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16. Abstract

This report described in detail the rehabilitation and maintenance optimization system (RAMS) that has been developed for use by District offices in the state of Texas. The procedure involves the use of a computer program which is completely documented, including a User's Guide, in this report. The input data that are required include the current condition rating of all segments of the District's roadway network which are considered to be candidates for rehabilitation or maintenance work each year. The program uses an integer programming technique devised by Toyoda and Senju and adapted to this use at Texas Transportation Institute. Examples problems are worked to compare the results using this method with those of another procedures, including the continuous linear variable technique used in linear programming, and the intuitive procedure currently being used by the Texas State Department of Highways and Public Transportation. The results show that there is a distinct advantage to using the proposed method.

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by

N. V. Ahmed
D. Y. Lu
R. L. Lytton
J. P. Mahoney
D. T. Phillips

Research Report Number 207-3

Flexible Pavement Evaluation and Rehabilitation

Research Project 2-8-75-207

conducted for

The Texas State Department of Highways and
Public Transportation

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

Texas Transportation Institute
Texas A&M University

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ABSTRACT

This report describes in detail the rehabilitation and maintenance optimization system (RAMS) that has been developed for use by District offices in the state of Texas. The procedure involves the use of a computer program which is completely documented, including a User's Guide, in this report. The input data that are required include the current condition rating of all segments of the District's roadway network which are considered to be candidates for rehabilitation or maintenance work each year. The program uses an integer programming technique devised by Toyoda and Senju and adapted to this use at Texas Transportation Institute. Example problems are worked to compare the results using this method with those of other procedures, including the continuous linear variable technique used in linear programming, and the intuitive procedure currently being used by the Texas State Department of Highways and Public Transportation. The results show that there is a distinct advantage to using the proposed method.

SUMMARY

This report describes a complete District maintenance and rehabilitation management planning and control system, and includes a detailed description of the Texas rehabilitation and maintenance system (RAMS) which has been developed at Texas Transportation Institute to assist District offices in optimally allocating the construction, safety and betterment, RRR, and other funds which are intended to keep the quality of service of Texas highways at an acceptable level.

The description of the computer program includes a user's guide, an example problem using actual Texas pavement condition and cost data, and appendices which explain the integer programming algorithm used in the RAMS program, as well as of all of the input data used in the example problem. The results achieved by using the program are compared with the result of using other techniques for allocating funds. The RAMS method is shown to be superior to all other methods.

The analysis of the optimal fund allocation problem for pavement maintenance and rehabilitation shows how "benefit" is described mathematically for use in the computer program.

Previous use of these mathematical optimization integer programming methods, together with known wear-out rates of machine parts in manufacturing industries, has resulted in maintenance budget savings of 10-25 percent. The example problem worked in this report shows that such savings are possible in the field of pavement maintenance and rehabilitation as well.

IMPLEMENTATION STATEMENT

This report gives details of the Texas Rehabilitation and Maintenance System (RAMS), a computer program which has been developed for use by District offices in the state of Texas in optimally allocating pavement maintenance and rehabilitation funds and establishing priorities. The report is intended as a working document which can be used by implementation workshops to train Texas SDHPT personnel in the use of the RAMS program.

DISCLAIMER

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CHAPTER 1

INTRODUCTION

Public demands for higher levels of pavement quality are expected to increase exponentially in the near future, especially when the interstate highway system begins to require extensive repairs. The estimate of the total expenditures on highway pavement structural maintenance may run as high as billions of dollars per year for all the U.S. roads. Funding for highway maintenance operations can be expected to become more stringently controlled in the future. In addition, highway management decisions will be greatly affected by new social attitudes toward the use of scarce natural resources, environmental impact and human responses, values, and preferences. It has been recognized that strategic planning for the optimal allocation of limited resources will result in a significant amount of economic saving. Thus, a systematic methodology is urgently needed to establish priorities for the optimal investment of available resources while satisfying the demands of the public for quality highway pavements. Moreover, the use of analytical techniques for the determination of optimal resource allocation policies for a given highway system can identify maintenance practices that can potentially gain money by using the money more effectively.

Management scientists have developed many mathematical models for resource allocation optimization. In operations research, resource allocation problems can usually be formulated in two alternative optimization schemes: (1) to maximize the overall effectiveness subject to limited resources, or (2) to minimize the use of resources subject to minimum requirements of effectiveness. The former scheme is adopted herein for the system development since the current maintenance budget systems seem more consistent with maximizing effectiveness rather than minimizing the use of resources. However, the conversion from the one formulation to the other can easily be accomplished. In addition, the methodology based on zero-one integer linear programming techniques appears to be readily applicable to the resource allocation of a highway maintenance system.

This report presents basic concepts required for the development of a comprehensive pavement rehabilitation and maintenance management system. A conceptual model based on the zero-one integer linear programming algorithm is presented. Special emphases have been placed upon the following areas: (1) evaluation and rating of the condition of current pavement distress, (2) demands for pavement performance and service life, (3) effectiveness of different maintenance strategies and pavement maintenance survival rates, (4) requirements and availability of materials, supplies, equipment, manpower and overhead costs for pavement maintenance and rehabilitation, and (5) various budgetary constraints.

Management Planning and Control System

The pavement maintenance and management system can be organized within a framework of analysis as shown in Figure 1. The complete management function of planning and control involves an integration of three processes: strategic planning, management control and operational control. The three processes are complementary and obviously cannot be separated by sharply defined boundaries; one shades into another. Strategic planning is based on the policies and guidelines prescribed by top management. Strategic planning sets the guidelines for management control, and management control sets the guidelines for operational control. Definitions of these processes proposed by Anthony et al. (2, 3) are the following.

> *Strategic Planning* - the process of deciding on the objectives of the organization, on changes in these objectives, on the resources used to attain these objectives, and on the policies that are to govern the acquisition, use, and disposition of these resources.
>
> *Management Control* - the process by which managers assure that resources are obtained and used effectively and efficiently in the accomplishment of the organization's objectives.
>
> *Operational Control* - the process of assuring that specific tasks are carried out effectively and efficiently.

These are three essential activities which provide the necessary data for planning and control: financial accounting, reporting on operating conditions, and processing the information. Examples of each are given below:

> Financial accounting - determining budgetary constraints.
>
> Operating information - determining the current distressed condition of all of the pavements in a given roadway network and the equipment, supplies, and manpower available to perform needed maintenance and rehabilitation work.
>
> Information processing - organizing all of the financial and operating information in a form that is useful for the planning and control function.

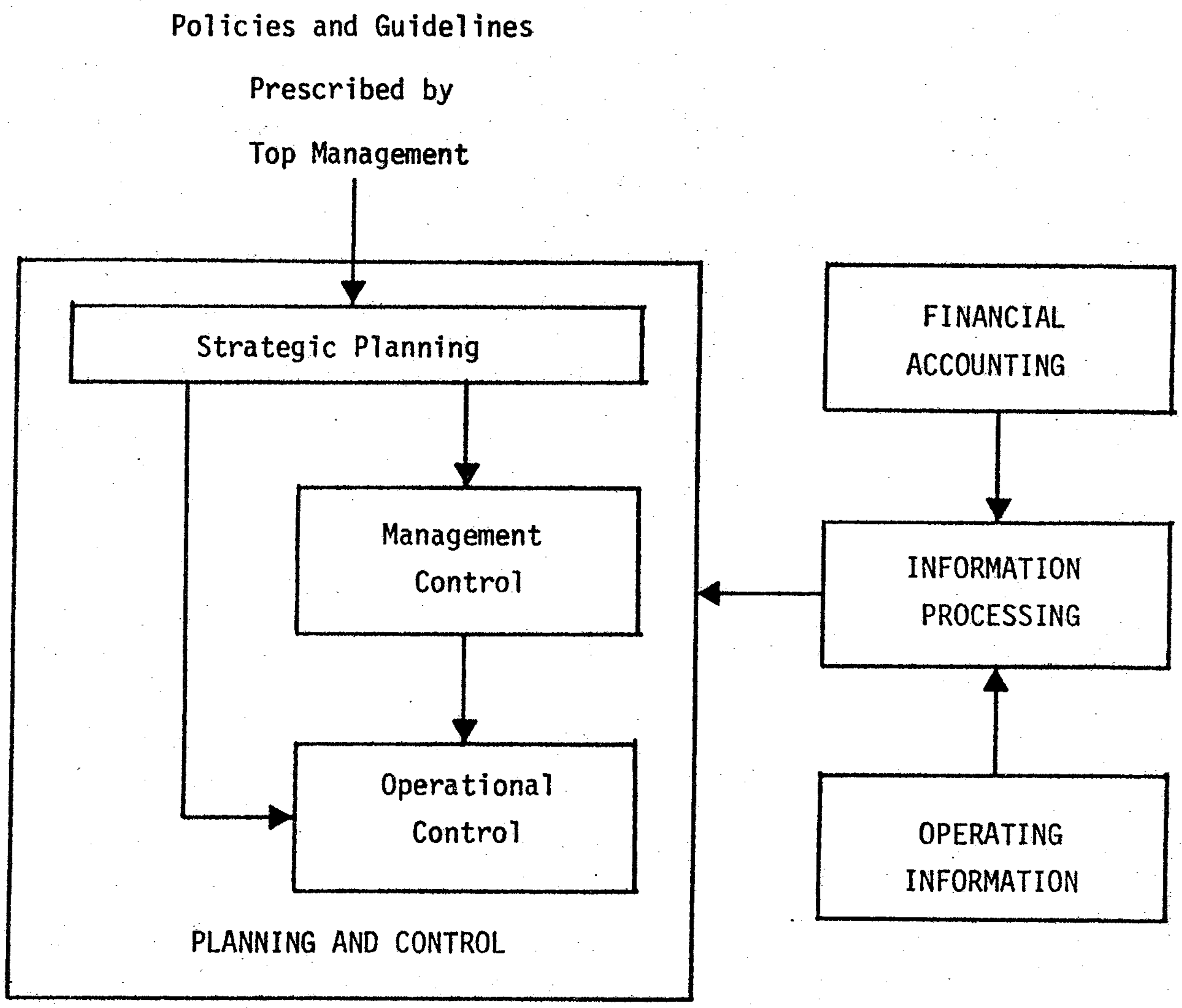


Figure 1. Management planning and control processes

In pavement maintenace management, strategic planning for resource allocation at the District highway department level is based on the policies and guidelines prescribed by the federal and state transportation administrations. The objective at the District level is to maximize the total effectiveness of all maintenance and rehabilitation activities scheduled for the next year. Strategic planning is essentially built around a financial structure in order to provide the most cost effective decisions on maintenance strategies so that all highway segments within the District can be maintained above a specified level of serviceability for normal driving. Guidelines set by strategic planning will eventually be carried out by District engineers for management control and construction foremen for operational control.

A strategic planning scheme for pavement maintenance and management has been developed as shown in Figure 2. The figure illustrates the usual phases of a management system as applied to pavement maintenance and rehabilitation. The three phases are as follows: (1) problem analysis and data collection. (2) formulation of the mathematical model, (3) optimization and analysis of solution.

The next several sections of this report will describe in some detail each of these phases. It should be noted that the verbs in Figure 2 have been chosen carefully to indicate the kind of activity envisioned in each subtask. Roughly, they are taken to mean the following:

Determine - make a policy decision

Find out - collect information

Evaluate - judge the current condition

Predict - estimate using a mathematical model

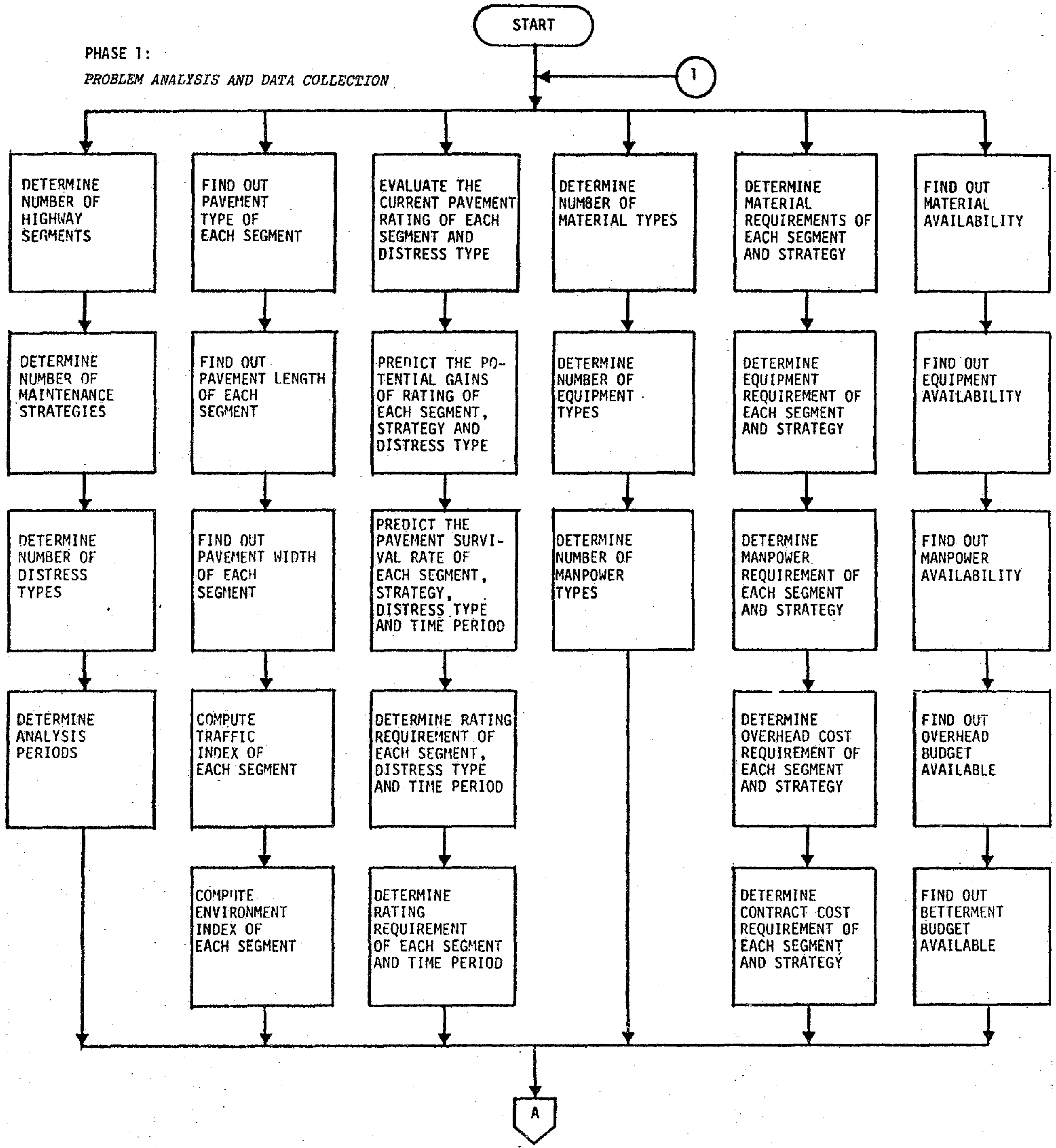


Figure 2: Strategic planning scheme for pavement maintenance and management

PHASE 2:

FORMULATION OF MATHEMATICAL MODEL

PHASE 3:

OPTIMIZATION

AND

ANALYSIS OF SOLUTION

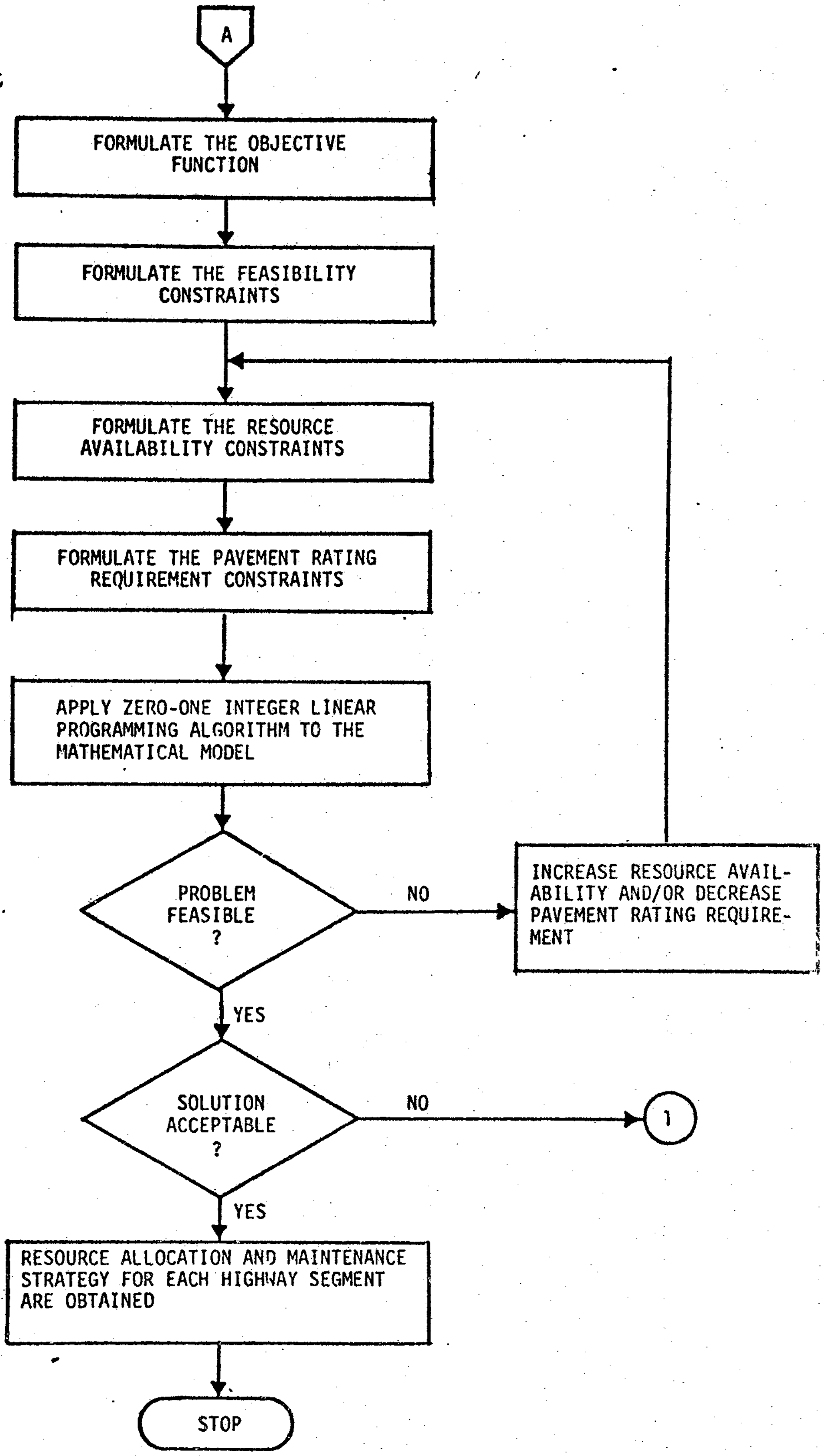


Figure 2: (Continued)

Formulate - devise mathematical models

Apply - use an existing method

CHAPTER II

PHASE 1: PROBLEM ANALYSIS AND DATA COLLECTION

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

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.

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 unity must be very similar if not identical. Then the strategic planning system will select an optimal maintenance strategy for each unity, that is, each highway segment specified by the decision-maker. Highway sections which are expected to provide acceptable serviceability and require no maintenance during the next year need not be included in the scope of the study.

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 mathematical programming of the problem. Consequently, the current list has been restricted to eleven rehabilitation and maintenance strategies, from strip seal to reconstruction, which are shown herein for illustration: (1) strip seal, (2) fog seal, (3) seal coat, (4) light patching and seal coat, (5) extensive patching and seal coat, (6) seal coat and planned thin overlay, (7) plant mix seal or open graded friction course, (8) thin overlay, less than 2 inches asphalt concrete, (9) moderately heavy overlay, 2 to 3 inches asphalt concrete, (10) heavy overlay, 3 to 6 inches asphalt concrete and (11) reconstruction. These strategies are listed in order of increasing unit cost. Usually, strategies 1-4, as shown above, are funded from the state maintenance budget. Funding for strategies 5-8 is either from state maintenance budget or from the betterment budget. Strategies 9-11 are funded from the betterment budget as contract work.

Pavement Distress. Usually, pavement distress manifestations can be categorized into the following nine types: (1) rutting, (2) ravelling, (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 (6, 8, 12, 23).

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 is necessary to analyze the pavement survival rates over a specified time period. An analysis period should be selected to be longer than the expected life of any maintenance or rehabilitation method, including reconstruction.

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. 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.

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 organized into a roadway inventory matrix as shown in Figure 3. Traffic and environmental indexes shown in that figure are multiplying factors which increase with traffic and climatic conditions that accelerate the appearance of various forms of distress. The formulation of these two indexes will be discussed subsequently.

Pavement Condition

The pavement condition can be analyzed in the following aspects:

(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 maintenance 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

	HIGHWAY SEGMENT NUMBER						
	1	2	3	...	...	...	N_H
PAVEMENT TYPE							
PAVEMENT LENGTH							
PAVEMENT WIDTH							
TRAFFIC INDEX							
ENVIRONMENT INDEX							

N_H - the total number of highway segments in analysis.

