2, \dots, O$$

$$PQ_{it\ell} \geq RMIN_{t\ell}, \quad \text{for } t = 1, 2, \dots, T \quad (15)$$

$$i = 1, 2, \dots, N$$

$$\ell = 1, 2, \dots, D$$

$$PQ_{it\ell} \geq RTOL_{t\ell}, \quad \text{for all } \ell = 1, 2, \dots, D$$

$$\sum_{j=2}^S X_{ijt} = 0, \quad \text{for } i = 1, 2, \dots, N \quad (16)$$

$$t = 1, 2, \dots, T$$

$$PQ_{it} = PQ_{i,t-1,\ell} + \sum_{j=1}^S X_{ijt} \cdot RIMP_{j\ell}, \quad \text{for } i = 1, 2, \dots, N \quad (17)$$

$$t = 1, 2, \dots, T$$

$$\ell = 1, 2, \dots, D$$

$$X_{ijt} = 0 \text{ or } 1, \quad \text{for } i = 1, 2, \dots, N \quad (18)$$

$$t = 1, 2, \dots, T$$

$$j = 1, 2, \dots, S$$

where,

X_{ijt} = is a 0-1 decision variable and represents alternative 'j' for highway segment 'i' during time period 't';

$B_{ijt}(\dots)$ = benefit coefficient for variable X_{ijt} and is a function of the decisions in the prior period;

N = number of highway segments;

S = number of maintenance strategies;
 T = length of planning horizon;
 D = number of distress types;
 M = types of manpower resources;
 E = types of equipments;
 O = types of materials used;
 C_t = the district budget for time period 't';
 CR_{ijt} = the capital required to implement alternative 'j' on highway segment 'i' during time period 't';
 AM_{tm} = manpower of type 'm' available during time period 't', in man-days;
 RM_{ijtm} = manpower required to implement alternative 'j' highway segment 'i' during time period 't', in man-days;
 AE_{te} = equipment type 'e' available during time period 't', in man-days;
 RE_{ijte} = equipment type 'e' required to implement alternative 'j' on highway segment 'i' during time period 't', in man-days;
 MA_{to} = material type 'o' available in time period 't';
 MR_{ijto} = the amount of material type 'o' required to implement alternative 'j' on highway segment 'i' during time period 't';
 PQ_{itel} = pavement quality level of highway segment 'i' during time period 't' for distress type 'l';
 $RMIN_{tel}$ = minimum pavement quality level acceptable for distress type 'l' during time period 't';

$RTOL_{t\ell}$ = tolerable quality level such that if the pavement quality level is above this level in any time period 't', then the highway segment is not considered for maintenance in that particular time period.

This formulation of the highway maintenance problem results in a binary nonlinear integer program (0-1 INLP). The nonlinearity in the problem is in the objective function as well as in the constraints. The benefit function is calculated as the area under the pavement quality level curves during any single time period. It is a function of the initial condition of this road segment and the maintenance strategies selected in the preceding time periods. The constraints can be classified into two types: 1) the resource constraints (constraints sets (11), (12), (13), (14)), and 2) strategy feasibility constraints (constraints (10), (15), (16), and (17)). The resource constraints consist of four types of resources: budget, manpower, equipment and material. The strategy feasibility constraints are used to determine the feasible strategies for a highway segment during any single time period. Constraints (10) force the problem to choose only one strategy for each highway segment in any one time period. (Note: Strategy '1' is a 'do-nothing' strategy). Constraint (15) is used to eliminate any alternative that does not meet the minimum highway pavement quality level requirements for a highway segment in some time period 't'. Constraint (16) ensures that a highway segment is not considered for maintenance if its condition is better than a pre-defined tolerance level ' $RTOL_{t\ell}$ ', during a given time period 't'.

As previously stated, this mathematical formulation of the highway maintenance problem is a 0 - 1 INLP problem. In general, a nonlinear programming problem is much more difficult to solve than a linear programming

problem and the integer nature of the variable compounds the difficulty. This INLP formulation of the highway maintenance scheduling problem has (N).(S).(T). variables. Normally a district has about 150-200 highway segments, 10-15 maintenance strategies, and a planning period around 10 years. Thus, the number of 0 - 1 decision variables is around 30,000 and the number of constraints in the neighborhood of 10,000. This INLP problem is not only nonlinear, but the number of variables is extremely large for this class of problems.