Figure 3. Roadway inventory matrix

Table 1: Deduct Values for Flexible Pavement

Type of Distress	Degrees of Distress	Extent or Amount of Distress (1)	(2)	(3)
Rutting	Slight	0	2	5
	Moderate	5	7	10
	Severe	10	12	15
Raveling	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Flushing	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Corrugations	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Alligator Cracking	Slight	5	10	15
	Moderate	10	15	20
	Severe	15	20	25
Patching	Good	0	2	5
	Fair	5	7	10
	Poor	7	15	20

Deduct Points for Cracking

Longitudinal Cracking

	Sealed (1)	(2)	(3)	Partially Sealed (1)	(2)	(3)	Not Sealed (1)	(2)	(3)
Slight	2	5	8	3	7	12	5	10	15
Moderate	5	8	10	7	12	15	10	15	20
Severe	8	10	15	12	15	20	15	20	25

Transverse Cracking

	Sealed (1)	(2)	(3)	Partially Sealed (1)	(2)	(3)	Not Sealed (1)	(2)	(3)
Slight	2	5	8	3	7	10	3	7	12
Moderate	5	8	10	7	10	15	7	12	15
Severe	8	10	15	10	15	20	12	15	20

Failures				20		30		40
Mays Meter	Deduct Points	50	40	30	20	10	5	0
	SI	2.4	2.7	2.9	3.1	3.3	3.5	4.7

FOREMAN NO.				
HIGHWAY CLASS				
COUNTY NO.				LOCATION
HIGHWAY NO.				
CONTROL				
SECTION				
FROM				
TO				
LANE				
MAYS METER				PAVEMENT
SLIGHT / MODERATE / SEVERE	① 1-15 ② 16-30 ③ > 30	% AREA	RUTTING	
SLIGHT / MODERATE / SEVERE	① 1-15 ② 16-30 ③ > 30	% AREA	RAVELING	
SLIGHT / MODERATE / SEVERE	① 1-15 ② 16-30 ③ > 30	% AREA	FLUSHING	
SLIGHT / MODERATE / SEVERE	① 1-15 ② 16-30 ③ > 30	% AREA	CORRUGATIONS	
SLIGHT / MODERATE / SEVERE	① 1-5 ② 6-25 ③ > 25	% AREA	ALLIGATOR CRACKING	
SLIGHT / MODERATE / SEVERE	① 10-99 ② 100-199 ③ >200	LIN FT PER STA/LN	LONGITUDINAL CRACKING	
SLIGHT / MODERATE / SEVERE	① 1-4 ② 5-9 ③ >10	NO PER STA	TRANSVERSE CRACKING	
CRACKS (1) SEALED (2) PARTIALLY SEALED (3) NOT SEALED				
GOOD / FAIR / POOR	① 1-5 ② 6-15 ③ > 16	% AREA	PATCHING	
(1) 1-5 (2) 6-10 (3) >10		FAILURES / MILE		
RIDE / CONTRAST / PAVEMENT EDGE / SHOULDER EDGE / CRACKS / RAVELING / VEGETATION			PAVED	SHOULDER
PAVEMENT EDGE / RUTTING, CORRUGATIONS, LOOSE ROCK			UNPAVED	
LITTER / MOWING / VEGETATION / SLOPE EROSION			ROADSIDE AND DRAINAGE	
CULVERTS / DITCHES, OUTFALL, CHANNELS / ROADSIDE DRAINAGE				
GUARDRAILS / SIGNS / DELINEATORS / STRIPING / AUXILIARY MARKINGS			TRAFFIC SERVICE	
OTHER				

DISTRICT NO.	1
RATERS	5 – 28
DATE	MONTH 30 – 51
	60 DAY 65
	YEAR 70

Figure 4. Maintenance Rating Form for Flexible Pavements

(5) the rating requirement of each segment and time period.

Current Pavement Condition Rating. Several pavement condition rating systems which are currently in use (6, 8, 12, 23) are readily applicable to the resource allocation model developed herein. Table 1 and Figure 4 show the rating system which is currently being implemented in Texas (4). Using such a rating system, a current pavement condition rating matrix as shown in Figure 5 can be filled out based on the rating of each highway segment and each distress type.

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 kind of distress cannot exceed the amount of rating that it lost by that form of distress as shown in Table 1. A gain-of-rating matrix as shown in Figure 6 is devised for each highway segment. When the number of segments gets 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 reduce the pavement ratings of certain distress types. An an example, seal coating does not improve rutting, and a fog seal may accentuate flushing. In these cases, a zero or negative gain-of-rating will be required.

Pavement Survival Rate. Figure 7 shows a pavement survival matrix which contains the survival probability of each highway segment, for each distress type and maintenance strategy over the analysis period. 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. For instance,

		HIGHWAY SEGMENT NUMBER						
		1	2	3	...	...	...	N_H
DISTRESS TYPE	1							
	2							
	3							
	...							
	...							
	N_D							

N_H - the total number of highway segments in analysis.

N_D - the total number of distress types.

Figure 5. Current pavement condition rating matrix

		DISTRESS TYPE						
		1	2	3	...	...	...	N_D
MAINTENANCE STRATEGY	1	12	10	8				10
	2	10	10	7				8
	3	8	10	6				6
	...							
	...							
	N_S	0	5	-4				-6

N_S - the total number of maintenance strategies

N_D - the total number of distress types.

Figure 6. Gain-of-rating matrix of each highway segment

		TIME AFTER MAINTENANCE						
		0	1	2	3	4	... ...	N_T
MAINTENANCE STRATEGIES	1	1.00	.90	.70	.40	0.0		
	2	1.00	.80	.50	.20	0.0		
	3	1.00	.60	.20	0.0			
	...							
	...							
	N_S	1.00	0.50	0.0				

N_S - the total number of maintenance strategies

N_T - the analysis period in years.

Figure 7. Pavement survival matrix of each highway segment and distress type.

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:

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

This example indicates that the pavement survival rate is 100% immediately after the maintenance work is accomplished, 90%, 70% and 40%, respectively, at the end of the first, second and third year and 0% at and after the end of the fourth year. Suppose the current rating of a specific distress type k is 5 and the gain of rating of distress type k is 15 if maintenance strategy j is applied, then the rating after the maintenance is done is 20. The rating drops to 18.5, 15.5, and 11, respectively, at the end of the first, second and third year. The rating will be back down to 5 after the end of the fourth year.

The maintenance effectiveness when strategy j is applied per unit surface area of highway segment i when distress type k is presented 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, at time t; and

N_T = number of years in analysis period.

To estimate the potential gains of rating of each highway segment can be a painstaking process for highway engineers. For instance, if 100 highway segments are considered in the analysis framework, the data for 100 gain-of-rating matrices as shown in Figure 6 must be assembled. This problem may be simplified by categorizing the existing pavements into several major types, e.g., (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 and an environment adjustment index to the basic matrix. The maintenance effectiveness can be rewritten as

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

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.

The master matrix of probability of pavement survival, P_{ijkt}, 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 and b_i, will always be 1 or greater. Thus an increase in a_i or b_i will represent increasingly heavier traffic loading or more severe environmental conditions and will reduce the probability of survival. This is shown in Figure 8.

Minimum Rating Requirement. Figure 9 illustrates a rating requirement matrix of each highway segment. Instructions for preparing the matrix are as follows:

1. For highway segment i and distress type k, the rating requirement $R_{ikt} = 0$ if $t \geq T_{ik}$. T_{ik} is the expected service life of the next year's maintenance activity of that highway segment and distress type, that is, another maintenance activity will be scheduled for highway segment i at or before time T_{ik}.
2. For highway segment i, the total rating requirement of all distress types $W_{it}=0$ if $t \geq T_i$. T_i is the expected service life of the next year's maintenance activity of highway segment i. Another maintenance activity will be scheduled for this segment at or before time T_i.
3. There are two alternatives to assign the pavement rating requirement. In Figure 10(a), the rating requirement remains unchanged with time. In Figure 10(b), the rating requirement increases with time due to increasing public demands for better highways and increasing traffic volumes. Figure 10 also shows the predicted pavement ratings of five different maintenance strategies. In Figure 10(a) strategies 3, 4, and 5 satisfy the rating requirement at service life, T. However, strategy 3 does not

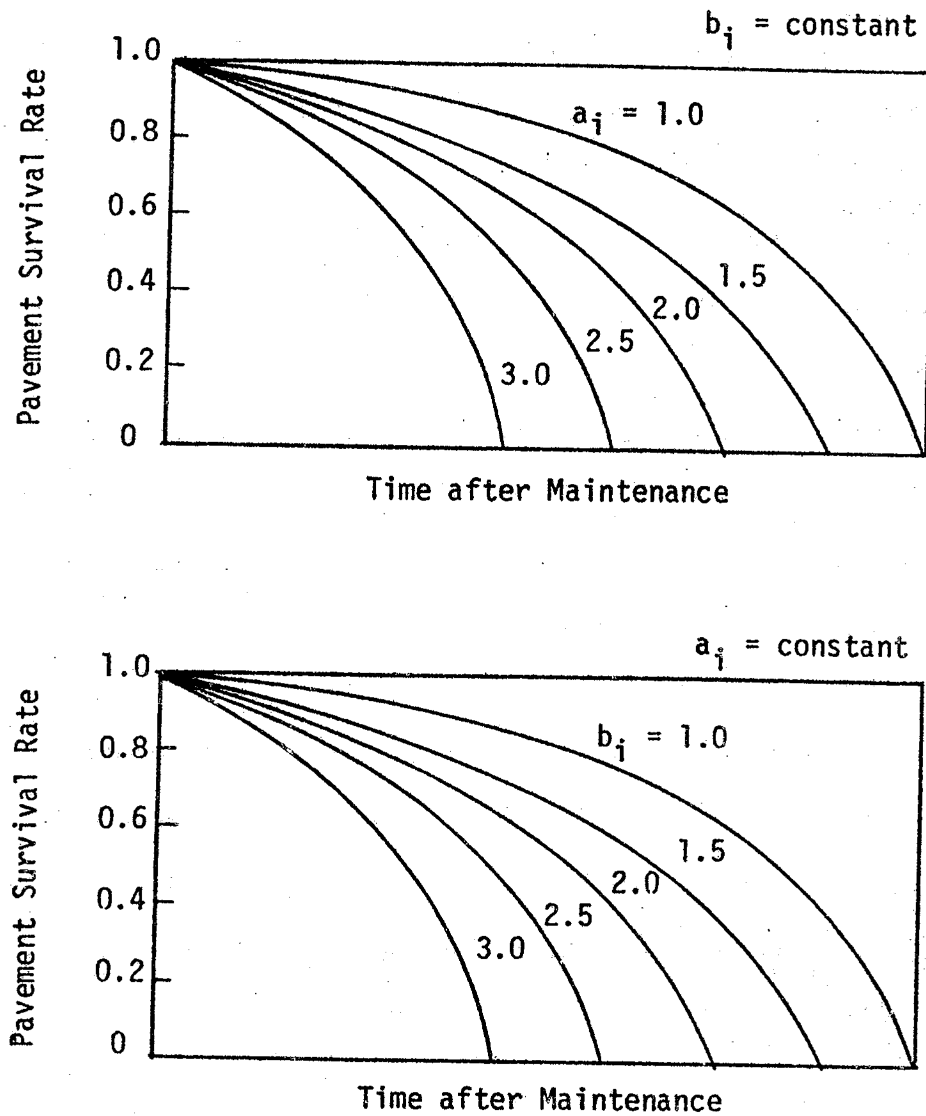


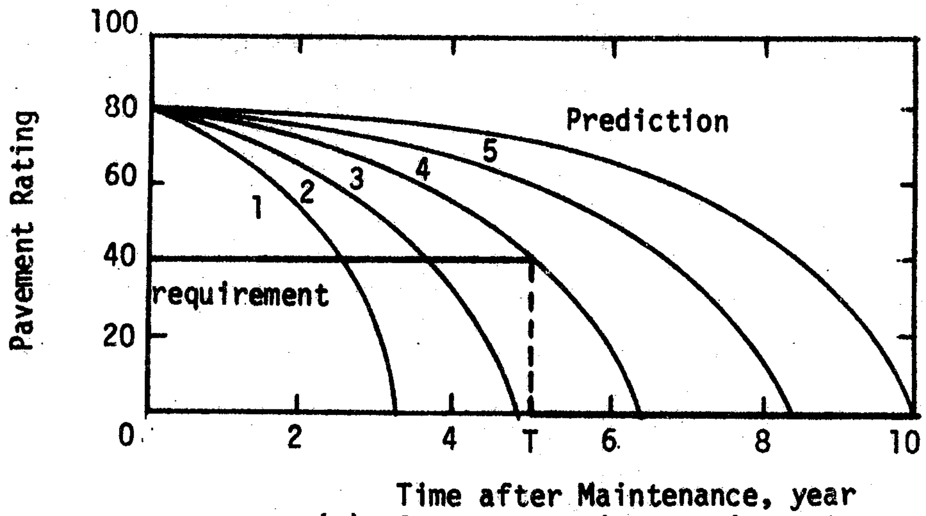
Figure 8. Effects of traffic and environmental adjustment indices

		TIME AFTER MAINTENANCE				
		0	1	2	... ...	N_T
DISTRESS TYPES	1					
	2					
	3					
	...					
	...					
	N_D					
TOTAL						

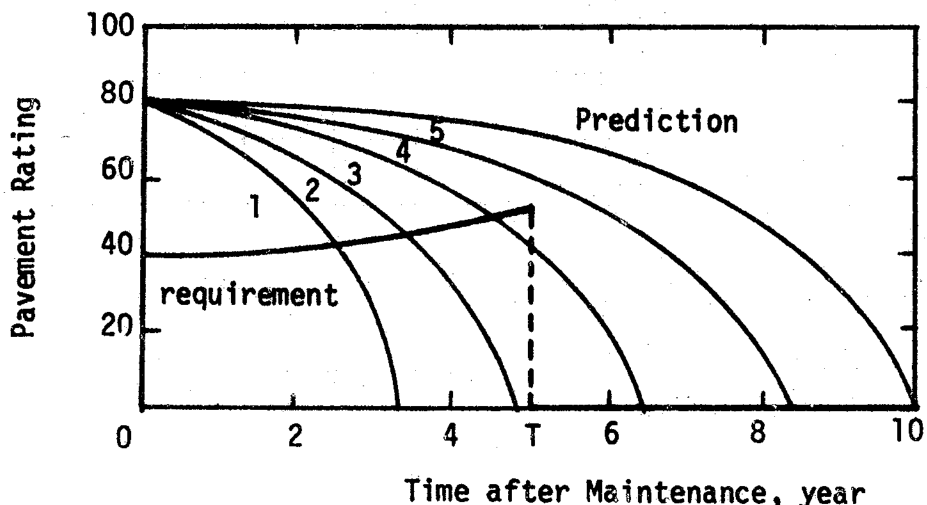
N_D - the total number of distress types.

N_T - the analysis period in years.

Figure 9. Minimum rating-requirement matrix of each highway segment



(a) Constant rating requirement



(b) Increasing rating requirement

Figure 10. Pavement rating history and requirement

satisfy the increasing requirement in Figure 10(b) at the same time.

4. The total rating requirement is not necessarily the sum of the rating requirements of all distress types. Usually, for highway segment i, and at time t,

$$W_{it} > \sum_{k=1}^{N_D} R_{ikt}$$

where N_D is the total number of distress types in the analysis. The constraint of total rating requirement is unnecessary if

$$W_{it} \geq \sum_{k=1}^{N_D} Rikt$$

Resource Information

The resource allocation scheme described below is especially devised for 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) manpower, (4) district overhead cost and (5) betterment budget for contract work. 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 matrices shown in Figure 11. This unusual unit area measurement is to allow segment lengths to be recorded in miles and pavement widths recorded in feet. The numbers entered into the materials requirement matrix are in units that are consistent with the way the material is ordinarily measured, for instance, pounds, tons or cubic feet of material per one-mile-long and one-foot-wide unit surface area. The requirements for equipment and manpower can be represented, respectively, by equipment-days and manpower-days per unit surface area as mentioned before. The overhead and betterment costs use monetary terms as dollars per unit surface area.

Figure 12 illustrates the resource-availability matrices should be consistent with the units used in the respective columns of the resource-requirement matrices. Resource-availability matrices show the quantities of all of the materials available for maintenance and rehabilitation activities. These inventories should be updated each time a new resource allocation decision is to be made.

		MATERIAL TYPE				
		1	2	3	... ...	N_G
MAINTENANCE STRATEGY	1					
	2					
	3					
	...					
	N_S					

(a) Material-requirement matrix

		EQUIPMENT TYPE				
		1	2	3	... ...	N_F
MAINTENANCE STRATEGY	1					
	2					
	3					
	...					
	N_S					

(b) Equipment-requirement matrix

		MANPOWER TYPE				
		1	2	3	... ...	N_Q
MAINTENANCE STRATEGY	1					
	2					
	3					
	...					
	N_S					

(c) Manpower-requirement matrix

		OVERHEAD COST
MAINTENANCE STRATEGY	1	
	2	
	3	
	...	
	N_S	

(d) Overhead-cost-requirement matrix

		BETTERMENT COST
MAINTENANCE STRATEGY	1	
	2	
	3	
	...	
	N_S	

(e) Betterment-cost-requirement matrix

N_S - the total number of maintenance strategies.

N_G - the total number of material types.

N_F - the total number of equipment types.

N_Q - the total number of manpower types.

Figure 11. Resource-requirement matrices of each highway segment

	MATERIAL TYPE					
	1	2	3	...	...	N_G
AVAILIBILITY						

(a) Material-availibility matrix

	EQUIPMENT TYPE					
	1	2	3	...	...	N_G
AVAILIBILITY						

(b) Equipment availibility matrix

	MANPOWER TYPE					
	1	2	3	...	...	N_Q
AVAILIBILITY						

(c) Manpower-availability matrix

	OVERHEAD BUDGET
AVAILIBILITY	

(d) Overhead-budget-availibility matrix

	BETTERMENT BUDGET
AVAILIBILITY	

(e) Betterment-budget-availability matrix

N_G - the total number of material types.

N_F - the total number of equipment types.

N_Q - the total number of manpower types.

Figure 12. Resource-availability matrices for all highway segments

CHAPTER III

PHASE 2. MATHEMATICAL MODEL

Formulation of the Highway Pavement Problem

The objective of the 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 of pavement quality and service life. Mathematically, the problem as formulated by Lu and Lytton (5) is as follows:

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

subject to

multiple choice decision variable constraints,

$$\sum_{j=1}^{N_S} x_{ij} \leq 1 \qquad i = 1,2,3,\ldots,N_H \qquad (2)$$

material availability constraint,

$$\sum_{i=1}^{N_H} \sum_{j=1}^{N_S} S_{ijg} L_{1i} L_{2i} x_{ij} \leq S_g \quad g = 1,2,\ldots,N_G \tag{3}$$

equipment availability constraint,

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

manpower availability constraint,

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

available overhead constraint,

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

minimum rating requirement constraint,

$$cr_{ik} + \sum_{j=1}^{N_S} d_{ijk} P_{ijkt} x_{ij} \geq R_{ikt} \quad \begin{array}{l} i = 1,2,\ldots,N_H \\ k = 1,2,\ldots,N_D \\ t = 0,1,\ldots,N_T \end{array} \tag{7}$$

overall pavement rating requirement constraint.

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

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 Highway Pavement 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 maintenance operations are planned by highway districts rather than the entire state as a single unit, and funds are allocated by districts.

In an average subsystem the number of highway segments may be 300 and on the average there may be 15 strategies per segment. Hence there are typically around 300 x 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 300 multiple-choice constraints, one for each highway segment. The number of minimum rating requirement constraints and the overall rating requirement constraints 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 overall system (subsystem) efficiency. Hence, an average size problem may consist of 4500 0-1 variables, 60 to 70 resource constraints, 300 multiple-choice constraints, and several hundred minimum and overall pavement rating constraints. For the current state of the art in 0-1 integer linear programming, the above problem is considered to be very large and indeed formidable.

CHAPTER IV

PHASE 3. OPTIMIZATION AND ANALYSIS OF SOLUTION

Optimizing the maintenance strategies for a large number of highway segments with numerous strategies, resources and feasibility constraints exceeds the capacity of current state of the art of integer programming. A special algorithm (solution technique) is developed in this report to solve for large-scale problems as are encountered in the optimization of highway maintenance operations. The concept utilized in the development of this algorithm is termed effective gradient. The idea of effective gradient is briefly described in the following section. The detailed algorithmic development to solve large-scale 0-1 integer programming problem is presented in Appendix A. In Appendix B the documentation of the RAMS (Rehabilitation and Maintenance) program is presented with an example.

Effective Gradient Method

Consider a simple example by using five highway segments. The data for these highway segments comes from a larger, more realistic problem which will be discussed later. The goal of this short example is to demonstrate by use of the effective gradient method how the five segments can be maintained optimally. For simplicity it is assumed that only one maintenance strategy and two resources are needed. The maintenance strategy chosen in reconstruction and the two resources are the amount of budget and materials available to accomplish the work. The RAMS problem presented later actually considers six maintenance strategies and the resources of materials, equipment, manpower, and budget.

Table 2 shows a listing of the five segments (designated H_1, H_2, ..., H_5) and the percentage of the total resources used for each. These segments correspond to the last five segments shown in Table 5. The maintenance strategy that is considered is reconstruction with a total available budget of $300,000. The cost to reconstruct each segment was obtained by multiplying the length and width by the cost per unit area. The percentage of materials required by each segment was assumed to approximate the percentage of the budget consumed. The total required for each resource is shown and is the sum of the individual percentages for each highway segment. For the budget resource, the total required is larger than the available budget by a factor of 2.85. A similar situation occurs for the material resource.

Maintenance effectiveness is also shown in Table 2 and is computed from the objective function in Equation 1. Thus, the maintenance effectiveness is obtained by multiplying together the length, width, gain-of-rating for each distress, and the sum of the survival probabilities (gain-of-rating and survival probabilities will be discussed in more detail later in the paper). The maintenance effectiveness would be greater for highly distressed pavements as opposed to nondistressed pavements of equal length and width. Highway segment H_5 will be used to demonstrate how maintenance effectiveness is computed. For H_5:

1. Length = 7.444 mi (11.980 km)
2. Width = 20 ft (6.1m)
3. Gain-of-rating points for reconstruction for distress types present on roadway:

Table 2. Resource Requirements for Five Highway Segments

Highway Segment	Percent of Total Available Budget Resource Used	Percent of Total Available Material Resource Used	Maintenance Effectiveness
H_1	74	70	6507
H_2	46	45	4072
H_3	76	70	3863
H_4	42	40	78,109
H_5	47	50	78,355
Total Required	285	275	170,906
Total Available (Limit)	100	100	
Extra Resource Required	185	175	

Total Available Budget = $300,000

Distress type		Maximum Points Available		Current Condition Rating		Gain-of-Rating
(a) Rutting	=	15	-	10	=	5
(b) Alligator cracking	=	25	-	10	=	15
(c) Longitudinal cracking	=	25	-	10	=	15
(d) Transverse cracking	=	20	-	8	=	12
(e) Failures/mile	=	40	-	20	=	20

4. Probability of survival for reconstruction summed over ten years for distress types present on roadway:

   (a) Rutting = 7.97

   (b) Alligator cracking = 6.86

   (c) Longitudinal cracking = 9.25

   (d) Transverse cracking = 9.25

   (e) Failures/mile = 6.69

5. Maintenance effectiveness = $L_{15}L_{25} \sum_{i=1}^{1} \sum_{j=1}^{1} \sum_{k=1}^{5} \sum_{t=1}^{10} d_{ijk}P_{ijkt}$

   $= (7.444)(20)\{(5)(7.97) + (15)(9.25) + (12)(9.25) + (20)(6.69)\} = 78{,}355$

In Figure 13 the vectors $\overline{H}_1, \overline{H}_2, \ldots, \overline{H}_5$ are plotted as a function of the required resources for each highway segment, i.e., $\overline{H}_1$ denotes the amount of budget and materials required if reconstruction is done to this segment. The following vectors are defined:

Let $\overline{R}$ = resultant vector of all highway segments

$= \overline{H}_1 + \overline{H}_2 + \overline{H}_3 + \overline{H}_4 + \overline{H}_5$

$\overline{L}$ = limiting resources vector

= (100,100) in example

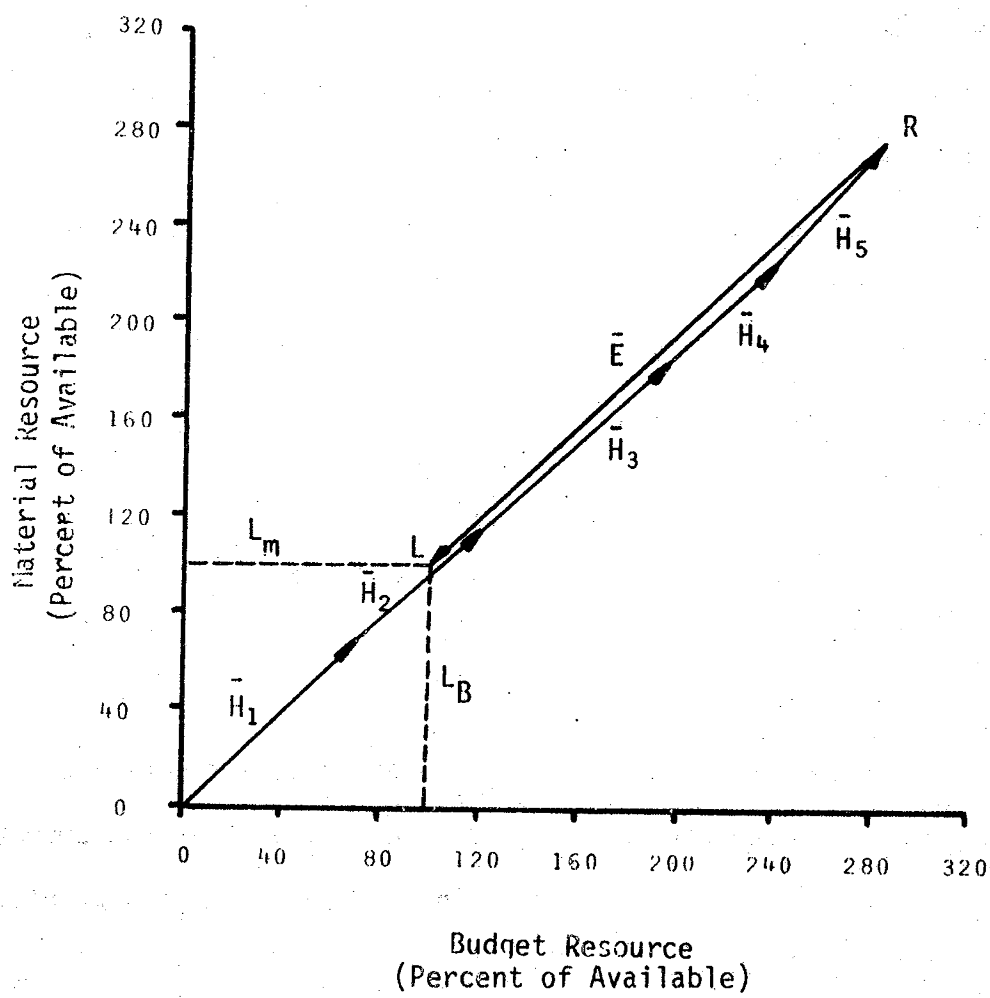


Figure 13. Vector Sum of Resource Requirements For Each Highway Segment

$\overline{E}$ = excess vector

$= \overline{R} - \overline{L} = (285,275) - (100,100) = (185,175)$

If enough resources are available to reconstruct all five highway segments, that is what should be done. Of course, this situation will rarely occur. Resources are generally scarce so maintenance cannot be applied to all the highway segments being considered. The maintenance should be applied to that combination of highway segments that maximize the overall maintenance effectiveness and satisfy the available resource restraints. Thus, some method must be used to determine which segments are dropped from consideration.

Figure 14 shows highway segment H_5 being dropped. This caused the point R to move in the general direction of L and 78,355 units of maintenance effectiveness is lost. Highway segment H_5's contribution toward moving back toward L (to satisfy the resource availability constraint requirement) is expressed by the projected length of vector $\overline{H}_5$ on the excess vector $\overline{E}$ (denoted by $\overline{A'R}$). The decision to drop a highway segment should be based on a comparison of maintenance effectiveness with the projected length on the vector $\overline{E}$. This comparison determines the "effective gradient" and is taken as the ratio of maintenance effectiveness for a highway segment to the projected length $\overline{A'R}$ for that highway segment. Phrased another way, effective gradient indicates which highway segments have the greatest maintenance effectiveness for the smallest amount of resources. Highway segments with small effective gradients are less desirable to schedule for maintenance than segments with large effective gradients. Therefore, the effective gradient for each segment is

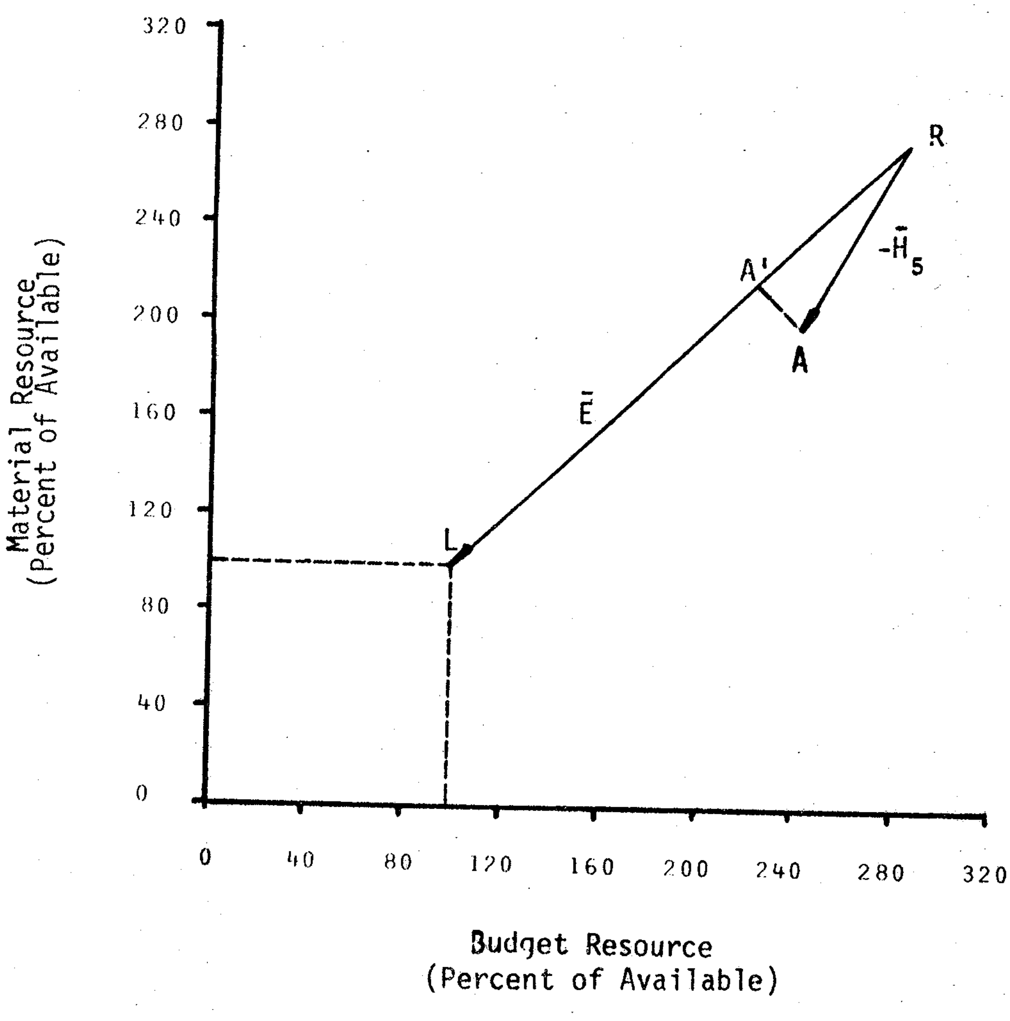


Figure 14. Effective Reduced Length For Highway Segment 5

is calculated and those segments with the smallest gradients are dropped until the availability resource constraints are satisfied.

The effective gradient for each highway segment is shown in Table 3. The following will demonstrate how the effective gradient is calculated. Let $\overline{U}$ stand for a unit vector parallel to $\overline{E}$ and with the same sense.

$$\overline{U} = \overline{E}/\ |\overline{E}|$$

and from the example

$$\overline{U} = \{185/(185^2 + 175^2)^{1/2},\ 175/(185^2 + 175^2)^{1/2}\}.$$

Let U_5 = projection of vector = $\overline{H}_5$ on vector - $\overline{U}$ where U_5 is given by the scalar product of vectors - $\overline{H}_5$ and -U

$$U_5 = -\overline{H}_5 \cdot -\overline{U} = (47)(185/(185^2 + 175^2)^{1/2}) + (50)(175/(185^2 + 175^2)^{1/2})$$

$$= 68.5.$$

Let G_5 = effective gradient of maintenance effectiveness

$$= \frac{\text{maintenance effectiveness}}{U_5}$$

$$= \frac{78,355}{68.5} = 1144$$

Similarly, the effective gradients for the other four highway segments were computed.

By using the ranked effective gradients, a choice of highway segments to be dropped can be made. The segments dropped are shown in Table 4. It can be seen that after dropping highway segments H_3, H_2, and H_1, 11 percent of the budget and 10 percent of the materials are not used. The overall result is that only segments H_4 and H_5 can be reconstructed and represent the optimal solution.

The problem of determining optimum maintenance strategies grows

Table 3. Five Highway Segments Ranked By Effective Gradient

Proposed Order	Effective Gradient
H_3	37
H_2	63
H_1	64
H_5	1144
H_4	1347

Table 4. Selection of Highway Segments by Dropping Least Effective

	Budget Resource	Material Resource
Initial Excess Resource Requirements	185	175
Subtract H_3 (76, 70)	109	105
Subtract H_2 (46, 45)	63	60
Subtract H_1 (74, 70)	-11	-10

rapidly when additional strategies, resources, and distress considerations are added. The RAMS program treats this kind of problem.

Program Steps

The RAMS program considers the following steps in obtaining optimal maintenance solutions:

1. Finds the feasible maintenance strategies for each highway segment according to the minimum rating for each distress constraint (Equation 7 and Table 11) and the overall pavement rating constraint (Equation 8 and Table 11).

2. Ranks the feasible strategies for each highway segment according to the ratio of maintenance effectiveness to resource requirement. The ranking criterion is computed as follows:

$$r_{ij} = \frac{M_{ij}}{\sum_{l=1}^{m} a_{ijl}}$$

where:

r_{ij} = ranking ratio for highway segment i and strategy j.

M_{ij} = maintenance effectiveness if strategy j is applied to highway segment i.

a_{ijl} = percent of l^{th} type of resource needed if strategy j is applied to highway segment i.

For each highway segment the feasible strategies are ranked according to the highest value of the ranking ratio.

3. Selects the best ranked feasible strategy for each highway segment and calculates the effective gradient.

4. Sorts the effective gradients for all highway segments.

5. Selects the highway segment with the smallest effective gradient and exchanges its currently considered strategy with the next best available. This highway segment with its exchanged strategy and the remaining highway segments with their current strategies are used to recalculate the effective gradients for all highway segments. The program then switches back to Step 4 unless all the available, feasible strategies for this highway segment are exhausted in which case the program goes to Step 6.

6. One of two possible decisions are made at this step. These two decisions are:

(a) If any of the constraints are exceeded, drop the highway segment from the solution and subtract the resources required for the segment from the excess resource vector. The effective gradients for the remaining highway segments with their current strategies are recalculated and the program then returns to Step 4.

(b) If all of the constraints are satisfied, there is no need to drop more highway segments. The program goes to Step 7.

7. The remaining highway segments together with their corresponding strategies constitute the optimal solution set. If additional or "slack" capacity is availalbe in the resource constraints then additional highway segments may be added back to eliminate or reduce this capacity.

Example Problem Using the RAMS Program

The purpose of this larger example problem is to compare the maintenance strategies that were selected by TSDHPT personnel and with those selected by the RAMS program. The problem was prepared using actual field data which was obtained from fifteen highway segments located in TSDHPT District 17. This district is located in eastern-central Texas.

Eleven of the fifteen highway segments selected were scheduled for various kinds of contracted highway maintenance or rehabilitation within the next several months. The highway department has actually scheduled these segments for either a seal coat, asphalt concrete overlay, or reconstruction. Four additional highway segments were added to the initial eleven because they were considered to be in excellent condition and as such to require no significant maintenance. Although the intent of the methodology contained in RAMS was not to optimize maintenance on segments which require none, it was felt that adding the four segments would demonstrate that the program could distinguish a segment that needed rehabilitation from one that does not.

The following outline will be used in describing this example problem:

1. A description of the highway segments used.
2. Pavement condition determination for each segment.
3. The gain-of-rating matrices used.
4. The pavement survivor matrices used and how these matrices were obtained.
5. Resource information with emphasis on the budget.
6. A comparison of the TSDHPT selected maintenance strategies and those selected by the RAMS program.

Description of Highway Segments

Table 5 contains general information for each highway segment used. It includes a general description of each segment and the TSDHPT scheduled maintenance strategies. Additionally, the average Serviceability Index (SI) for each segment is shown and was obtained by use of the Mays Ride Meter. As can be seen in the table, a mixture of US, State and Farm-to-Market highways were used. The pavement length and width for each highway were direct inputs into the computer.

Pavement Condition For Each Highway Segment

The pavement condition rating system used is the one currently being implemented in Texas (6, 7) with slight modifications. This system is based on evaluating the quantity and severity of nine different distress manifestations. Due to reasons which will be explained later, only five distress types were used in this example problem.

Each distress type is assigned a certain amount of "points" up to a maximum amount. The "points" determine the current pavement rating of highway segment i and distress type k. The more points assigned to a certain highway segment and distress type, the less distress is present. The summation of available points for the individual distress types for a given highway segment will determine the overall rating. Table 6 shows the current condition rating information which was used as input to the computer program. Note that the maximum overall rating score taken over the five distress types is 125, not 100 as used in many other rating systems (8). The "Percent of Total" is taken as the ratio of the overall rating to the maximum rating and is equivalent to a pavement score based on a 0 to 100 scale.

Table 5. General Description of Highway Segments Used In Example Problem

Segment Number	Highway	County	Segment Length mi (km)	Segment Width ft (m)	Avg. SI	TSDHPT Scheduled Maintenance
1	US 79	Milam	4.525 (7.282)	26 (7.9)	2.7	2.5 cm HMAC Overlay + Extensive Patching
2	US 77	Milam	12.316 (19.821)	28 (8.5)	2.5	2.5 cm HMAC Overlay
3	US 190	Milam	3.617 (5.821)	26 (7.9)	2.1	3.8 cm HMAC Level-up Overlay
4	SH OSR	Madison	7.000 (11.265)	20 (6.1)	2.3	Seal Coat
5	SH OSR	Madison	2.257 (3.632)	22 (6.7)	1.9	Seal Coat
6	FM 1696	Walker	13.804 (22.215)	20 (6.1)	1.9	Seal Coat
7	FM 1791	Walker	12.374 (19.914)	22 (6.7)	0.8	Seal Coat
8	FM 2821	Walker	3.337 (5.370)	24 (7.3)	2.1	Seal Coat
9	SH 30	Walker	7.385 (11.885)	26 (7.9)	3.4	Seal Coat
10	SH 36	Burleson	12.021 (19.346)	26 (7.9)	3.9	None
11	US 290	Washington	9.019 (14.515)	26 (7.9)	3.9	None
12	US 79	Milam	5.644 (9.083)	26 (7.9)	4.5	None
13	SH 36	Burleson	9.321 (15.001)	26 (7.9)	4.7	None
14	SH OSR	Brazos	6.667 (10.729)	20 (6.1)	0.9	Recondition Base and Surfacing
15	FM 908	Milam	7.444 (11.980)	20 (6.1)	1.5	Recondition Base and Surfacing

Table 6. Current Pavement Condition Rating Information For Highway Segments

Distress Type	Highway Segment Number															Maximum Points Available
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Rutting	10	10	10	10	10	10	8	10	15	15	15	15	13	8	10	15
Alligator Cracking	5	15	10	20	25	25	0	15	25	25	25	25	25	5	10	25
Longitudinal Cracking	20	25	15	20	25	25	10	25	5	25	25	25	25	0	10	25
Transverse Cracking	17	20	13	20	20	20	20	20	5	20	17	17	20	17	8	20
Failures/Mile	20	40	40	40	40	40	10	20	40	40	40	40	40	20	20	40
Total Points (Overall Rating)	72	110	88	110	120	120	48	90	90	125	122	122	123	50	58	125
Percent of Total	58	88	70	88	96	96	38	72	72	100	98	98	98	40	46	100

Gain-of-Rating Matrix

The gain-of-rating matrix represents the d_{ijk} input for the RAMS program. The gain-of-rating "points" are the same kind of points as used in determining the pavement condition for the highway segments.

There are three kinds of ratings (points) which are used to generate the gain-of-rating matrix. These are: Maximum points available (Table 6) for a given type of distress, Maximum gain-of-rating points (Table 7) for a given maintenance strategy and distress type and current pavement rating (Table 6) for a given highway segment and distress type. The maximum points available for a distress type indicates what magnitude of points constitute a perfect rating (no distress condition). The maximum gain-of-rating points indicate the maximum gain which can be expected by using a given kind of maintenance strategy to treat a specific distress. Current pavement rating was previously discussed.

The three ratings are used by the RAMS program to generate the gain-of-rating points (d_{ijk}) for each highway segment (i), maintenance strategy (j) and distress type (k) by one of two possible procedures. If the maximum gain-of-rating and the current pavement rating points sum to less than the maximum points available for a given highway segment and distress type, then the maximum gain-of-rating points is used at the d_{ijk} input. If the above sum of points is greater than the maximum points available, then the difference between the maximum points available and current pavement rating points is used as the d_{ijk} input. For example, if a moderate overlay, thick overlay, or reconstruction maintenance strategy is used, the maximum gain-of-rating points for rutting is 15. This indicates for a highway segment

Table 7. Maximum Gain-of-Rating Matrix for All Highway Segments

Maintenance Strategy	Distress Type				
	Rutting	Alligator Cracking	Longitudinal Cracking	Transverse Cracking	Failures Mile
Seal Coat	0	15	15	15	10
Thin Overlay (3.8cm or less)	13	20	20	20	25
Moderate Overlay (>3.8 to 7.6cm)	15	25	25	20	30
Thick Overlay (>7.6cm)	15	25	25	20	35
Reconstruction (Light-Duty)	15	25	25	20	40
Reconstruction (Heavy-Duty)	15	25	25	20	40

with a rutting distress rating of 0 (which is the most severe rutting condition), application of one of these three strategies would completely eliminate the distress manifestation immediately after the required work was performed. Some maintenance strategies may have negative gain-of-rating points for some types of distress indicating that they have accentuated the distress.

The six maintenance strategies used in this example problem are considered to be typical of the maintenance performed on TSDHPT District 17 pavements. The only maintenance strategies which require additional description are light-duty and heavy-duty reconstruction. Light-duty reconstruction is generally used on low traffic highways and consists of scarifying the existing surface and base, recompacting, and then applying a one course surface treatment. Heavy-duty reconstruction is generally used on higher traffic highways and consists of scarifying the existing surface and base, adding additional flexible base (unstabilized), recompacting and applying a thin (3.8 cm or less) asphalt concrete surface.

The maximum gain-of-rating points associated with each maintenance strategy and distress type were obtained from subjective ratings by TTI personnel and are expected to change slightly as TSDHPT personnel begin to use the computer program.

Pavement Survivor Matrices

Pavement survivor matrices were developed for each distress type and maintenance strategy combination. An example of this is Table 8 which shows the probability of survival for the six maintenance strategies obtained for transverse cracking conditions. The determination of the

Table 8. Pavement Survival Matrix For Transverse Cracking

Maintenance Strategy	Time After Maintenance (Yrs)									
	1	2	3	4	5	6	7	8	9	10
Seal Coat	1.00	0.92	0.86	0.85	0.67	0.38	0.33	0.18	0.09	0.06
Thin Overlay (3.8 cm or less)	1.00	1.00	0.94	0.94	0.43	0.18	0.18	0.14	0.06	0.01
Moderate Overlay (>3.8 to 7.6 cm)	1.00	1.00	1.00	1.00	1.00	0.63	0.26	0.22	0.11	0.04
Thick Overlay (>7.6 cm)	1.00	1.00	1.00	1.00	1.00	0.33	0.33	0.28	0.17	0.17
Reconstruction (Light-Duty)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.65	0.60
Reconstruction (Heavy-Duty)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.65	0.60

probabilities for each of the five distress types used in this example problem will be described in detail below. The maintenance strategies considered are: (1) seal coat, (2) thin overlay, (3) moderate overlay, (4) thick overlay, (5) reconstruction (light-duty), (6) reconstruction (heavy-duty).

To determine the probability of survival for a given maintenance strategy, failure must first be defined. Sivazlian and Stanfel (19) define it as ". . . an event associated with a shift in the operating characteristics of a system from its permissible limits". Thus pavement failure may be when the Serviceability Index for a given highway type reaches or goes below a preselected lower limit. Failure could also be defined as when the highway develops a certain amount of a particular distress manifestation. But, for this problem, the time to failure for a given maintenance strategy will be taken as that time when some type of maintenance strategy must be accomplished which supersedes the previously applied maintenance.

The pavement survival matrices are currently based on subjective "failure analysis" data obtained from TSDHPT district maintenance management personnel. This data was obtained from a diagnostic examination of pavement segments located in four separate areas within the state. The district personnel evaluated these highway segments for future maintenance and rehabilitation needs based on their visual observations of the pavement and objectively measured data which was provided to them. These data included traffic, skid, deflection, ride, and construction histories.

From such information, time to failure was calculated for each maintenance strategy considered. For seal coats, a time to failure is determined when any of the six maintenance strategies considered were rescheduled for application. For the three overlays and reconstruction, a time to failure is determined only when one of these five maintenance strategies are rescheduled for application i.e., seal coats were not considered as superseding any of these five.