D: RAMS-SOFA-2

This model will aid in allocating the state-wide budget to the individual districts and at the same time, allocate scarce resources within the districts. The task of projecting the required budget levels for the annual maintenance program is also considered in this dynamic programming model.

The model is as follows:

$$\text{Max.} \quad \sum_{d=1}^D \sum_{j=1}^N r_{jd}(X_j)$$

Subject to:

$$\sum_{j=1}^N a_{ijd}(X_j) \leq b_{id} \quad i = 1, 2, \dots, M-1$$

$$\sum_{d=1}^D \sum_{j=1}^N C_{jd}(X_j) \leq TC$$

X_j is contained in S_{jd} where

$$S_{jd} = 1, 2, \dots, K_{jd}$$

where

$a_{ij d}$ = the amount of resource type i (excluding overhead cost) consumed as a function of strategy X_j , for highway segment j at district d .

$b_{i d}$ = total amount of type i available resource (excluding budget level) at district d .

$C_{j d}$ = the amount of consumption of overhead cost, which is a function of strategy X_j , for highway segment j at district d .

D = the number of districts in the analysis.

$K_{j d}$ = the number of maintenance strategies that can be applied to highway segment j at district d .

M = the number of resource constraints excluding overhead cost.

$r_{j d}$ = the return function of strategy X_j , for highway segment j , at district d .

TC = total amount of available budget for entire state.

X_j = the decision variable indicating the type of strategy to be selected.

The above problem can be decomposed into two parts. The first part is to decompose the problem according to individual districts. Each district can then be considered as a single stage of a total dynamic programming problem. The second part is a decomposition of each district subproblem which yields a problem form similar to the district problem (a decomposition process according to the highway segments). This process can be more clearly illustrated by expanding the above formulation.

$$\text{Max. } \sum_{j=1}^N r_{j1}(X_j) + \sum_{j=1}^N r_{j2}(X_j) + \dots + \sum_{j=1}^N r_{jD}(X_j)$$

Subject to:

$$\sum_{j=1}^N a_{ij1}(x_j) \leq b_{i1}$$

$$\sum_{j=1}^N a_{ij2}(x_j) \leq b_{i2}$$

$$\vdots$$

$$\sum_{j=1}^N a_{ijD}(x_j) \leq b_{iD}$$

for $i = 1, 2, \dots, M-1$

$$\sum_{j=1}^N C_{j1}(x_j) + \sum_{j=1}^N C_{j2}(x_j) + \dots + \sum_{j=1}^N C_{jD}(x_j) \leq TC$$

where

b_{id} = total amount of type i available resource (excluding budget) at district d .

Referring to the above problem, the limitations on all the resources are considered independently for each district with the exception of the limitation on the budget level (TC) which interrelates the decisions in all districts. However, the allocation process within each district may be developed independently if it were developed as a function of the budget level in a particular district. That is, a vector presenting the optimal return as a function of budget level in each district could be obtained. These districts benefits and associated cost levels may be used for the allocation of total budget to individual districts. This two-level allocation process can be suitably performed using a non-serial dynamic programming model.

The above model can also be used for projection of budget levels over the planning time horizon for each district. The entity "district" is replaced by the "time period" of the planning horizon. This modification will not result in any major change in the structure of the model. The minor changes needed will be associated with relating the current condition of highway segments to the future conditions.

A multiple-constrained dynamic programming model for the pavement maintenance management problem is developed for the allocation of resources within each district. The model is in the form of a nonlinear discrete variable problem which requires a special algorithm for obtaining an optimal solution to the problem. It can be easily visualized that a 0 - 1 model for the state optimal fund allocation problem will be a large one.

E: RAMS-DO-2

The RAMS-DO-2 model is similar to RAMS-SOFA-2. The RAMS-SOFA-2 optimizes the state fund allocation and determines the best rehabilitation and maintenance strategy for each section of the highway network, district by district. Whereas, the RAMS-DO-2 optimizes the district fund allocation to its residences by selecting the best strategy on each project. The mathematical formulations and the optimization procedure are the same for both the models.