The time to failure data obtained for each maintenance strategy was arranged into histograms. These histograms approximate the failure density distribution curve discussed in reliability theory (9, 10). Failure density distributions are similar to normal distributions of data in that the area under the curve is equal to one.

From these histograms or failure density distributions, the failure density function can be defined by f(x) taken over $0 < x < \infty$ where x defines a time scale. The probability that a maintenance strategy will fail within a time interval (x,x + dx) is given by f(x)dx.

The corresponding cumulative density function can be defined by F(x) also taken over the interval $0 < x < \infty$ and is the probability that a given maintenance strategy will fail on or before some time t. This can be expressed as follows:

$$\text{Probability of failure on or before } t = F(t) = \int_0^t f(x)dx$$

The above expression assumes that a maintenance strategy will survive past time t is given by R(t) and is expressed as:

$$R(t) = 1-F(t) = \int_t^\infty f(x)dx$$

This expression can be adequately approxmiated for a given maintenance strategy by a cumulative frequency distribution which may be plotted from a histogram of time to failure data. The result is a survival curve, a generalized form of which is shown as Figure 15. Data from such curves are entered into the RAMS program in matrix form as is demonstrated by the use of Table 8.

The pavement survival matrices currently being used will be updated in the near future. This will be accomplished by combining the subjectively obtained data just described with objective data from a pavement data base assembled for Texas pavements. It is planned to use Bayesian techniques to accomplish this task.

Budget Resource

There are four types of resource constraints used in the program: (1) material and supply, (2) equipment, (3) manpower, and (4) cost. Each resource constraint has two major inputs: requirements and availability. The requirement input indicates how much of a given resource will be used by a maintenance strategy and availability indicates how much of a given resource is available to be used. Of the four types of resource constraints, budget is the most significant in this example problem.

The available budget used as input was essentially the same amount as the contract funds allocated for the TSDHPT selected maintenance strategies. This is an important constraint because it forced the computer program to consider maintenance decisions within approximately the same financial framework used by TSDHPT personnel. This value is shown in Table 8 as the total available funds.

The budget requirement matrix indicates the required cost per unit area for each maintenance strategy and is shown in Table 9. The costs

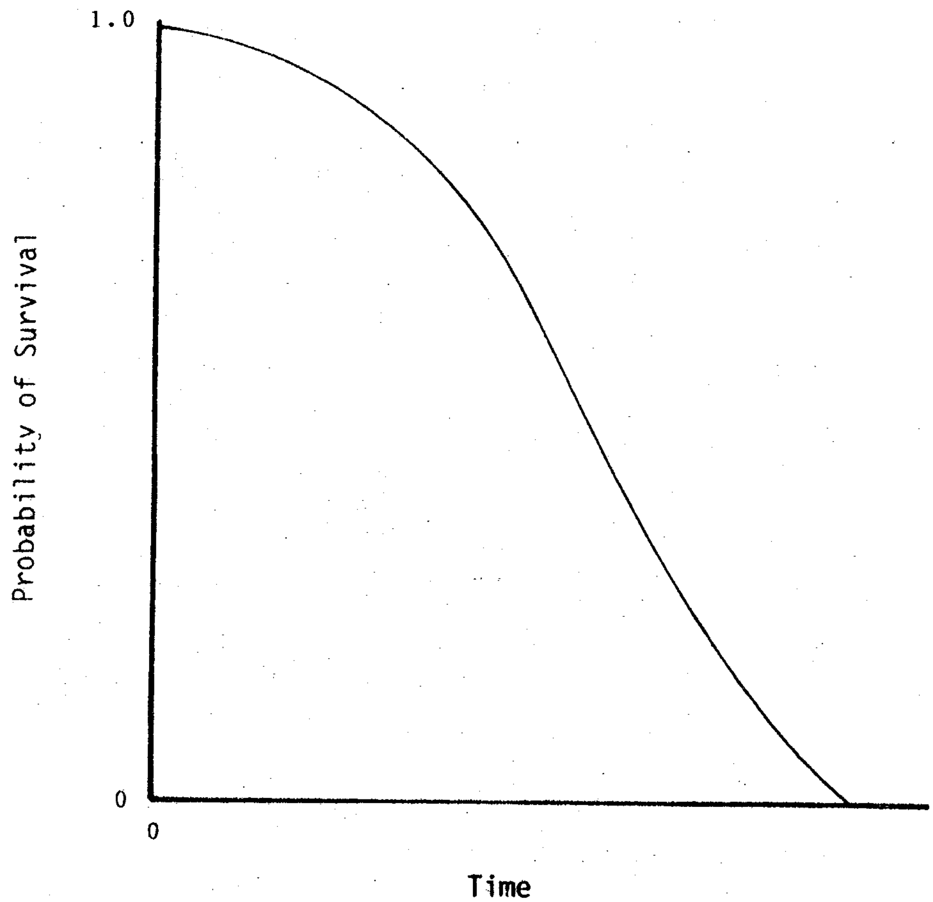


Figure 15. Generalized Form of a Survival Curve For A Maintenance Strategy

Table 9. Cost Requirements Per Unit Area for Each Maintenance Strategy and Total Available Funds

Maintenance Strategy	Cost Per Unit Area $/ft-mi	($/m-km)
Seal Coat	214	(436)
Thin Overlay	925	(1886)
Moderate Overlay	2000	(4078)
Thick Overlay	3549	(7234)
Reconstruction (Light-Duty)	944	(1925)
Reconstruction (Heavy-Duty)	2600	(5301)

Total Available Funds = $ 1,130,000

generally increase as the maintenance strategies become more extensive. The notable exceptions to this are the two kinds of reconstruction.

Comparison of TSDHPT and RAMS Selected Maintenance Strategies

Comparisons of the TSDHPT and RAMS selected maintenance strategies for the fifteen highway segments in the example are shown in Table 10. First, the TSDHPT and RAMS (Case 1) selected strategies are shown and both use the same original TSDHPT budget amount. Another RAMS solution (Case 2) is also shown and was obtained by increasing the TSDHPT budget by approximately six percent. To facilitate discussion of the comparisons, those highway segments which reveal little or no difference between the TSDHPT and RAMS (Case 1 and 2) selected maintenance strategies will not be examined.

A combination of highway types was used in this example and the RAMS program treated all with equal priority except in applying the two kinds of reconstruction. For low traffic segments (Segment Numbers 4, 5, 6, 7, 8, 14 and 15), the program was restricted to applying only the light-duty type of reconstruction (if required) and for the remaining higher traffic segments only the heavy-duty type of reconstruction could be used. Traffic and climate indices can also be used as input to account for differences in highway types. Additionally, groupings of similar highway types can be assembled and processed together if desired.

Table 10 shows that the selected strategies for Segment Number 2 differ. The TSDHPT selected strategy is a thin overlay and the RAMS program (Cases 1 and 2) selected a seal coat. The pavement distress manifestations for this segment are comprised of alligator cracking and extensive flushing (flushing is not considered in this run of the RAMS program). All maintenance

Table 10. Comparison of TSDHPT and RAMS Selected Maintenance Strategies

Segment Number	Highway	*Overall Pavement Rating	Percent of Total	**Serviceability Index (SI)	TSDHPT Selected Maintenance Strategies	RAMS Computer Program Selected Maintenance Strategies Using TSDHPT Budget (Case 1)	RAMS Computer Program Selected Maintenance Strategies Using TSDH Budget + 6.3% (Case 2)
1	US 79	72	58	2.7	2.5cm HMAC Overlay +Extensive Patching	Moderate HMAC Overlay	Moderate HMAC Overlay
2	US 77	110	88	2.5	2.5cm HMAC Overlay	Seal Coat	Seal Coat
3	US 190	88	70	2.1	3.8cm HMAC Level-up Overlay	Thin HMAC Overlay	Thin HMAC Overlay
4	SH OSR	110	88	2.3	Seal Coat	Seal Coat	Seal Coat
5	SH OSR	120	96	1.9	Seal Coat	None	None
6	FM 1696	120	96	1.9	Seal Coat	None	None
7	FM 1791	48	38	0.8	Seal Coat	Light Duty Reconstruction	Light Duty Reconstruction
8	FM 2821	90	72	2.1	Seal Coat	Thin HMAC Overlay	Thin HMAC Overlay
9	SH 30	90	72	3.4	Seal Coat	None	Thin HMAC Overlay
10	SH 36	125	100	3.9	None	None	None
11	US 290	122	98	3.9	None	(Seal Coat)	None
12	US 79	122	98	4.5	None	(Seal Coat)	None
13	SH 36	123	98	4.7	None	None	None
14	SH OSR	50	40	0.9	Recondition Base and Surfacing	Light Duty Reconstruction	Light Duty Reconstruction
15	FM 908	58	46	1.5	Recondition Base and Surfacing	Light Duty Reconstruction	Light Duty Reconstruction

*Perfect OPR = 125
Poorest OPR = 0

**Smoothest SI = 5.0
Roughest SI = 0.0

Budget Used = 100% ($1,130,000)

Budget Used = 97.8% ($1,105,140)

Budget Used = 106.3% ($1,201,520)

strategies are feasible on this segment as determined by the minimum and overall rating constraints, the results of which are shown in Table 11. Thus, on this section the RAMS program evaluated five maintenance strategies (seal coat, thin overlay, moderate overlay, thick overlay and heavy-duty reconstruction). For this segment, the maintenance effectiveness computed for a seal coat is about one-half of that calculated for a thin overlay but the cost of a thin overlay is four times as great. It can be seen in a subjective way that a seal coat is an attractive maintenance strategy. The TSDHPT decision to use a thin overlay may have been additionally based on the rough ride and flushing present on this highway.

Segment Numbers 5 and 6 were scheduled for seal coats by the TSDHPT and no strategies were scheduled by the RAMS program. An examination of the Table 6 shows that no distress manifestations, with the exception of minor rutting, were present on these pavements. But, in fact, flushing was present (not shown in Table 6) and may have been a consideration in the TSDHPT decision.

Segment Number 7, which has numerous and extensive distress manifestations, is scheduled for maintenance by RAMS. The feasible strategies allowed by the minimum and overall rating constraints shown in Table 11 indicate that only a thick overlay strategy or greater is allowable. A similar situation occurs with Segment Number 8.

For Segment Number 9, the TSDHPT scheduled a seal coat but the RAMS program (Case 1) scheduled no maintenance. This occurred because there was not enough budget to allow application of a thin overlay or greater to this segment. The inexpensive seal coat alternative was eliminated by the minimum and overall rating constraints. For the RAMS (Case 2) selection, the orginial TSDHPT budget was increased by approximately six percent.

Table 11. Feasible Maintenance Strategies Allowable by the Minimum Distress Rating and Overall Rating Constraints

Highway Segment	Maintenance Strategy: Feasible = 1, Infeasible = 0					
	Seal Coat	Thin Overlay	Moderate Overlay	Thick Overlay	Reconstruction (Light Duty)	Reconstruction (Heavy Duty)
1	0	0	1	1	1	1
2	1	1	1	1	1	1
3	0	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	0	0	0	1	1	1
8	0	1	1	1	1	1
9	0	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1
12	1	1	1	1	1	1
13	1	1	1	1	1	1
14	0	0	0	0	1	1
15	0	0	1	1	1	1

This small budget change allowed the segment to be scheduled for a suitable, cost effective maintenance strategy (thin overlay).

As shown by use of Segment Number 9, the RAMS program can also be used to help estimate required maintenance budgets. This can be accomplished by inputting all data as previously discussed but varying the budget amount. The budget could be selected where adequate maintenance is scheduled for all necessary segments.

Segment Numbers 11 and 12 are in excellent condition with both having only minor transverse cracking. The RAMS program in Case 1 scheduled seal coats for these segments since some benefit could be obtained by using this strategy. This occurred because the program maximizes the maintenance effectiveness for the amount of budget available. In Case 2, the funds were more adequately used by slightly increasing the available budget with one result being that these two seal coats were eliminated.

A comparison of overall maintenance effectiveness resulting from the TSDHPT, RAMS, Case 1 and Case 2 maintenance strategy selections provides an indication of the optimality of the computer solutions. The maintenance effectiveness obtained by use of Equation 1 for the three maintenance programs are:

TSDHPT: 359,412

RAMS - Case 1: 425,106

RAMS - Case 2: 451,318

Comparing the TSDHPT and RAMS Case 1 selections shows that use of the computer program increased the maintenance effectiveness by 18 percent and resulted in a two percent budget savings. But, Case 1 selections did exclude one pavement segment which needed maintenance. Case 2 selections filled this need and resulted in an increase in maintenance effectiveness of 26 percent over TSDHPT selections. The RAMS program accomplished this by using a budget approximately six percent larger than used by the TSDHPT.

CHAPTER V

SUMMARY

The main thrust behind this research effort was to develop a comprehensive technique to optimize the allocation of resources for maintenance and rehabilitation of Texas State highway system. The different subtasks considered was (1) problem analysis and data collection, (2) formulation of a mathematical model that realistically represents the state highway maintenance and rehabilitation (3) optimization and analysis of solution.

The state highway maintenance problem was realistically represented by a 0-1 integer linear programming formulation. To include all the aspects in highway management, this 0-1 integer linear programming formulation becomes very large in terms of number of variables and constraints. Only small size 0-1 integer linear programming problem can be solved by the current state of the art. A special solution technique is developed so that large 0-1 integer programming problems as are encountered in highway management can be solved efficiently.

An operating computer program based on the solution techniques developed was constructed to determine optimal strategies for pavement maintenance. The program uses the current pavement condition, potential-gain-of-rating, and survivor matrices as input to maximize the overall maintenance effectiveness for any group of highway segments. The program can use numerous maintenance strategies, resources, and feasibility constraints in determining optimal solutions. The required inputs can be expanded or reduced as necessary. The documentation of the program is provided in Appendix B.

An example problem with fifteen highway segments located in one highway district in Texas was used to demonstrate the program. Based on the actual field data a comparison of the computer program and TSDHPT selected maintenance strategies revealed similar selections with notable exceptions. It was shown that by using the RAMS program with the same budget the maintenance effectiveness of the selected maintenance strategies could be increased by 18 percent over TSDHPT selections. The maintenance effectiveness was increased by 26 percent with a six percent increase in the available budget.

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APPENDIX A

AN ALGORITHM TO SOLVE 0-1 INTEGER LINEAR PROGRAMMING PROBLEMS WITH MULTIPLE-CHOICE CONSTRAINTS

A generally accepted efficient procedure for solving small to medium sized 0-1 integer linear programming problems is to apply an implicit e-numeration algorithm (9) which uses branch and bound techniques or tree-search procedures. The cutting plane method (11) and/or combinations of implicit enumeration in association with the cutting plane procedure are also frequently used. An exact optimal solution may be obtained in most cases if the number of variables is not large (30 or less variables). However, if the number of variables becomes large, branch and bound and other algorithms may require excessive computation. In addition it may not be practical to obtain an optimal solution or even a "good" feasible solution (a feasible solution which is close to optimal) in the algorithmic procedure.

This report documents the development of a computationally efficient algorithm to obtain optimal or near optimal solutions to large scale integer linear programming problems with multiple-choice constraints. The solution approach is based on a preference indicator among the solution variables referred to as "the effective gradient".

Explanation of the Effective Gradient

In this section the concept of the effective gradient, which was originally developed by Toyoda, (22) is presented through a numerical ex-ample. Suppose one considers the capital budgeting problem where an opti-mal selection of projects is to be made from a choice of nine different projects. The objective will be to maximize profit, subject to the stated constraints. For simplicity it is assumed that only two resources, A and B are required for implementing each project. The resource requirement and profit from each project is shown in Table A-1. Investing in all projects is not feasible due to the lack of available resources. Therefore one seeks to select those projects which maximize profit while simultaneously satisfying the resource availability constraints. Specifically, let

$\overline{I}_i$ = i^{th} project vector (resource vector of i^{th} project),

$\overline{R}$ = resource vector of all projects,

$= \overline{I}_1 + \overline{I}_2 + \overline{I}_3 + \ldots, + \overline{I}_9,$

= (48, 50),

$\overline{L}$ = limiting resource vector or availability vector,

= (38, 38), and

$\overline{S}$ = surplus vector = $\overline{R} - \overline{L}$,

= (10, 12).

In Figures A. 1 and A. 2 R' and L' represent the end points of the vectors $\overline{R}$ and $\overline{L}$ originating from the origin.

As it is not possible to select all of the projects due to resource limitations, it may be necessary to move back from the resultant point R' in Figure A. 1 towards the feasible zone by dropping some projects in such a way that the remaining profit is maximized.

If project 9 is dropped, the point R' moves along-$\overline{I}_9$ and \$700 in profit is lost. $\overline{I}_9$'s contribution to moving back towards the point L' is expressed by the projected length B'R' on the surplus vector $\overline{S}$ as illustrated in Figure A. 2. It is preferable to drop the projects which possess smaller

TABLE A-1

An Example with Two Resources

Project	Resource Requirements A	Resource Requirements B	Profit
1	3	5	150
2	8	3	300
3	2	7	200
4	5	8	600
5	3	1	150
6	7	6	700
7	5	7	400
8	6	8	650
9	9	5	700
TOTAL	48	50	
AVAILABLE	38	38	
EXCESS NEEDED	10	12	

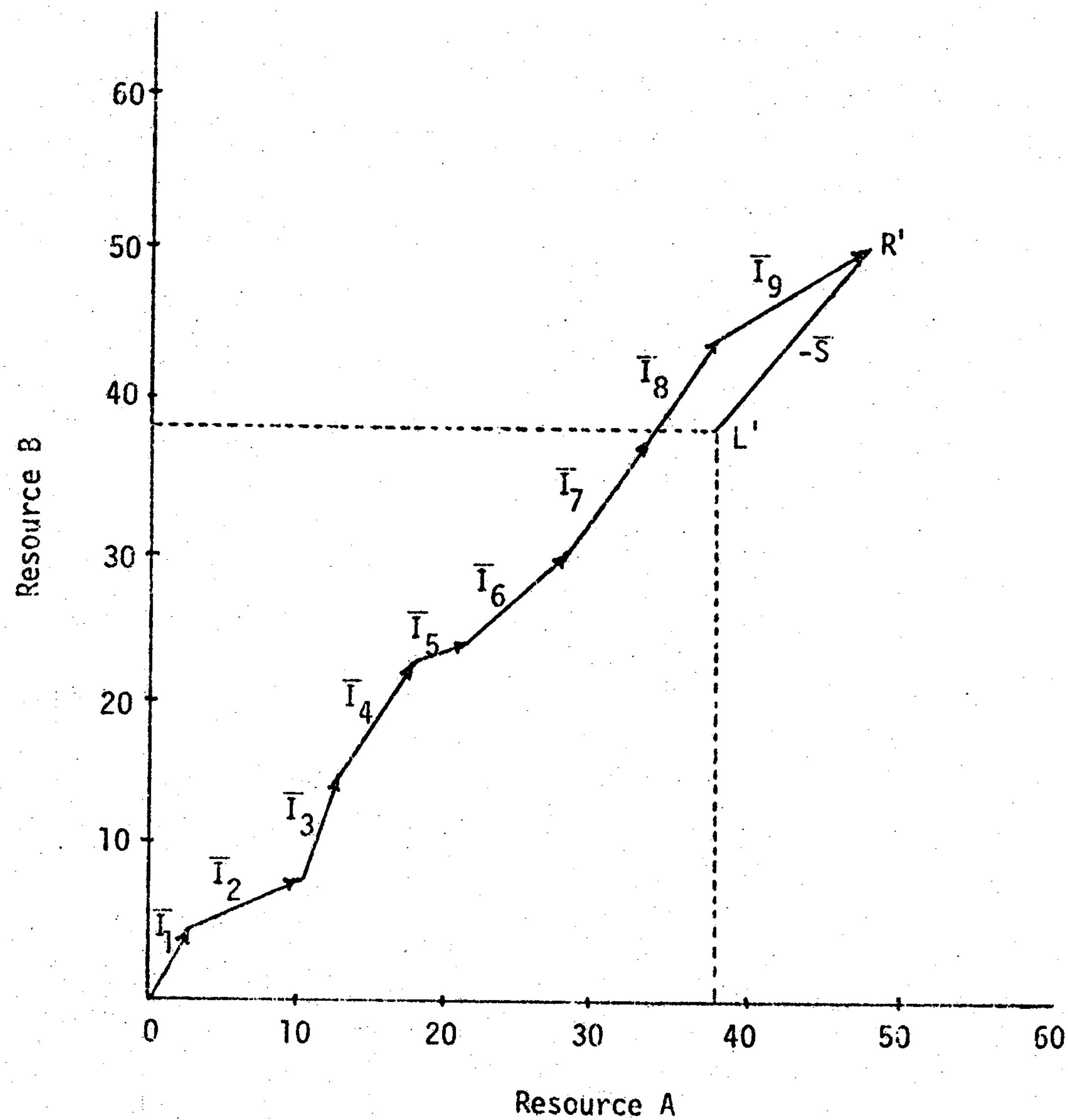


Fig. A.1 Vector Sum of Projects

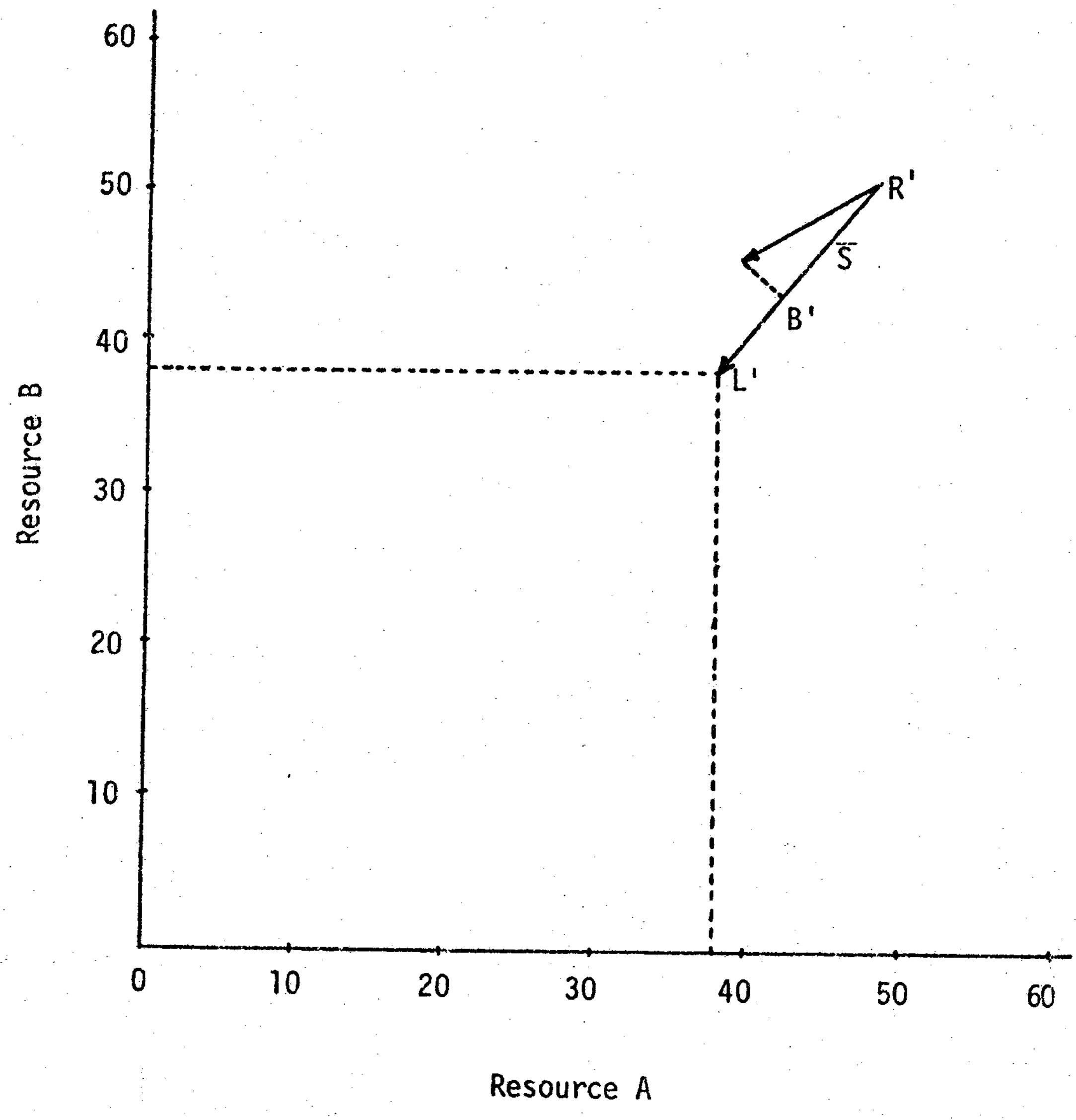


Fig. A.2 Effective Gradient

profits compared to their projected length on the surplus vector $\overline{S}$. In dropping a project, the ratio of the projected length B'R' to the profit is significant. This ratio is termed the <u>effective gradient</u> of profit. To determine which projects should be dropped to maximize profit, it is essential to calculate the effective gradients of all the projects. Hence, those projects which have the least effective gradients should be dropped in a sequence of increasing effective gradients until the resource requirements are satisfied. It may be noted that, this still may not generate an optimal solution but it will be feasible.

Calculation of the Effective Gradient

Let $\overline{V}$ be a unit vector parallel to the surplus vector $\overline{S}$ as shown in Figure A.2. Thus,

$$V = \overline{S} \; / \; | \; \overline{S} \; | \; , \tag{A-1}$$

and in the example shown in Table 3-1 (p. 17),

$$V = \{10/(10^2 + 12^2)^{\frac{1}{2}}, \; 12/(10^2 + 12^2)^{\frac{1}{2}}\}$$

Let,

$$P_i = \text{projection of vector } -\overline{I}_i \text{ on } -\overline{V},$$

P_i is given by the scalar product of the vectors $-\overline{I}_i$ and $-\overline{V}$,

$$P_i = -\overline{I}_i \cdot -\overline{V} = \overline{I}_i \cdot \overline{V}. \tag{A-2}$$

Thus, $P_1 = -\overline{I}_1 \cdot -\overline{V} = \overline{I}_1 \cdot \overline{V}$,

$$= (3 \times 10) \; / \; (10^2 + 12^2)^{\frac{1}{2}} + (5 \times 12) \; / \; (10^2 + 12^2)^{\frac{1}{2}}$$

$$= (3 \times 10 + 5 \times 12) \; / \; (10^2 + 12^2)^{\frac{1}{2}}.$$

Now define E_i as effective gradient of profit for project i, where

$$E_i = \frac{\text{Profit for project } i}{P_i} \quad . \qquad \text{(A-3)}$$

Thus, E_1 = effective gradient of profit for project 1 ,

$$= \frac{\text{Profit for project 1}}{P_1} ,$$

$$= \frac{150}{90/(10^2 + 12^2)^{\frac{1}{2}}} ,$$

$$= 26 \cdot 03.$$

Similarly, effective gradients of profit for all the other projects are:

$$E_2 = \frac{300}{(8 \times 10 + 3 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 40 \cdot 40$$

$$E_3 = \frac{200}{(2 \times 10 + 7 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 30 \cdot 40$$

$$E_4 = \frac{600}{(5 \times 10 + 8 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 69 \cdot 94$$

$$E_5 = \frac{150}{(3 \times 10 + 1 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 55 \cdot 78$$

$$E_6 = \frac{700}{(7 \times 10 + 6 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 77 \cdot 00$$

$$E_7 = \frac{400}{(5 \times 10 + 7 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 46 \cdot 62$$

$$E_8 = \frac{650}{(6 \times 10 + 8 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 70 \cdot 50$$

$$E_9 = \frac{700}{(9 \times 10 + 5 \times 12)/(10^2 + 12^2)^{\frac{1}{2}}} = 72 \cdot 89$$

At this point, effective gradients for all the projects are arranged in ascending order. This is shown in Table A-2. Those projects which have the least effective gradients should be dropped until the resource

TABLE A-2

Sorting of Projects According to the Negative Priority of Effective Gradient

Project	Effective Gradient
1	E_1 = 26·03
3	E_3 = 30·04
2	E_2 = 40·40
7	E_7 = 46·62
5	E_5 = 55·78
4	E_4 = 69·94
8	E_8 = 70·50
9	E_9 = 72·89
6	E_6 = 77·00

requirement is satisfied. The process of dropping the project is shown in Table A-3. It may be observed that after dropping the projects 1, 2, and 3 in Table A-3, there remains some slack capacity in the resource constraints. Sometimes it may be possible to include additional projects from the projects already dropped. For this example it is not possible to add more projects. The final solution is shown in Table A-4.

TABLE A-3

Dropping of Projects

	Surplus	
	Resource A	Resource B
Initial Surplus	10	12
Subtract $\overline{I}_1$ (3, 5)	7	7
Subtract $\overline{I}_3$ (2, 7)	5	0
Subtract $\overline{I}_2$ (8, 3)	- 3	- 3

TABLE A-4

Resultant Selection of Projects

Project	Profit	Net Profit
4	600	
5	150	
6	700	3200
7	400	
8	650	
9	700	

Generalization.

In general consider the following formulation :

(IP A-1) $$\text{maximize} \sum_{i=1}^{n} C_i x_i$$

subject to

$$\sum_{i=1}^{n} a_i \; x_i \le b_\ell \qquad \ell = 1, 2, \ldots, m,$$

$$x_i = 0, 1 \qquad i = 1, 2, \ldots, n.$$

where

C_i = profit if i^{th} project is implemented,

$a_{i\ell}$ = amount of ℓ^{th} resource needed for i^{th} project, and

b_ℓ = amount of ℓ^{th} resource available.

In the preceding example for $\overline{V} = \overline{S} / |\overline{S}|$, $|\overline{S}| = (10^2 + 12^2)^{\frac{1}{2}}$, was common for all of the effective gradients. However $|\overline{S}|$ is not necessary as the relative measure of effective gradient is essentially important, not the absolute measure. So $\overline{V}$ may be replaced by $\overline{V}' = \overline{S}$ where,

P_i' = projection of vector $-\overline{I}_i$ on $\overline{V}'$,

$= -\overline{I}_i \cdot -\overline{V}'$

$= \overline{I}_i \cdot \overline{S}$, (A-4)

E_i' = relative effective gradient or simply the effective gradient of project i,

$$= \frac{\text{Profit for the } i^{th} \text{ Project}}{P_i'} ,$$

$$= \frac{C_i}{\overline{I_i \cdot S}} . \qquad \text{(A-5)}$$

It may be advantageous to express the resource requirement $a_{i\ell}$ as the percent of total resource of the ℓ^{th} type available. Since the upper limit on all resource is 100%, the project which individually exceeds one or more resource limitations may be automatically excluded from consideration. Let $w_{i\ell}$ denote the percent of ℓ^{th} resource needed for the i^{th} project, then

$\overline{R}$ = resultant vector of all projects ,

$$\overline{R} = \left(\sum_{i=1}^{n} W_{i1}, \sum_{i=1}^{n} W_{i2}, \ldots, \sum_{i=1}^{n} W_{i\ell} \right). \qquad \text{(A-6)}$$

When a resource has some slack capacity, that is when a strict inequality holds, viz.

$$\sum_{i=1}^{n} W_{i\ell} \leq 100 , \qquad \text{(A-7)}$$

that resource can be neglected. Generally, the ℓ^{th} component of surplus vector $\overline{S}$, may be expressed as,

$$S_\ell = \sum_{i=1}^{n} W_{i\ell} - 100, \text{ if } \sum_{i=1}^{n} W_{i\ell} > 100 ,$$

$$= 0, \qquad \text{if } \sum_{i=1}^{n} W_{i\ell} \leq 100 . \qquad \text{(A-8)}$$

when $S_\ell = 0$, this implies that the resource which has slack capacity should be neglected.

The project vector $\overline{I}_i$ can be expressed as,

$$\overline{I}_i = (W_{i1}, W_{i2}, \ldots W_{i\ell}) . \qquad \text{(A-9)}$$

The scalar product P_i' of the i^{th} project vector and surplus vector is

$$P_i' = \overline{I}_i \cdot \overline{S},$$

$$= (W_{i1}, W_{i2}, \ldots, W_{i\ell}) \cdot (S_1, S_2, \ldots, S_\ell),$$

$$= \sum_{\ell=1}^{m} W_{i\ell} \cdot S_\ell . \qquad \text{(A-10)}$$

In rare instances, it may occur that P_i' is zero. When this occurs one should select project i. The reason is that for the ℓ^{th} resource, it's addition neither exceeds the limitations when $S_\ell = 0$ (Since $\sum_{i=1}^{n} W_{i\ell} \leq 100$), nor effects the surplus (since $W_{i\ell} = 0$).

So the effective gradient of the i^{th} project may be redefined as,

$$E_i' = \frac{\text{Profit for project } I_i}{P_i'},$$

$$= \frac{C_i}{P_i'} . \qquad \text{(A-11)}$$

For the example problem shown in Table 3-1 (p. 17),

$$E_1' = \text{Effective gradient of project 1}$$

$$= \frac{\text{Profit for project 1}}{P_1},$$

$$E_1' = \frac{150}{3 \times 10 + 5 \times 12} = \frac{150}{90} = 1{\cdot}66,$$

$$E_2' = \frac{300}{8 \times 10 + 3 \times 12} = \frac{300}{116} = 2{\cdot}59,$$

$$E_3' = \frac{200}{2 \times 10 + 7 \times 12} = 200 = 1{\cdot}92,$$

and so on. The projects are dropped in order of negative priority of effective gradient until the resultant point R in Figure a.1 enters the feasible region.

An Algorithm to Solve Multiple-Choice 0-1 Integer Linear Programming Problem

In the preceding section Toyoda's (21) algorithm to solve 0-1 integer linear programming problems without multiple-choice constraints was discussed. In this section an algorithm developed by the author to solve 0-1 integer linear programming problems with multiple-choice constraints is presented. The algorithm utilizes the concept of an effective gradient incorporating successive deletion of the least preferred variable from the variables in the GUB set.

In order to develop these concepts, consider the capital budgeting problem with GUB/(generalized upper bound or multiple-choice) constraints of the following form:

(IP A-2) $$\text{maximize} \sum_{i=1}^{n} \sum_{j=1}^{P_i} C_{ij}\, x_{ij}$$

subject to

$$\sum_{i=1}^{n} \sum_{j=1}^{P_i} a_{ij\ell}\, xij \le b_\ell, \quad \ell = 1, 2, 3, \ldots, m,$$

$$\sum_{j=1}^{p_i} x_{ij} \leq 1, \qquad i = 1, 2, 3, \ldots, n,$$

$$x_{ij} \in \{0, 1\}.$$

where

C_{ij} = profit if i^{th} project is implemented with j^{th} policy,

$a_{ij\ell}$ = amount of ℓ^{th} resource required if i^{th} project is implemented with j^{th} policy,

b_ℓ = amount of ℓ^{th} resource available, and

p_i = number of available policies for implementing i^{th} project.

In the above problem, each project with its corresponding policies may be assumed to constitute a generalized upper bound (GUB) set. The variables x_{ij}, $j = 1, 2, \ldots, p_i$ are the decision variables in GUB set i, where $x_{ij} \in \{0, 1\}$. When $x_{ij} = 1$ this implies that, project i using the j^{th} policy should be implemented and when $x_{ij} = 0$, that i^{th} project with j^{th} policy should not be implemented.

The problem is solved in three phases. First, a good feasible solution based upon the concept of the effective gradient is obtained. Secondly an attempt is made to include additional variables in the current (feasible) solution provided there are some slack capacities in the resource constraints. Finally, within each GUB set a search is made to improve upon the current solution. The steps of the algorithm are as follows:

Phase 1. Finding a good feasible solution based upon the concept of the effective gradient.

Step 0: Initially set all $x_{ij} = 0$. In each GUB set, consider the variable that has the highest value of profit. Set those variables to 1. Check whether the resource constraints are satisfied. If all the resource constraints are satisfied go to Step 11. Otherwise go to Step 1.

Step 1: Rank the variables in each GUB set in descending order i.e. the highest value first. To facilitate the ranking, define the ranking factor γ_{ij} as:

$$\gamma_{ij} = \frac{C_{ij}}{\sum_{\ell=1}^{m} a_{ij\ell}/b_{\ell}} \qquad \text{(A-12)}$$

Step 2: Set all $x_{ij} = 0$, then let the highest ranked variable from each GUB set, to 1.

Step 3: If all of the resource constraints are satisfied go to Step 7. If at least one resource constraint is not satisfied, go to Step 4.

Step 4: Calculate the effective gradients of the variables in the solution set.[1] Sort the variables in ascending order of the effective gradient. Consider the GUB set that contains the variable having the least effective gradient. Search for any lower ranked variable in that particular GUB set. If there is any lower ranked variable, go to Step 5. Otherwise go to Step 6.

Step 5: Set the lower ranked variable in this GUB set to 1,

---

[1] The term solution set is used to specify the set of variables having value 1.

and the variable that previously had the least effective gradient to 0. Go to Step 3.

Step 6: Set the variable that previously had the least effective gradient to 0. The corresponding GUB set is temporarily excluded from the solution set. The current solution set now consists of the previous solution set minus the variable that was just set to 0. Go to Step 3.

Phase 2. Inclusion of additional variables.

Step 7: Check whether all GUB sets are in solution. If all GUB sets are in solution, go to Step 9. Otherwise consider the GUB sets not in the solution. Within each such GUB set determine the variables that are feasible with respect to the remaining slack capacity in the resource constraints. If there is no such feasible variable go to Step 9. Otherwise go to Step 8.

Step 8: Rank the candidate (feasible) variables in each GUB set determined in Step 7, according to the ranking criterion used in Step 1. Consider the highest ranked variable in each such GUB set. Rank these variables according to the descending order of ranking ratio. Set the variable with highest ranking ratio to 1. Go to Step 7.

Phase 3. The GUB Search

Step 9: Consider the GUB sets which are currently in solution. In each such GUB set, search for the feasible variables whose profit coefficient is higher than the variable in solution. This may be accomplished by adding the resource requirements of the variable in consideration to the total resource requirements, and subtracting the resource requirements of the variable in the solution. If the resource constraints are satisfied, then the corresponding variable is feasible. If there is any such feasible variable go to Step 10. Otherwise the solution is optimal or near optimal. Go to Step 11.

Step 10: For each feasible variable, find the difference in profit. This can be obtained by subtracting the profit of the variable in solution from the profit of the variable being considered in that particular GUB set. Set the variable with maximum profit difference to 1. Go to Step 9.

It may be worth mentioning that instead of selecting the variable with greatest profit difference, one could select a combination of variables which together, may yield a better profit difference. From computational experience it has been observed that though this situation may occur in some cases, the subsequent improvement in the objective function value is relatively small. From a practical viewpoint, the small improvement may not offset the additional computational cost for enumerating different combinations of variables for large problems.

Step 11: The solution is optimal or near optimal. Terminate.

The steps of the algorithm is summarized by means of a flow chart in Figure A-3.

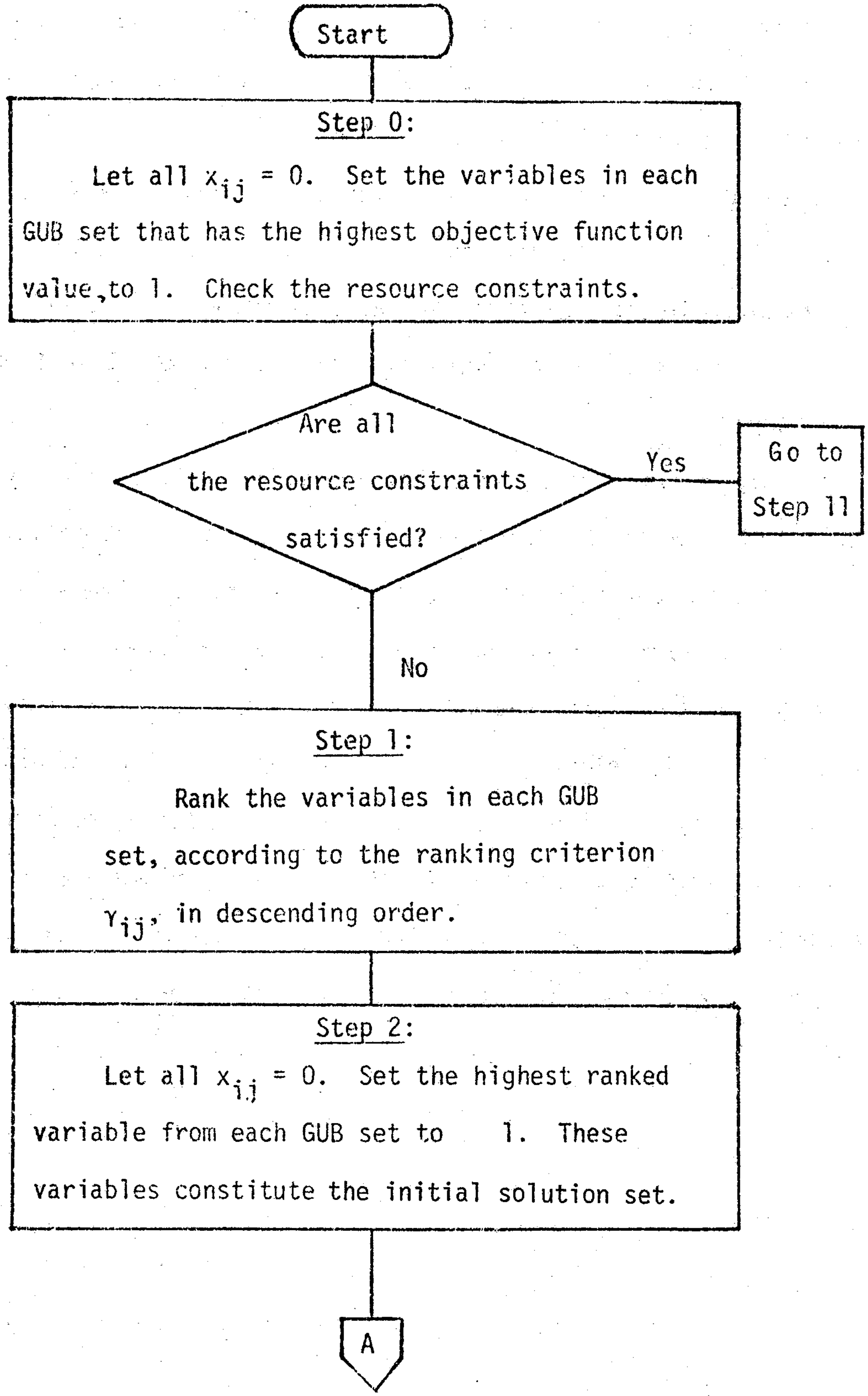


Fig. A-3 Flow Chart

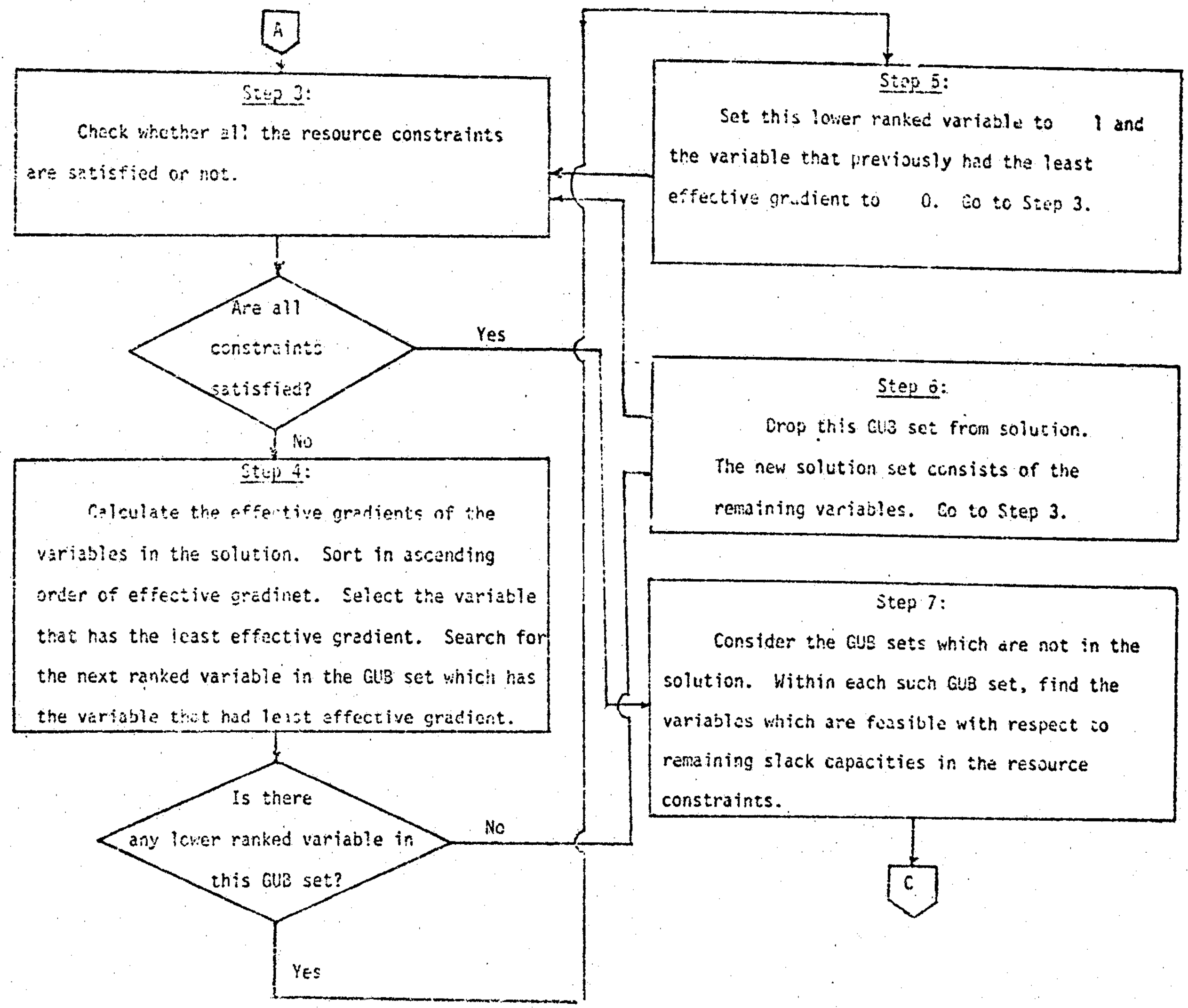

A
Step 3:
Check whether all the resource constraints are satisfied or not.
Are all constraints satisfied?
Yes
No
Step 4:
Calculate the effective gradients of the variables in the solution. Sort in ascending order of effective gradinet. Select the variable that has the least effective gradient. Search for the next ranked variable in the GUB set which has the variable that had least effective gradient.
Is there any lower ranked variable in this GUB set?
No
Yes
Step 5:
Set this lower ranked variable to 1 and the variable that previously had the least effective gradient to 0. Go to Step 3.
Step 6:
Drop this GUB set from solution. The new solution set consists of the remaining variables. Go to Step 3.
Step 7:
Consider the GUB sets which are not in the solution. Within each such GUB set, find the variables which are feasible with respect to remaining slack capacities in the resource constraints.
C

Fig. A-3 Cont'd.