CHAPTER IV

TASK III: OPTIMIZATION OF THE MODELS

All the five models presented are indeed large as far as integer programming problems are concerned. Ahmed (1), and Phillips developed an algorithm to solve the district optimization problem (RAMS-DO-1). This algorithm is based on an efficient algorithm by Toyoda to solve large zero-one integer linear programming problems, but has been modified suitably. Toyoda's original algorithm lacks the ability to handle multiple choice constraints (Equation 2, RAMS-DO-1 model). In addition, it cannot accommodate "greater than or equal to" type constraints (pavement rating requirements, equations 7 and 8 of RAMS-DO-1 model). The computer program and the user's guide to solve the RAMS-DO-1 model is documented in Texas Transportation Institute Research Report No. 207-2 (2). Phillips, et.al., (12) employed dynamic programming techniques to determine the exact optimal solution to the integration model (RAMS-SOFA-1). It is a very simple, but highly efficient technique. Sathaye (15) and Phillips developed a solution technique to solve the multiperiod district optimization problem (RAMS-DTO-1). As seen earlier, RAMS-DTO-1 is a zero-one integer nonlinear programming problem. The solution methodology uses the concepts of relaxation, decomposition and network modelling to convert the 0 - 1 INLP problem to an equivalent 0 - 1 ILP problem of manageable size. Relaxation of resource constraints and the separable nature of the relaxed problem enables further decomposition of the 0 - 1 INLP problem into smaller independent subproblems. These subproblems are modelled as longest path network problems, and a combination of best and worst can be evaluated for each subproblem. The solutions to all subproblems are synthesized by using a 0 - 1 ILP formulation and a good

feasible solution is determined. The solutions evaluated for a subproblem form a subset of the total solutions to each subproblem, and hence the region of investigation for the 0 - 1 ILP problem is a subset of the region for the 0 - 1 INLP problem. In other words, the 0 - 1 ILP problem is a restriction of the 0 - 1 INLP problem. Thus, the optimality of the solution depends upon the region of investigation, and only 'near' optimality can be guaranteed for this solution methodology.

A computer program was developed for the 0 - 1 INLP algorithm. The program consists of two separate sections; one to generate and solve network models for subproblems and the second to solve the 0 - 1 ILP problem. An overlay structure was used to reduce core requirements. The program can solve problems with up to 100 projects, 10 alternatives and 10 time periods and uses 512K of core memory. The size of network models for subproblems is limited to 3000 nodes; 5000 arcs. The number of resource constraints is limited to 500, or an average of 49 constraints in each time period.

The computer program; the user's guide and example problems are given in Texas Transportation Institute Research Report No. 239 - 3 (14).

Tari (4) and Phillips developed an algorithm for solving separable non-linear, multi-dimensional knapsack problems. The algorithm is called a "hybrid algorithm", and it is essentially a dynamic programming approach in the sense that the problem is divided into smaller subproblems. However, the idea of fathoming the partial solution by branch and bound is incorporated within the algorithm. The main feature of the hybrid algorithm is its capability of reducing the state-space which otherwise would render dynamic programming solution techniques intractable in solving multiple-constraint dynamic programming problems. Part of this reduction is due to

the use of Morin and Marstens (9) imbedded-state approach, which reduces an M-dimensional dynamic program to a one-dimensional problem. Other reductions are made through fathoming the state-space and subsequent elimination of state-space regions, which tend to eliminate inferior solutions compared to the predetermined lower bound or updated lower bound (10).

The use of a surrogate constraint methodology (5) is implemented in the algorithm to obtain initial lower and upper bounds for the objective function. At each stage, the lower and upper bounds are also updated by use of a surrogated problem, and the updated upper bound will be used for termination criteria. The procedure for updating lower and upper bounds in the surrogated problem is very efficient. In addition, the primary advantages of using the surrogate problem to estimate these bounds, are (1) it provides a narrow range between the lower and upper bound, (2) it may provide the optimal solution to the problem at the first step.

A modification of the hybrid algorithm has been developed for application to large scale nonlinear knapsack problems (NKP's). However, the modified algorithm, though computationally much faster, may not provide an optimal solution to some problems, but will obtain a near-optimal solution. The modified algorithm follows roughly the same procedure as the hybrid algorithm. However, instead of evaluating all promising solution spaces, it attempts only to improve the lower bound calculated by the surrogated problem.

The hybrid algorithm and its modified version are used to solve the state optimization model (RAMS-SOFA-2). The computer program, user's guide and examples are presented in Texas Transportation Institute Research Report No. 239 - 2 (13).

The solution procedure employed to determine the optimal solution to the district fund allocation program. RAMS-D0-2 is the same as that of the state fund allocation program RAMS-SOFA-2.