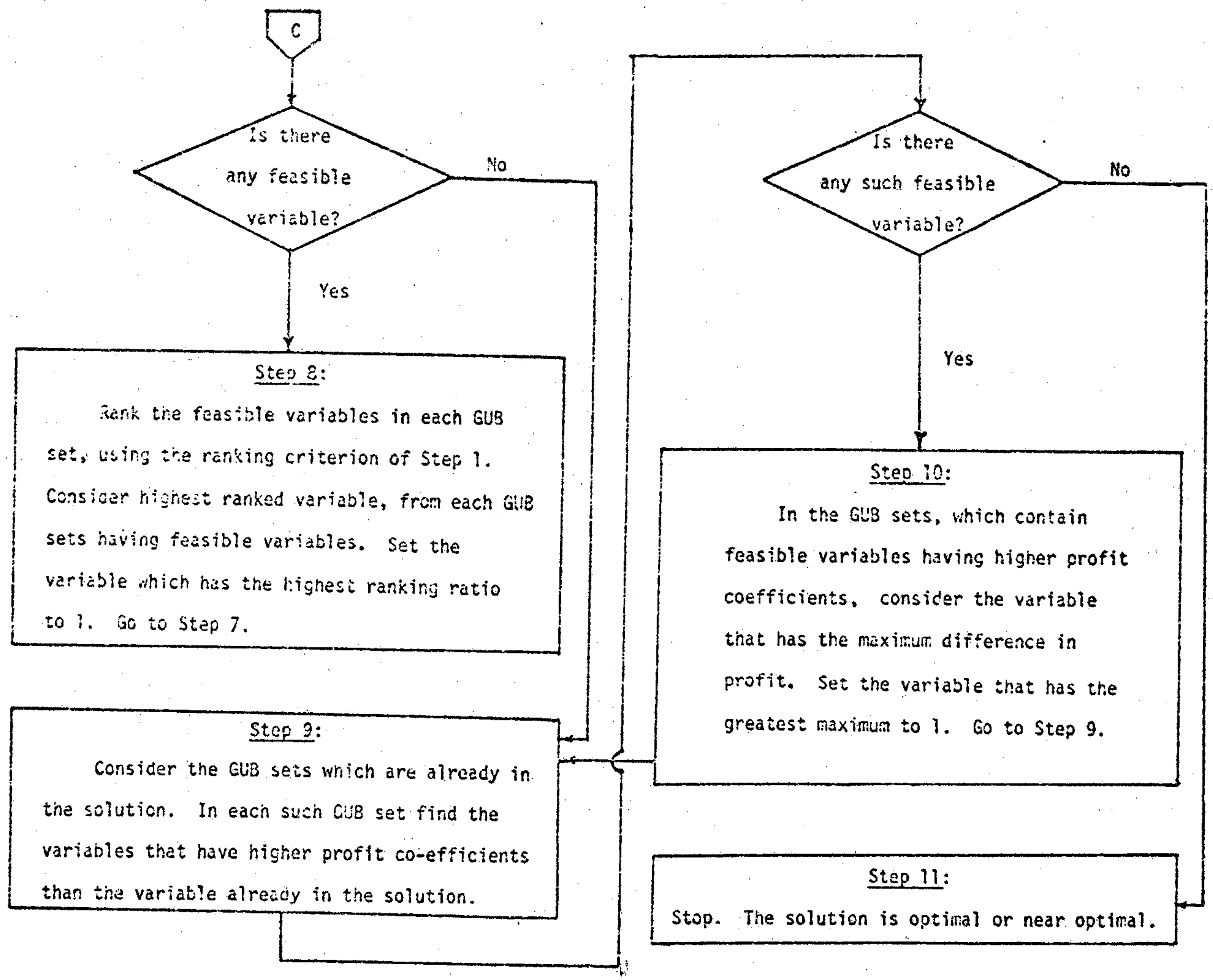

C
Is there any feasible variable?
No
Yes
Step 8:
Rank the feasible variables in each GUB set, using the ranking criterion of Step 1. Consider highest ranked variable, from each GUB sets having feasible variables. Set the variable which has the highest ranking ratio to 1. Go to Step 7.
Step 9:
Consider the GUB sets which are already in the solution. In each such GUB set find the variables that have higher profit co-efficients than the variable already in the solution.
Is there any such feasible variable?
No
Yes
Step 10:
In the GUB sets, which contain feasible variables having higher profit coefficients, consider the variable that has the maximum difference in profit. Set the variable that has the greatest maximum to 1. Go to Step 9.
Step 11:
Stop. The solution is optimal or near optimal.

Fig. A-3 Cont'd.

A Numerical Example

The following numerical example is used to illustrate the Steps of the algorithm. In this example,

$$n = \text{number of GUB sets} = 13,$$

$$m = \text{number of resource constraints} = 4,$$

$$\text{and } p = \text{number of variables in each GUB set} = 4.$$

The problem may be stated as follows:

$$\begin{aligned}
\text{maximize} \quad & 71\,x_{1\,1} + 80\,x_{1\,2} + 94\,x_{1\,3} + 86\,x_{1\,4} + \\
& 81\,x_{2\,1} + 71\,x_{2\,2} + 83\,x_{2\,3} + 82\,x_{2\,4} + \\
& 78\,x_{3\,1} + 93\,x_{3\,2} + 83\,x_{3\,3} + 95\,x_{3\,4} + \\
& 70\,x_{4\,1} + 103\,x_{4\,2} + 107\,x_{4\,3} + 71\,x_{4\,4} + \\
& 80\,x_{5\,1} + 103\,x_{5\,2} + 85\,x_{5\,3} + 93\,x_{5\,4} + \\
& 94\,x_{6\,1} + 84\,x_{6\,2} + 83\,x_{6\,3} + 92\,x_{6\,4} + \\
& 78\,x_{7\,1} + 89\,x_{7\,2} + 99\,x_{7\,3} + 82\,x_{7\,4} + \qquad (R0) \\
& 75\,x_{8\,1} + 104\,x_{8\,2} + 86\,x_{8\,3} + 95\,x_{8\,4} + \\
& 73\,x_{9\,1} + 94\,x_{9\,2} + 103\,x_{9\,3} + 72\,x_{9\,4} + \\
& 79\,x_{10\,1} + 73\,x_{10\,2} + 101\,x_{10\,3} + 102\,x_{10\,4} + \\
& 102\,x_{11\,1} + 98\,x_{11\,2} + 70\,x_{11\,3} + 88\,x_{11\,4} + \\
& 71\,x_{12\,1} + 91\,x_{12\,2} + 98\,x_{12\,3} + 95\,x_{12\,4} + \\
& 88\,x_{13\,1} + 71\,x_{13\,2} + 102\,x_{13\,3} + 94\,x_{13\,4}
\end{aligned}$$

subject to

$$\begin{aligned}
& 14\,x_{1\,1} + 5\,x_{1\,2} + 8\,x_{1\,3} + 6\,x_{1\,4} + \\
& 14\,x_{2\,1} + 12\,x_{2\,2} + 9\,x_{2\,3} + 13\,x_{2\,4} +
\end{aligned}$$

$$
\begin{aligned}
&15\,x_{3\,1} + 9\,x_{3\,2} + 7\,x_{3\,3} + 5\,x_{3\,4} + \\
&15\,x_{4\,1} + 13\,x_{4\,2} + 8\,x_{4\,3} + 5\,x_{4\,4} + \\
&13\,x_{5\,1} + 15\,x_{5\,2} + 4\,x_{5\,3} + 7\,x_{5\,4} + \\
&14\,x_{6\,1} + 6\,x_{6\,2} + 14\,x_{6\,3} + 10\,x_{6\,4} + \\
&15\,x_{7\,1} + 7\,x_{7\,2} + 13\,x_{7\,3} + 8\,x_{7\,4} + \\
&5\,x_{8\,1} + 11\,x_{8\,2} + 8\,x_{8\,3} + 12\,x_{8\,4} + \\
&10\,x_{9\,1} + 5\,x_{9\,2} + 13\,x_{9\,3} + 10\,x_{9\,4} + \\
&10\,x_{10\,1} + 4\,x_{10\,2} + 5\,x_{10\,3} + 9\,x_{10\,4} + \\
&6\,x_{11\,1} + 4\,x_{11\,2} + 7\,x_{11\,3} + 6\,x_{11\,4} + \\
&6\,x_{12\,1} + 11\,x_{12\,2} + 14\,x_{12\,3} + 7\,x_{12\,4} + \\
&4\,x_{13\,1} + 13\,x_{13\,2} + 13\,x_{13\,3} + 10\,x_{13\,4} \le 100
\end{aligned}
\tag{R1}
$$

$$
\begin{aligned}
&14\,x_{1\,1} + 8\,x_{1\,2} + 9\,x_{1\,3} + 13\,x_{1\,4} + \\
&4\,x_{2\,1} + 8\,x_{2\,2} + 12\,x_{2\,3} + 7\,x_{2\,4} + \\
&12\,x_{3\,1} + 14\,x_{3\,2} + 4\,x_{3\,3} + 10\,x_{3\,4} + \\
&6\,x_{4\,1} + 4\,x_{4\,2} + 4\,x_{4\,3} + 8\,x_{4\,4} + \\
&5\,x_{5\,1} + 4\,x_{5\,2} + 4\,x_{5\,3} + 8\,x_{5\,4} + \\
&8\,x_{6\,1} + 15\,x_{6\,2} + 7\,x_{6\,3} + 8\,x_{6\,4} + \\
&10\,x_{7\,1} + 4\,x_{7\,2} + 11\,x_{7\,3} + 11\,x_{7\,4} + \\
&5\,x_{8\,1} + 7\,x_{8\,2} + 5\,x_{8\,3} + 12\,x_{8\,4} + \\
&12\,x_{9\,1} + 13\,x_{9\,2} + 10\,x_{9\,3} + 9\,x_{9\,4} + \\
&5\,x_{10\,1} + 8\,x_{10\,2} + 4\,x_{10\,3} + 12\,x_{10\,4} + \\
&14\,x_{11\,1} + 13\,x_{11\,2} + 11\,x_{11\,3} + 7\,x_{11\,4} + \\
&14\,x_{12\,1} + 11\,x_{12\,2} + 4\,x_{12\,3} + 15\,x_{12\,4} + \\
&12\,x_{13\,1} + 13\,x_{13\,2} + 13\,x_{13\,3} + 11\,x_{13\,4} \le 100
\end{aligned}
\tag{R2}
$$

$$
\begin{aligned}
&14\,x_{1\,1} + 4\,x_{1\,2} + 5\,x_{1\,3} + 5\,x_{1\,4} + \\
&6\,x_{2\,1} + 13\,x_{2\,2} + 4\,x_{2\,3} + 10\,x_{2\,4} + \\
&4\,x_{3\,1} + 14\,x_{3\,2} + 8\,x_{3\,3} + 10\,x_{3\,4} + \\
&6\,x_{4\,1} + 11\,x_{4\,2} + 8\,x_{4\,3} + 12\,x_{4\,4} + \qquad \text{(R3)} \\
&10\,x_{5\,1} + 9\,x_{5\,2} + 10\,x_{5\,3} + 8\,x_{5\,4} + \\
&14\,x_{6\,1} + 7\,x_{6\,2} + 5\,x_{6\,3} + 5\,x_{6\,4} + \\
&6\,x_{7\,1} + 15\,x_{7\,2} + 11\,x_{7\,3} + 14\,x_{7\,4} + \\
&11\,x_{8\,1} + 11\,x_{8\,2} + 13\,x_{8\,3} + 8\,x_{8\,4} + \\
&14\,x_{9\,1} + 15\,x_{9\,2} + 15\,x_{9\,3} + 8\,x_{9\,4} + \\
&9\,x_{10\,1} + 11\,x_{10\,2} + 6\,x_{10\,3} + 14\,x_{10\,4} + \\
&14\,x_{11\,1} + 12\,x_{11\,2} + 10\,x_{11\,3} + 5\,x_{11\,4} + \\
&15\,x_{12\,1} + 11\,x_{12\,2} + 13\,x_{12\,3} + 12\,x_{12\,4} + \\
&11\,x_{13\,1} + 9\,x_{13\,2} + 4\,x_{13\,3} + 7\,x_{13\,4} \quad \leq 100
\end{aligned}
$$

$$
\begin{aligned}
&4\,x_{1\,1} + 5\,x_{1\,2} + 13\,x_{1\,3} + 7\,x_{1\,4} + \\
&13\,x_{2\,1} + 10\,x_{2\,2} + 12\,x_{2\,3} + 11\,x_{2\,4} + \\
&13\,x_{3\,1} + 12\,x_{3\,2} + 7\,x_{3\,3} + 10\,x_{3\,4} + \\
&5\,x_{4\,1} + 14\,x_{4\,2} + 5\,x_{4\,3} + 11\,x_{4\,4} + \\
&9\,x_{5\,1} + 15\,x_{5\,2} + 5\,x_{5\,3} + 5\,x_{5\,4} + \\
&5\,x_{6\,1} + 9\,x_{6\,2} + 15\,x_{6\,3} + 11\,x_{6\,4} + \\
&12\,x_{7\,1} + 6\,x_{7\,2} + 6\,x_{7\,3} + 9\,x_{7\,4} + \qquad \text{(R4)} \\
&14\,x_{8\,1} + 6\,x_{8\,2} + 10\,x_{8\,3} + 9\,x_{8\,4} + \\
&12\,x_{9\,1} + 7\,x_{9\,2} + 14\,x_{9\,3} + 5\,x_{9\,4} + \\
&10\,x_{10\,1} + 8\,x_{10\,2} + 10\,x_{10\,3} + 8\,x_{10\,4} +
\end{aligned}
$$

$$15\, x_{11\,1} + 6\, x_{11\,2} + 15\, x_{11\,3} + 6\, x_{11\,4} +$$
$$15\, x_{12\,1} + 6\, x_{12\,2} + 11\, x_{12\,3} + 12\, x_{12\,4} +$$
$$8\, x_{13\,1} + 12\, x_{13\,2} + 6\, x_{13\,3} + 6\, x_{13\,4} \le 100$$
$$x_{ij} = 0, 1 \qquad i = 1, 2, 3 \ldots, 13,$$
$$j = 1, 2, 3, 4.$$

Equation (R0) is the objective function which is to be maximized. Equations (R1), (R2), (R3) and (R4) are resource constraints. It is assumed that each GUB set has 4 variables. In general the number of variables in each GUB set need not be the same.

Iteration 1.

Step 0: The variable with the highest objective function coefficient is selected from each GUB set. Table A-5 lists those variables which have the highest value of objective function coefficients. The resource requirements for the variables in Table A-5 sums to more than that available. Hence, the solution is not feasible. The value of the objective function is 1286.

Step 1: All variables in each GUB set are ranked according to the ranking criterion described by equation A-12.

In GUB set 1,

$$\gamma_{11} = \frac{71}{14/100 + 14/100 + 14/100 + 4/100} = 154.35$$

$$\gamma_{12} = \frac{80}{5/100 + 8/100 + 4/100 + 5/100} = 363.64$$

$$\gamma_{13} = \frac{94}{8/100 + 9/100 + 5/100 + 13/100} = 268.57$$

$$\gamma_{14} = \frac{86}{6/100 + 13/100 + 5/100 + 7/100} = 277.42$$

Hence, for GUB set 1, the variables should be ranked according to the order $x_{1\ 2}$, $x_{1\ 4}$, $x_{1\ 3}$ and $x_{1\ 1}$. All variables in each GUB set are ranked as shown in Table A-6.

TABLE A-5

Variables with Highest Profit Coefficient

GUB set	Variable	Profit
1	$x_{1\ 3}$	94
2	$x_{2\ 3}$	83
3	$x_{3\ 4}$	95
4	$x_{4\ 3}$	107
5	$x_{5\ 2}$	103
6	$x_{6\ 1}$	94
7	$x_{7\ 3}$	99
8	$x_{8\ 2}$	104
9	$x_{9\ 3}$	103
10	$x_{10\ 4}$	102
11	$x_{11\ 1}$	102
12	$x_{12\ 3}$	98
13	$x_{13\ 3}$	102

Step 2: The highest ranked variable is selected from each GUB set. The initial solution set consists of the variables, $x_{1\ 2}$, $x_{2\ 3}$, $x_{3\ 3}$,

TABLE A-6

Ranking of Variables in Each GUB set

GUB Set	Ranked Variables			
	Rank 1	Rank 2	Rank 3	Rank 4
1	$x_{1\ 2}$	$x_{1\ 4}$	$x_{1\ 3}$	$x_{1\ 1}$
2	$x_{2\ 3}$	$x_{2\ 1}$	$x_{2\ 4}$	$x_{2\ 2}$
3	$x_{3\ 3}$	$x_{3\ 4}$	$x_{3\ 2}$	$x_{3\ 1}$
4	$x_{4\ 3}$	$x_{4\ 2}$	$x_{4\ 1}$	$x_{4\ 4}$
5	$x_{5\ 3}$	$x_{5\ 4}$	$x_{5\ 2}$	$x_{5\ 1}$
6	$x_{6\ 4}$	$x_{6\ 1}$	$x_{6\ 2}$	$x_{6\ 3}$
7	$x_{7\ 2}$	$x_{7\ 3}$	$x_{7\ 4}$	$x_{7\ 1}$
8	$x_{8\ 2}$	$x_{8\ 3}$	$x_{8\ 4}$	$x_{8\ 1}$
9	$x_{9\ 2}$	$x_{9\ 4}$	$x_{9\ 3}$	$x_{9\ 1}$
10	$x_{10\ 3}$	$x_{10\ 4}$	$x_{10\ 2}$	$x_{10\ 1}$
11	$x_{11\ 4}$	$x_{11\ 2}$	$x_{11\ 1}$	$x_{11\ 3}$
12	$x_{12\ 3}$	$x_{12\ 2}$	$x_{12\ 4}$	$x_{12\ 1}$
13	$x_{13\ 3}$	$x_{13\ 4}$	$x_{13\ 1}$	$x_{13\ 2}$

$x_{4\ 3}$, $x_{5\ 3}$, $x_{6\ 4}$, $x_{7\ 2}$, $x_{8\ 2}$, $x_{9\ 2}$, $x_{10\ 3}$, $x_{11\ 4}$, $x_{12\ 3}$ and $x_{13\ 3}$.

Step 3: The resource requirements for the variables in the initial solution set add up to 102 units of resource 1, 92 units of resource 2, 108 units of resource 3, and 112 units of resource 4. Since the limiting resource is 100 units for all resources, all resource constraints except the second are violated, so the solution is infeasible. The value of the objective function is 1210.

Step 4: The effective gradients for the variables in the initial solution set are calculated and shown in Table A-7. From this table it can be observed that variable $x_{7\ 2}$ has the least effective gradient. From Table A-6, variable $x_{7\ 3}$ is the next lower ranked variable in GUB set 7.

Step 5: The variable $x_{7\ 2}$ is exchanged with the variable $x_{7\ 3}$. The current solution set consists of the variables $x_{1\ 2}$, $x_{2\ 3}$, $x_{3\ 3}$, $x_{4\ 3}$, $x_{5\ 3}$, $x_{6\ 4}$, $x_{7\ 3}$, $x_{8\ 2}$, $x_{9\ 2}$, $x_{11\ 4}$, $x_{12\ 3}$, and $x_{13\ 3}$.

TABLE A-7

Effective Gradient of the Variables

in First Iteration

Variable in Solution	Effective Gradient
$x_{1\ 2}$	1·5385
$x_{2\ 3}$	1·2206
$x_{3\ 3}$	0·9022
$x_{4\ 3}$	1·1146
$x_{5\ 3}$	0·8854
$x_{6\ 4}$	1·150
$x_{7\ 2}$	0·6014
$x_{8\ 2}$	0·7879
$x_{9\ 2}$	0·6714
$x_{10\ 3}$	1·4853
$x_{11\ 4}$	1·3750
$x_{12\ 3}$	0·6215
$x_{13\ 3}$	1·2143

Iteration 2

Step 3: Summing the resource requirements for the variables in the current solution, it is observed that the constraints are not satisfied. The objective function value at this iteration is 1212.

Step 4: The effective gradients of the variables in the current solution set are calculated as shown in Table A-8.

TABLE A-8

Effective Gradient of Variables in Second Iteration

Variable in Solution	Effective Gradient
$x_{1\ 2}$	1·2121
$x_{2\ 3}$	0·7830
$x_{3\ 3}$	0·8137
$x_{4\ 3}$	0·9554
$x_{5\ 3}$	1·0625
$x_{6\ 4}$	0·7667
$x_{7\ 3}$	0·5690
$x_{8\ 2}$	0·6753
$x_{9\ 2}$	0·8446
$x_{10\ 3}$	1·3649
$x_{11\ 4}$	1·1000
$x_{12\ 3}$	0·5104
$x_{13\ 3}$	0·6986

In Table A-8 the variable $x_{12\ 3}$ has the least effective gradient. From Table A-6, the variable $x_{12\ 2}$ is the next lower ranked variable in GUB set 12.

Step 5: The variable $x_{12\ 3}$ is exchanged for the variable $x_{12\ 2}$ in GUB set 12. The current solution set consists of the variables $x_{1\ 2}$, $x_{2\ 3}$, $x_{3\ 3}$, $x_{4\ 3}$, $x_{5\ 3}$, $x_{6\ 4}$, $x_{7\ 3}$, $x_{8\ 2}$, $x_{9\ 2}$, $x_{10\ 3}$, $x_{11\ 4}$, $x_{12\ 2}$, $x_{13\ 3}$.

Iteration 3

Step 3: Summing the resource requirements for the current solution set, it is observed that the constraints are not satisfied. The value of the objective function is 1205.

Step 4: The effective gradients of the variables in the current solution set are calculated as shown in Table A-9. Variable $x_{12\ 2}$ has the least effective gradient. From Table A-6, the variable $x_{12\ 4}$ is the next lower ranked variable in GUB set 12.

Step 5: $x_{12\ 4}$ is exchanged for the variable $x_{12\ 2}$ in GUB set 12. The current solution set consists of the variables $x_{1\ 2}$, $x_{2\ 3}$, $x_{3\ 3}$, $x_{4\ 3}$, $x_{5\ 3}$, $x_{6\ 4}$, $x_{7\ 3}$, $x_{8\ 2}$, $x_{9\ 2}$, $x_{10\ 3}$, $x_{11\ 4}$, $x_{12\ 4}$ and $x_{13\ 3}$.

Iteration 4

Step 3: The resource requirements are summed for the variables in the current solution set. The resource constraints are not satisfied. The objective function value is 1209.

Step 4: The effective gradients of the varialbes in the current solution set, is calculated as shown in Table A-10. The variable $x_{12\ 4}$ has the least effective gradient. $x_{12\ 1}$ is the next lower ranked variable in GUB set 12.

TABLE A-9

Effective Gradients of the Variables

in Third Iteration

Variables in the Solution	Effective Gradient
$x_{1\ 2}$	0·8791
$x_{2\ 3}$	0·5804
$x_{3\ 3}$	0·9326
$x_{4\ 3}$	1·1146
$x_{5\ 3}$	1·1806
$x_{6\ 4}$	0·7186
$x_{7\ 3}$	0·5531
$x_{8\ 2}$	0·7376
$x_{9\ 2}$	0·6574
$x_{10\ 3}$	1·4226
$x_{11\ 4}$	0·9362
$x_{12\ 2}$	0·5515
$x_{13\ 3}$	0·5763

TABLE A-10

Effective Gradients of the Variables

in Fourth Iteration

Variables in Solution	Effective Gradient
$x_{1\ 2}$	0.7477
$x_{2\ 3}$	0.5220
$x_{3\ 3}$	0.9765
$x_{4\ 3}$	1.2160
$x_{5\ 3}$	1.0366
$x_{6\ 4}$	0.7360
$x_{7\ 3}$	0.5440
$x_{8\ 2}$	0.7647
$x_{9\ 2}$	0.4948
$x_{10\ 3}$	1.3836
$x_{11\ 4}$	0.8544
$x_{12\ 4}$	0.4500
$x_{13\ 3}$	0.5636

Step 5: $x_{12\ 1}$ is exchanged for the variable $x_{12\ 4}$. The variables in the current solution set are: $x_{1\ 2}$, $x_{2\ 3}$, $x_{3\ 3}$, $x_{4\ 3}$, $x_{5\ 7}$, $x_{6\ 4}$, $x_{7\ 3}$, $x_{8\ 2}$, $x_{9\ 2}$, $x_{10\ 3}$, $x_{11\ 4}$, $x_{12\ 1}$ and $x_{13\ 3}$.

Iteration 5

Step 3: The resource constraints are not satisfied, as the resource requirements for the variables in the solution sum to more than the limiting resource. The objective function value is 1189.

Step 4: The effective gradients are calculated as shown in Table A-11. The variable $x_{12\ 1}$ has the least value of effective gradient. From Table A-6 it can be observed that there is no other varialbe in GUB set 12 that may be exchanged for the variable $x_{12\ 1}$.

Step 6: GUB set 12 is dropped from the solution set. The variables in the current solution set are, $x_{1\ 2}$, $x_{2\ 3}$, $x_{3\ 3}$, $x_{4\ 3}$, $x_{5\ 3}$, $x_{6\ 4}$, $x_{7\ 3}$, $x_{8\ 2}$, $x_{9\ 2}$, $x_{10\ 3}$, $x_{11\ 4}$ and $x_{13\ 3}$.

Iteration 6

Step 3: The resource requirements for the variables in the current solution set add to 96 units of resource 1, 95 units of resource 2, 91 units of resource 3 and 86 units of resource 4. Since all resource constraints are satisfied, the current solution set is feasible. The objective function value is 1118. The slack capacities in the four resource constraints are 4, 5, 9 and 14 units respectively.

Step 7: GUB set 12 is the only GUB set which is not in solution. The variables in GUB set 12, are $x_{12\ 1}$, $x_{12\ 2}$, $x_{12\ 3}$ and $x_{12\ 4}$. The resource requirements for these variables are shown in Table A-12. From Table A-12 it can be observed that there are no feasible variables that can be added which simultaneously satisfy the remaining slack capacities in the resource constraints. Thus, GUB set 12 will not be added back to the solution set.

Iteration 7

Step 9: The GUB sets in the solution are 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 13. GUB sets 1, 3, 5, 6, 9, 10, and 11 have variables with higher objective function coefficients than the variables in the solution. Table 3-13

TABLE A-11

Effective Gradients of the Variables

in Fifth Iteration

Variables in Solution	Effective Gradient
$x_{1\ 2}$	0·7207
$x_{2\ 3}$	0·5124
$x_{3\ 3}$	0·7905
$x_{4\ 3}$	1·0191
$x_{5\ 3}$	0·7798
$x_{6\ 4}$	0·6918
$x_{7\ 3}$	0·5026
$x_{8\ 2}$	0·6624
$x_{9\ 2}$	0·4197
$x_{10\ 3}$	1·0979
$x_{11\ 4}$	0·7928
$x_{12\ 1}$	0·2922
$x_{13\ 3}$	0·5896

TABLE A-12

Resource Requirements for the Variables of the GUB Sets Not Included in the Solution

Variable	Resource Requirements			
	Resource 1	Resource 2	Resource 3	Resource 4
$x_{12\ 1}$	6	14	15	15
$x_{12\ 2}$	11	11	11	6
$x_{12\ 3}$	14	4	13	11
$x_{12\ 4}$	7	15	12	12
Slack Capacity	4	5	9	14

(p. 49) shows the variables that can be exchanged for the variables in solution and still satisfy the resource constraints.

Step 10: Table A-13 shows the feasible variables which can be brought into the solution in exchange for the variables already in the solution, and also the corresponding difference in the objective function value. Variable $x_{1\ 3}$ has the maximum difference in profit. Any other combination of feasible variables shown in Table 3-13 does not yield a better objective function value than that obtained by bringing $x_{1\ 3}$ into the solution. Therefore, $x_{1\ 3}$ is brought into solution in exchange for $x_{1\ 2}$. The new solution set consists of the variables $x_{1\ 3}$, $x_{2\ 3}$, $x_{3\ 3}$, $x_{4\ 3}$, $x_{5\ 3}$, $x_{7\ 3}$, $x_{8\ 2}$, $x_{9\ 2}$, $x_{10\ 3}$, $x_{11\ 4}$ and $x_{13\ 3}$. The objective function value is 1132. The resource requirements add up to 99, 96, 92 and 94 units of resources 1, 2, 3, and 4 respectively. Since there still exists some slack in the resource constraints, Step 9 is repeated.

TABLE A-13

Exchange of Variables Within the

GUB Sets in Solution

GUB Set	Variable With Higher Profit	Is Exchange Feasible?	Difference in Profit
1	$x_{1\ 3}$	yes	14
	$x_{1\ 4}$	yes	6
3	$x_{3\ 2}$	no	
	$x_{3\ 4}$	no	
5	$x_{5\ 2}$	no	
	$x_{5\ 4}$	yes	8
6	$x_{6\ 1}$	yes	2
9	$x_{9\ 3}$	no	
10	$x_{10\ 4}$	yes	1
11	$x_{11\ 1}$	no	
	$x_{11\ 2}$	no	

Iteration 8

Step 9: Variables having higher profit co-efficients than the ones currently in solution, are not feasible. This is due to the fact that they cannot satisfy the remaining slack capacities in the resource constraints.

Step 11: The final solution is $x_{1\ 3} = 1$, $x_{2\ 3} = 1$, $x_{3\ 3} = 1$, $x_{4\ 3} = 1$, $x_{5\ 3} = 1$, $x_{6\ 4} = 1$, $x_{7\ 3} = 1$, $x_{8\ 2} = 1$, $x_{9\ 2} = 1$, $x_{10\ 3} = 1$,

$x_{11\ 4} = 1$ and $x_{13\ 3} = 1$. The remaining variables are 0, and the final objective function value is 1132.

Fig. A.4 shows the value of the objective function in successive iterations. In iterations 1 through 5 the solution is infeasible. Feasibility is attained in iteration 6 and the value of the objective function is further improved in the 7th iteration. After that no further improvement is possible in the algorithmic procedure and consequently the algorithm is terminated.

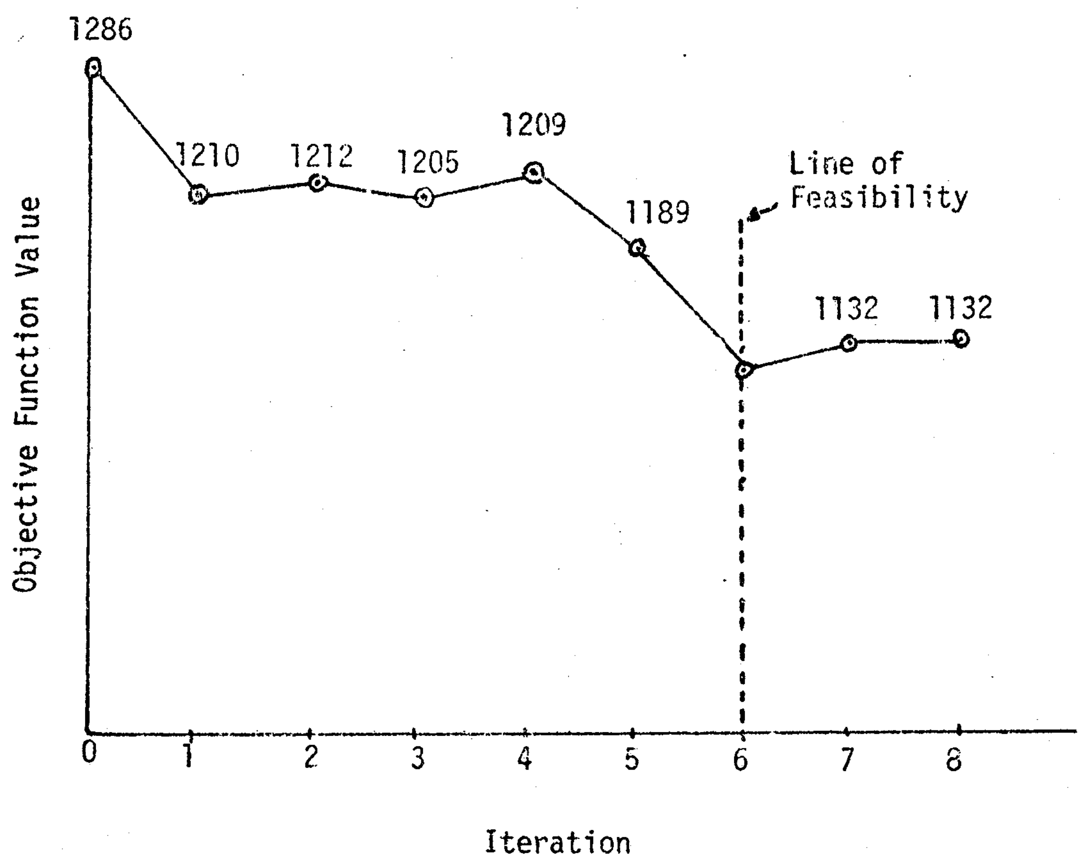


Fig. A.4 Change in Objective Function Value in Successive Iterations

Computational Experience:

Comparison with Other Algorithms

To test the veracity of the solution obtained by the proposed algorithm, several test problems were generated, using random number generators. All test problems are of the following form:

$$\text{(IP A.3)} \qquad \max \sum_{i=1}^{n} \sum_{j=1}^{P_i} C_{ij}\, x_{ij}$$

subject to

$$\sum_{i=1}^{n} \sum_{j=1}^{P_i} a_{ij\ell}\, x_{ij} \leq b_\ell, \quad \ell = 1, 2, \ldots, m,$$

$$\sum_{j=1}^{P_i} x_{ij} \leq 1 \quad i = 1, 2, \ldots, n,$$

$$x_{ij} = 0, 1 \qquad i = 1, 2, \ldots, n,$$

$$j = 1, 2, \ldots, P_i,$$

$$a_{ji\ell} \geq 0 \text{ for all } i, j, \ell, \text{ and}$$

$$C_{ij} \geq 0 \text{ for all } i, j.$$

The test problems were deliberately kept moderate in size, so that other algorithms can satisfactorily be applied. The algorithm developed [1] was coded in the FORTRAN IV computer language, and the test problems were run on an AMDHAL 470/V6 computer. To compare the solutions obtained, the test problems were also solved by the ILLIP-2 (24) code obtained from the University of Illinois. The ILLIP-2 code uses branch and bound and implicit enumeration technique (4, 9) to solve 0-1 integer linear programming problems. The ILLIP-2 is coded in FORTRAN IV and proved to be superior than other available general 0-1 integer programming codes because of it's ability to handle relatively larger problems.

The solutions obtained by the algorithm developed were used as the starting solutions for the ILLIP-2 code, so that convergence of ILLIP-2 could be obtained in minimum number of iterations. In only three cases better solutions (which were close to the solutions obtained by the algorithm) were obtained after 5000 iterations. In all other test problems, no better solutions could be obtained by the ILLIP02 code.

From Table A-14, it may be observed that, the solution times for problems having variables between 30 and 52, ranged from 1.06 seconds to 1.47 seconds by the proposed algorithm. The solution time for ILLIP-2 code ranged from 40 to 60 seconds. The average solution time for all the test problems were 1.36 seconds by the proposed algorithm and 56 seconds by ILLIP-2.

The proposed algorithm converges very rapidly, once the feasibility is attained. The solution time by ILLIP-2 code is longer as it implicity enumerates a large number of different possible solutions (for n variables, there may be 2^n possible enumerations). The ILLIP-2 code showed improvements in objective function values for test problems 2, 3, and 4. Note that the improvements were insignificant from the percentage standpoint and varied from 0.16% for test problem 4 to a maximum of 1.8% for test problem 3. The average improvement for 13 test problems was only 0.258% which is also insignificant for all practical purposes.

The computational speed and the sorting method employed in this computer program can both be improved still farther.

TABLE A-14

Comparison of Results

Test Problem #	1	2	3	4	5	6	7	8	9	10	11	12	13	Average
Number of Variables	30	52	50	40	50	50	40	50	50	50	50	50	40	46.3
Number of Resource Constraints	5	4	5	5	5	5	7	5	5	5	5	5	5	5.15
Number of GUB Constraints	10	13	10	10	10	10	10	10	10	10	10	10	10	10.2
Solution Time in Seconds by the Proposed Algorithm	1.06	1.36	1.3	1.29	1.39	1.31	1.46	1.45	1.45	1.43	1.42	1.47	1.33	1.36
Solution Time in Seconds by the ILLIP-2 Code	40	60	60	45	60	60	50	60	60	60	60	60	52	56
Does ILLIP-2 Code Give Better Solution?	No	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	
Percent Improvement by ILLIP-2 Code Over Proposed Algorithm	0	1.4	1.8	1.6	0	0	0	0	0	0	0	0	0	.258

Comparison to Continuous Linear Programming Solutions

One of the approaches used to judge the quality of solutions obtained by the proposed algorithm was to find the gap between the integer solution and the continuous linear programming solutions without the integrality requirement. This gap may be termed as the "integrality gap". In some cases at optimality, the integrality gap may not be very wide.

The algorithm was applied to two test problems developed by the Texas Transportation Institute of the Texas A&M University. The same test problems were also solved by the MPSX package (Mathematical Programming System) of IBM (International Business Machine), to generate continuous linear programming solutions. (The MPSX package at the Texas A&M University Computer Center did not have the 0-1 integer programming algorithm, during the period of this research.) The continuous linear programming solutions are infeasible (as they do not satisfy the integrality requirements of the 0-1 variables) and super optimal relative to the problems. However the objective function values obtained by the proposed algorithm were significantly close to that of continuous linear programming solutions. Table A-15 shows the comparison of results with the continuous linear programming solutions. From Table A-15 it may be observed that, for problems A and B the "integrality gap" is 5.9% and 0.72% respectively. This reflects that the solutions obtained by the proposed algorithm are significantly close to the continuous linear programming solutions. It may be noted that the solutions obtained by the proposed algorithm for problem B is either optimal or very close to optimal. However, for problem A the integrality gap is a little bit higher, but not significantly high to

TABLE A-15

Comparison of Results With MPSX Solution

Problem	No. of Variables	No. of GUB Constraints	No. of Resource Constraints	Objective Function Value by the Proposed Algorithm	Objective Function Value by MPSX	Difference in Objective Function Value
A	50	5	16	539401	572993 (310694)	5.9 %
B	50	5	16	705889	711047 (512849)	.72%

discard near optimality the integer programming solution. The figures in parentheses under the column "Objective Function Value by MPSX" represent the objective function value of the rounded integer LP solution. In both of the cases the objective function value is significantly lower than those obtained by the proposed algorithm.

Computational Experience With Large Problems

The main thrust behind this research effort is to develop an algorithm to solve large scale 0-1 integer programming problems with multiple-choice constraints. Several large test problems were generated through the use of random number generators. The test problems were run on the AMDHAL 470/V6 computer. These test problems could not be checked by other algorithms with regard to the optimality of solution. The reason is due to the fact that available algorithms are incapable of handling such large scale problems. The average solution times (on the basis of 6 problems) for problems of different sizes are presented in Table A-16. From Table A-16 it may be observed that solution times for fairly large problems (variables between 200 - 1000) is relatively low. Also the solution times for very large problems (> 1000 variable) is within manageable limits. Solution time for a problem of 4000 variables is 719 seconds which is reasonable, relative to the size of the problem. Solution time seems to increase linearly up to 200 variables, then the increase follows an exponential pattern.

TABLE A-16

Average Solution Time

for Large Scale Problems

Number of Variables	Number of GUB Constraints	Number of Resource Constraints	Average Solution Time in Seconds
200	40	5	2.37
500	100	18	10.43
600	100	19	17.91
1000	100	15	24.30
4000	400	5	719.00

APPENDIX B

DOCUMENTATION OF HIGHWAY REHABILITATION AND MAINTENANCE COMPUTER PROGRAM

PROGRAM FOR REHABILITATION AND

MAINTENANCE OF HIGHWAY SYSTEMS

Author:	Nazim Uddin Ahmed
Installation:	AMDHAL 470/V6 at Texas A&M University
Date written:	Spring 1978

The program consists of the following subroutines.

(1) INPUT

This subroutine reads the input data from cards.

(2) DATACK

This subroutine provides the printout of the input data.

(3) ECOCK

This subroutine prints the objective function coefficients and the constraint coefficients in the form of a 0-1 integer programming problem. This subroutine is optional to the program and may be executed, only if necessary.

(4) SORT

This subroutine sorts an array in ascending order.

(5) SORT 1

This subroutine sorts an array in descending order.

(6) MINDIS

This subroutine finds the feasible strategies for all highway segments according to the minimum pavement rating requirement constraint.

(7) ALLDIS

This subroutine obtains the feasible strategies for all highway segments according to the overall rating requirement constraint.

(8) CALC

This subroutine calculates the objective function coefficients, converts the constraint coefficients as the percent of respective resources available and ranks the feasible strategies in each highway segment.

(9) GRAD

This subroutine generates the initial feasible solution, utilizing the criterion of effective gradient.

(10) PICKUP

This subroutine attempts to include additional highway segments into the solution, after the initial feasible solution is obtained in subroutine GRAD.

(11) SEARCH

The purpose of this subroutine is to improve the solution, by searching for better strategies than the ones obtained in subroutines GRAD and PICKUP.

(12) RPRINT

This subroutine prints the initial optimal solution and adds strategy-section combinations to use the remaining budget, with preference for the lowest rated sections.

(13) IPRINT

This is an auxiliary subroutine used as input to subroutine RPRINT.
The organization of the subroutines is presented in Figure B. 1.