CHAPTER V

TASK IV: ANALYSIS OF SOLUTION

Task IV of strategic planning is the analysis of the solution. The mathematical models assembled in Task II are solved in Task III. However, before we analyze the solution it will be appropriate to look into what the models are optimizing (Maximizing). The objective is to maximize benefit. Benefit is defined earlier in terms of the increase in the effectiveness of a road segment for all distress types after application of a particular maintenance strategy. Should it include passenger vehicles - miles and truck ton - miles? In the viewpoint of a direct user (who operates a vehicle) of highways, measuring benefit in terms of passenger vehicle - miles and truck ton - miles may seem suitable. But, it will be hard to measure. So also, putting a monetary value on the benefits does not seem easy; benefits of having a good highway system are tangible and intangible. Hence, benefit, defined as the difference between what the pavements should deliver with or without the envisioned rehabilitation or maintenance strategy.

The planning process begins at the district level. Selected pavement segments are inspected and the condition survey data are key punched. The validated corrected (RAMS-DCV) condition data are sent to the state authorities, who utilizing the RAMS-SCE program will determine the approximate rehabilitation and maintenance selection and the schedule for the next pavement inspection for each and every district. The lower and upper limits on the district budgets are determined by the state and the information is sent back to the appropriate districts. Using the RAMS-DO-1 program, each district determines the optimal rehabilitation and maintenance strategies for one year and the benefits for different budget levels between the lower and upper limits on

the budget specified by the state. However, constraints on resource availability and pavement rating requirements may be too binding to obtain a feasible solution. When this is the case, a management decision is required to increase the availability of specific types of resources, e.g., material, equipment-days, district budget and betterment budget; and/or decrease the rating requirement of specific highway segments. After the reformulation of the resource availability and/or pavement rating requirement constraints, the appropriate solution method is applied to the revised mathematical model. The problem feasibility is checked again. When infeasible, the procedure mentioned above is iterated until a feasible solution is reached. The computed results must be examined carefully by the maintenance engineer and top management. If unacceptable, it is necessary to go back to Task I of the strategic planning to reevaluate and readjust the problem analysis and data collection. When every district determines an optimal solution, the benefits for various budget levels in each district are sent back to the state from all the districts. Using this information, the state determines (RAMS-SOFA-1) the optimum budget level at each district which maximizes the state-level benefit with the available state budget. The RAMS-SOFA-2 will aid the state in determining the statewide strategy and fund allocation on Interstate and spine networks district by district. The above information is transferred back to the districts which in turn utilizes RAMS-DO-2 program to determine the fund allocation to the residences

The system is capable of accepting social and political mandates from management, if they are deemed necessary. Political pressure may force a minimum level of funds to be allocated to any one district or an upper limit on maintenance funds on any one district. Besides, it may force maintenance on any particular highway segment(s), to keep that highway at a

high quality level or may force utilization of any resource on a chosen job. These mandates may or may not result in sub-optimal allocation of funds; but, the system will optimally allocate funds remaining after such mandates are considered.

The system is also capable of keeping the relative distress ratings among districts within defined limits set by the central office.

Finally, utilizing the RAMS-DT0-1 program individual districts may determine the funds required for every year of a finite (5, 10 or 15 years) planning horizon , maintain the road segments at a certain pavement quality. This in turn will help the state to assess the needs and requirements in planning the rehabilitation and maintenance of highways in the state in future years.

CHAPTER VI

CONCLUSIONS

This report has summarized five different optimization models for highway rehabilitation and maintenance. The combined and sequential use of the RAMS-DCV program and the RAMS-SCE program with the optimization models will enable maintenance management to allocate money, men, machinery, and materials to the various districts of a state in an optimal way. It will also help in planning rehabilitation and maintenance work on the pavement for a given planning horizon. Although these models were developed specifically for the Texas State Department of Highways and Public Transportation, the models and the computer programs can be adapted by any highway administration for its own needs.

It can be concluded that the RAMS system will work, since all the mathematical formulations are robust models; but it should be added that the programs need to be run using real data.

The five optimization models presented are: zero-one integer linear programming, zero-one integer nonlinear programming, and dynamic programming formulations. Even though these models differ from one another in formulation and in the solution technique employed, they can use similar data sets as input. This will greatly reduce the efforts required to prepare data sets for the different models on the part of the users of the programs.

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