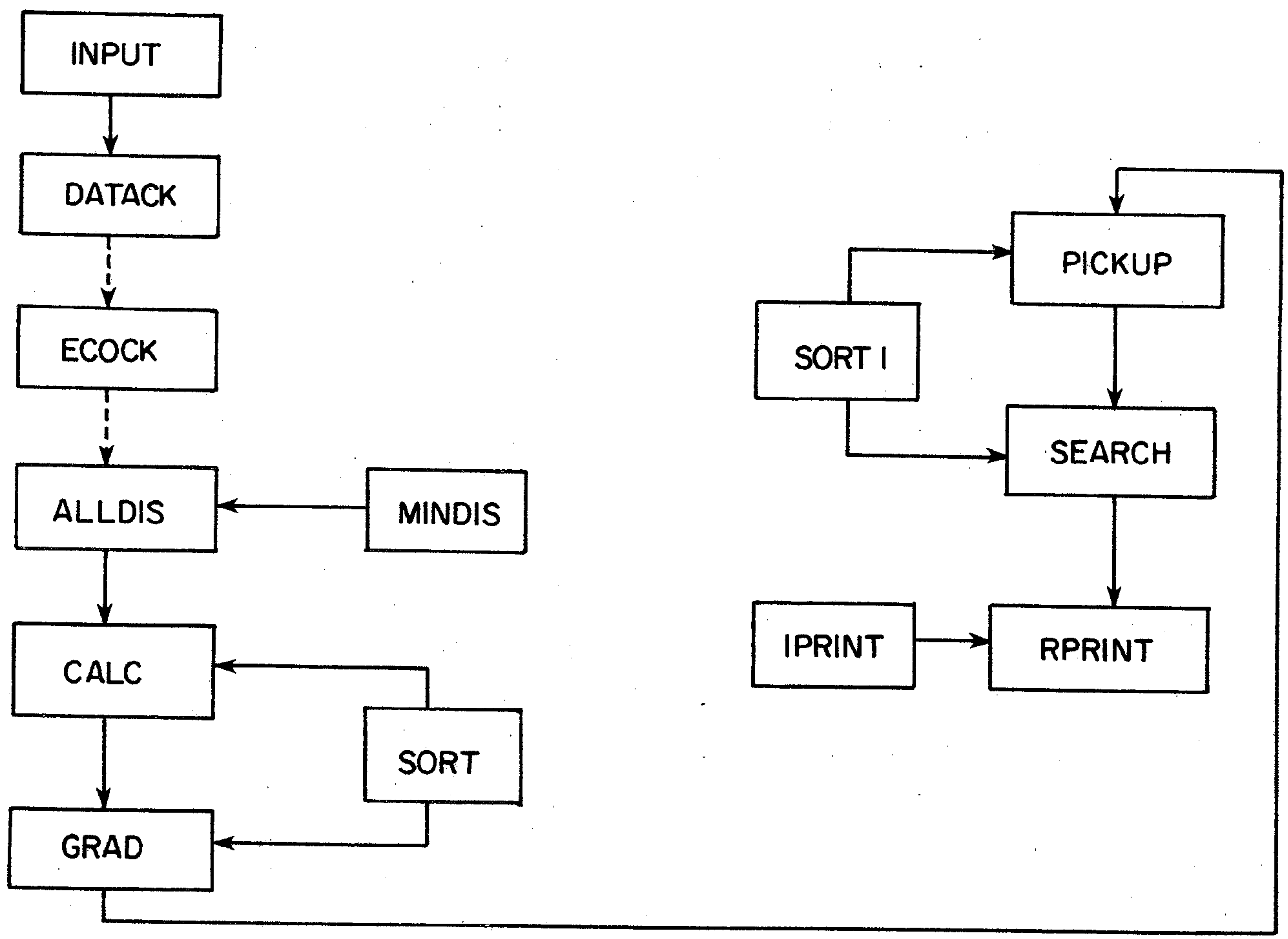


Fig. B.1 Organization of the Subroutines.

RAMSDO PROJECT CODING INSTRUCTIONS

The following instructions are designed to help users to code input data for the "RAMSDØ1" program.

1) A card to read in the title of the problem.

Column	Description	Data Type
1 - 80	Name of the problem	Alphanumeric

2) A card that reads in the following variables:

Column	Description	Data Type
1-5	NH = number of highway segments	Integer, right justified
5-10	NS = number of strategies	Integer, right justified
11-15	TDATA = number of years on input data	Integer, right justified
16-20	T = number of time periods used in analysis	Integer, right justified
21-25	ND = number of distress types	Integer, right justified
26-30	NHTYP = number of highway types	Integer, right justified
31-35	G = number of material types	Integer, right justified
36-40	F = number of equipment types	Integer, right justified
41-45	Q = number of manpower types	Integer, right justified

Column	Description	Data Type
46-50	IECK = An indicator for calling the subroutine ECØCK. If IECK=1, the subroutine ECØCK will be executed and the objective function coefficients and the constraint coefficients will be printed as in a regular integer programming problem.	Integer, right justified

3) Number of cards equals the number of highway segments, with each card containing the following information for each highway segment.

Column	Description	Data Type
1-8	L1(I) = Length of Ith highway segment in miles	Numeric, with a decimal point
9-16	L2(I) = Width of Ith highway segment in feet	Numeric, with a decimal point
17-20	HYTYP(I) = Type of Ith highway segment	Integer, right justified
21-28	TRAF(I) = Traffic Index of Ith highway segment	Numeric with a decimal point
29-36	ENVIR(I) = Environmental Index of Ith highway segment	Numeric with a decimal point
37-44	PAR1(I) = name of Ith highway segment	Alphanumeric, left justified
45-56	PAR2(I) = County name of the Ith highway segment	Alphanumeric, left justified
57-64	PAR3(I) = Control section name of the Ith highway segment	Alphanumeric, left justified
65-72	PAR4(I) = Beginning milepoint of the Ith highway segment	Numeric with a decimal point
73-80	PAR5(I) = Ending milepoint of the Ith highway segment	Numeric with a decimal point

4) Cards to read in name of strategies. Up to 3 names may be coded on one card. Users may use as many cards as required with each card having the following format:

Column	Description (I from 1 to NS)	Data Type
1-24	STRAT(I) = name of the Ith strategy	Alphanumeric, left justified
25-48	STRAT(I) = name of the Ith strategy	Alphanumeric, left justified
49-72	STRAT(I) = name of the Ith strategy	Alphanumeric, left justified

5) Cards to read in name of distress types. Up to 4 distress types may be coded on one card, users may use as many cards as required with each card having the following format:

Column	Description (K from 1 to ND)	Data Type
1-20	DISTR(K) = name of the Kth distress type	Alphanumeric, left justified
21-40	DISTR(K) = name of the Kth distress type	Alphanumeric, left justified
41-60	DISTR(K) = name of the Kth distress type	Alphanumeric, left justified
61-80	DISTR(K) = name of the Kth distress type	Alphanumeric, left justified

6) Cards to read in names of the material types. Up to 4 material types may be coded on each card. Use as many cards as required. Each card has the following format:

Column	Description (I from 1 to G)	Data Type
1-20	MAT(I) = name of Ith material type	Alphanumeric, left justified
21-40	MAT(I) = name of Ith material type	Alphanumeric, left justified
41-60	MAT(I) = name of Ith material type	Alphanumeric, left justified
61-80	MAT(I) = name of Ith material type	Alphanumeric, left justified

7) Cards to read in the amount available for each material type which is to be expressed as quantity divided by the number of mile-feet sections in the NH number of highway segments. Up to 8 items can be coded on each card. Use as many cards as required. Each card has the following format:

Column	Description (I from 1 to G)	Data Type
1-10	SG(I) = amount of material type I available	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

8) Cards to read in material requirement per mile-foot unit for each of the strategies applied. Up to 8 types of materials may be coded on each card. Use as many cards as needed for each strategy. Each card has the following format:

Column	Description (J from 1 to NS) (L from 1 to G)	Data Type
1-10	SGR(J,L) = Lth material requirement in tons/ft.mile if Jth strategy is applied	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

9) Cards to read in names of the equipemnt types per mile-foot unit. Up to 4 names may be coded on each card. Use as many cards as required. Each card ahs the following format:

Column	Description (I from 1 to F)	Data Type
1-20	EQUIP(I) = name of the Ith equipment type	Alphanumeric, left justified
21-40	" "	" "
41-60	" "	" "
61-80	" "	" "

10) Cards to read in amount available for each mile-foot unit in the NH number of segments of each equipment type. Up to 8 items may be coded on each card. Use as many cards as required. Each card has the following format:

Column	Description (I from 1 to F)	Data Type
1-10	EF(I) = amount of equipment type I available	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

11) Cards to read in equipment requirement per mile-foot unit for each strategy applied. Up to 8 items may be coded on each card. Use as many cards as needed for the equipment requirement for each strategy. Each card has the following format:

Column	Description (J from 1 to NS) (L from 1 to F)	Data Type
1-10	EFR(J,L) = Lth equipment requirement in equipment-days per ft. mile if Jth strategy is applied	Numeric with a decimal point

Column	Description (J from 1 to NS) (L from 1 to F)	Data Type
11-20	EFR(J,L) = Lth equipment requirement in equipment-days per ft. mile if Jth strategy is applied	Numeric with a decimal point
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

12) Cards to read in names of manpower types. Up to 4 names may be coded on each card. Use as many cards as needed. Each card has the following format:

Column	Description (I from 1 to Q)	Data Type
1-20	MANP(I) = name of the Ith manpower type	Alphanumeric, left justified
21-40	" "	" "
41-60	" "	" "
61-80	" "	" "

13) Cards to read in amount available per mile-foot unit in NH segments for each manpower type. Up to 8 items may be coded on each card. Use as many cards as needed. Each card has the following format:

Column	Description (I from 1 to Q)	Data Type
1-10	HQ(I) = amount of manpower type I available	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "

Column	Description (I from 1 to Q)	Data Type
41-50	HQ(I) = amount of manpower type I available	Numeric with a decimal point
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

14) Cards to read in manpower requirement per mile-foot unit for each strategy applied. Up to 8 items may be coded on each card. Use as many cards as needed for each strategy applied. Each card has the following format:

Column	Description (J from 1 to NS) (L from 1 to Q)	Data Type
1-10	HQR(J,L) = Lth manpower requirement in man-days per ft. mile if Jth strategy is applied	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

15) A card to read in name of the overhead budget. It has the following format:

Column	Description	Data Type
1-20	OVHD = overhead budget name	Alphanumeric, left justified

16) Cards to read in overhead budget requirement per mile-foot unit for each strategy applied. Use as many cards as needed. Each card has the following format:

Column	Description (I from 1 to NS)	Data Type
1-10	CR(I) = overhead budget requirement if Ith strategy is applied	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

17) A card to read in total budget available. It has the following format:

Column	Description	Data Type
1-20	CC = total overhead budget available	Numeric with a decimal point

18) Cards to read in potential gains of pavement rating for each distress type if a certain strategy is applied. Up to 8 items may be coded on each card. Use as many cards as needed for each strategy applied. Each card has the following format:

Column	Description (J from 1 to NS) (K from 1 to ND)	Data Type
1-10	DIST(J,K) = potential gains of pavement rating for Kth distress type if Jth strategy is applied	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "

Column	Description (J from 1 to NS) (K from 1 to ND)	Data Type
41-50	DIST(J,K) = potential gain of pavement rating for Kth distress type if Jth strategy is applied	Numeric with a decimal point
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

19) Cards to read in maximum possible rating for each of the distress types. Up to 8 items may be coded on one card. Use as many cards as needed. Each card has the following format:

Column	Description (K from 1 to ND)	Data Type
1-10	RMAX(K) = maximum possible rating for Kth distress type	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

20) Cards to read in current pavement rating for each highway segment if a certain distress type is present. Up to 8 items may be coded on one card. Use as many cards as needed for each highway segment. Each card has the following format:

Column	Description (I from 1 to NH) (K from 1 to ND)	Data Type
1-10	R(I,K) = current pavement rating for Ith highway segment if Kth distress is present	Numeric with a decimal point

Column	Description (I from 1 to NH) (K from 1 to ND)	Data Type
11-20	R(I,K) = current pavement rating for Ith highway segment if Kth distress is present	Numeric with a decimal point
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

21) Cards to read in minimum pavement rating requirement for a specific time period and distress type of a certain highway type. Up to 8 items may be coded on one card. Use as many cards as needed to code all time periods for each distress type. Each card has the following format:

Column	Description (II is 1 to NHTYP) (K is 1 to ND) (L is to TDATA)	Data Type
1-10	RMIN(K,L,II) = minimum pavement rating requirement for Lth time period and Kth distress type if the highway segment is of type II	Numeric with a decimal point
11-20	" "	" "
21-30	" "	" "
31-40	" "	" "
41-50	" "	" "
51-60	" "	" "
61-70	" "	" "
71-80	" "	" "

22) Cards to read in probability of survival for certain time period if certain strategy is applied. Up to 8 items may be coded on each card. Use as many cards as needed to code all time periods for each strategy. Each card has the following format:

Column	Description (K from 1 to ND) (J from 1 to NS) (L from 1 to TDATA)		Data Type	
1-10	P(J,K,L) =	probability of survival for the Lth time period if Kth distress type is present and strategy J is applied	Numeric with a decimal point	
11-20	"	"	"	"
21-30	"	"	"	"
31-40	"	"	"	"
41-50	"	"	"	"
51-60	"	"	"	"
61-70	"	"	"	"
71-80	"	"	"	"

23) Cards to read in overall pavement rating requirement of each highway type. Up to 8 items may be coded on each card. Users may use as many cards as needed. Each card has the following format:

Column	Description		Data Type	
1-10	WW(I) =	overall pavement rating requirement of the Ith highway type	Numeric with a decimal point	
11-20	"	"	"	"
21-30	"	"	"	"
31-40	"	"	"	"
41-50	"	"	"	"
51-60	"	"	"	"
61-70	"	"	"	"
71-80	"	"	"	"

24) Cards to read in restrictions on decision variable X(I,J). The first card in this group indicates the number of X(I,J) (or cards) to be read in. It has the following format:

Column	Description	Data Type
1-4	Number of X(K,J) or cards to be read in	Integer, right justified

Each of the rest of the cards reads in a value of I (a highway segment number), a value of J (a strategy number), and the value of X(K,J) (which is Ø for withhold) with the following format:

Column	Description	Data Type
1-5	Value of I	Integer, right justified
6-10	Value of J	Integer, right justified
11-15	Value of X(I,J)	Integer, right justified

25) Cards to read in a list of complete strategies withheld with a Ø at the end of the list. One strategy number is coded on each card with the following format:

Column	Description	Data Type
1-5	JOUT = strategy number	Integer, right justified

The last card on the list should be coded as follows:

Column	Data
1-4	Blanks
5	Ø

APPENDIX C

INPUT

FOR THE

HIGHWAY MAINTENANCE PROBLEM

TEST PROBLEM FOR THE STATE OF TEXAS

THE FOLLOWING REPRESENTS THE INPUT FOR THE PROBLEM

NO. OF HIGHWAY SEGMENTS= 15 NO. OF STRATEGIES= 8 NO. OF ANALYSIS PERIOD= 10
NO. OF DISTRESS TYPES= 6 NO. OF HIGHWAY TYPES= 2
IECK= 0
YEARS OF INPUT DATA= 20

NO. OF MATERIAL TYPES= 4 NO. OF EQUIPMENT TYPES= 8 NO. OF MANPOWER TYPES= 8

SEGMENT NUMBER	TYPE	HIGHWAY	COUNTY	CONTROL SECTION	LENGTH	WIDTH	BEGINNING MILE POINT	ENDING MILE POINT	TRAFFIC INDEX	ENVIRONMENTAL INDEX
1	1	US 79	MILAM	0204-05	4.530	26.000	0.0	0.0	1.000	1.000
2	1	US 77	MILAM	0209-05	12.320	28.000	0.0	0.0	1.000	1.000
3	1	US 190	MILAM	0815-02	3.620	26.000	0.0	0.0	1.000	1.000
4	2	SH OSR	MADISON	0475-04	7.000	20.000	0.0	0.0	1.000	1.000
5	2	SH OSR	MADISON	0475-03	2.260	22.000	0.0	0.0	1.000	1.000
6	2	FM1696	WALKER	1809-02	13.800	20.000	0.0	0.0	1.000	1.000
7	2	FM 1791	WALKER	1706-01	12.370	22.000	0.0	0.0	1.000	1.000
8	2	FM2821	WALKER	2805-01	3.340	24.000	0.0	0.0	1.000	1.000
9	1	SH 30	WALKER	0212-02	7.390	26.000	0.0	0.0	1.000	1.000
10	1	SH 36	BURLESON	0816-03	12.010	26.000	0.0	0.0	1.000	1.000
11	1	US 290	WASHINGTON	0114-09	9.021	26.000	0.0	0.0	1.000	1.000
12	1	US 79	MILAM	0204-08	5.640	26.000	0.0	0.0	1.000	1.000
13	1	SH 36	BURLESON	0186-02	9.320	26.000	0.0	0.0	1.000	1.000
14	2	SH OSR	BRAZOS	0475-02	6.670	20.000	0.0	0.0	1.000	1.000
15	2	FM 908	MILAM	0858-02	7.440	20.000	0.0	0.0	1.000	1.000

STRATEGY NO.	NAME
1	FOG SEAL
2	SEAL COAT
3	OGPMS
4	THIN OVERLAY
5	MODERATE OVERLAY
6	HEAVY OVERLAY
7	LIGHTDUTY RECONSTRUCTION
8	HEAVY DUTY RECONSTRT.

DISTRESS TYPE	NAME
1	RUTTING
2	ALLIGATOR CRACKING
3	LONGTUD. CRACKING
4	TRANSVERSE CRACKING
5	FAILURES/MILE
6	SERVICEABILITY INDEX

MATERIAL REQUIREMENT AND AVAILABILITY

MATERIAL TYPE	NAME
1	SURFACING AGGREGATE
2	ASPHALT CEMENT
3	AGGREGATE(ITEM 340:)
4	AGGREGATE ITEM 290

STRATEGY	MATERIAL TYPE 1	2	3	4
1	0.0	0.400	0.0	0.0
2	9.500	0.800	0.0	0.0
3	0.0	3.000	20.000	0.0
4	0.0	1.500	29.300	0.0
5	0.0	4.100	80.500	0.0
6	0.0	8.100	29.300	132.000
7	10.000	1.500	0.0	0.0
8	0.0	1.500	29.300	143.000
AVAILABLE	9.500	4.600	87.700	87.700

EQUIPMENT REQUIREMENT AND AVAILABILITY

EQUIPMENT TYPE	NAME
1	GRADER
2	PICKUP
3	LOADER
4	TRUCK
5	ROLLER
6	SPREADER
7	LAYDOWN MACHINE
8	ASPHALT DISTRIBUTOR

EQUIPMENT TYPE

STRATEGY	1	2	3	4	5	6	7	8
1	0.0	0.008	0.0	0.017	0.0	0.0	0.0	0.008
2	0.0	0.012	0.012	0.060	0.024	0.012	0.0	0.012
3	0.0	0.111	0.0	0.278	0.111	0.0	0.056	0.056
4	0.0	0.111	0.0	0.278	0.111	0.0	0.056	0.056
5	0.0	0.222	0.0	0.556	0.222	0.0	0.111	0.111
6	0.0	0.333	0.0	0.834	0.333	0.0	0.168	0.168
7	0.667	0.667	0.333	1.667	1.000	0.333	0.0	0.333
8	1.000	0.778	0.333	3.611	1.111	0.0	0.056	0.0
AVAILABLE	0.700	0.700	0.340	0.840	1.000	0.340	0.170	0.340

MANPOWER REQUIREMENT AND AVAILABILITY

MANPOWER TYPE	NAME
1	GRADER OPERATOR
2	LOADER OPERATOR
3	TRUCK OPERATOR
4	ROLLER OPERATOR
5	SPREADER OPERATOR
6	LAYDOWN MC. OPERATOR
7	ASPHALTDIS. OPERATOR
8	GENERAL LABOR

	MANPOWER TYPE							
STRATEGY	1	2	3	4	5	6	7	8
1	0.0	0.0	0.017	0.0	0.0	0.0	0.016	0.008
2	0.0	0.012	0.060	0.024	0.048	0.0	0.024	0.012
3	0.0	0.0	0.278	0.111	0.0	0.280	0.056	0.168
4	0.0	0.0	0.278	0.111	0.0	0.280	0.056	0.168
5	0.0	0.0	0.556	0.222	0.0	0.560	0.111	0.336
6	0.0	0.0	0.834	0.333	0.0	0.840	0.168	0.504
7	0.667	0.333	1.667	1.000	1.332	0.0	0.666	1.650
8	1.000	0.333	3.611	1.111	0.0	0.280	0.056	1.818
AVAILABLE	0.700	0.340	0.840	1.000	1.340	0.850	0.670	1.660

OVERHEAD BUDGET REQUIREMENT AND AVAILABILITY

STRATEGY	REQUIREMENT
FOG SEAL	56.000
SEAL COAT	214.000
OGPMS	950.000
THIN OVERLAY	925.000
MODERATE OVERLAY	2000.000
HEAVY OVERLAY	3549.000
LIGHTDUTY RECONSTRUCTION	944.000
HEAVY DUTY RECONSTRT.	2600.000
AVAILABLE	1202000.0

GAIN OF RATING MATRIX

DISTRESS TYPE

STRATEGY	1	2	3	4	5	6
1	0.0	5.000	5.000	5.000	2.000	2.000
2	0.0	15.000	15.000	15.000	10.000	2.000
3	13.000	19.000	19.000	19.000	24.000	45.000
4	13.000	20.000	20.000	20.000	25.000	45.000
5	15.000	25.000	25.000	20.000	30.000	50.000
6	15.000	25.000	25.000	20.000	35.000	50.000
7	15.000	25.000	25.000	20.000	40.000	50.000
8	15.000	25.000	25.000	20.000	40.000	50.000

MAXIMUM GAIN OF RATING

DISTRESS TYPE	GAIN OF RATING
1	15.000
2	25.000
3	25.000
4	20.000
5	40.000
6	50.000

CURRENT RATING
FOR DIFFERENT HIGHWAY SEGMENTS AND DISTRESS TYPES

DISTRESS TYPE

SEGMENT NUMBER	1	2	3	4	5	6
1	10.000	5.000	20.000	17.000	20.000	10.000
2	10.000	15.000	25.000	20.000	40.000	3.000
3	10.000	10.000	15.000	13.000	40.000	0.0
4	10.000	20.000	20.000	20.000	40.000	0.0
5	10.000	25.000	25.000	20.000	40.000	0.0
6	10.000	25.000	25.000	20.000	40.000	0.0
7	8.000	0.0	10.000	20.000	10.000	0.0
8	10.000	15.000	25.000	20.000	20.000	0.0
9	15.000	25.000	5.000	5.000	40.000	42.000
10	15.000	25.000	25.000	20.000	40.000	47.000
11	15.000	25.000	25.000	17.000	40.000	47.000
12	15.000	25.000	25.000	17.000	40.000	49.000
13	13.000	25.000	25.000	20.000	40.000	50.000
14	8.000	5.000	0.0	17.000	20.000	0.0
15	10.000	10.000	10.000	8.000	20.000	0.0

MINIMUM PAVEMENT RATING REQUIREMENT FOR DIFFERENT HIGHWAY TYPES

HIGHWAY TYPE= 1

TIME PERIOD

DISTRESS TYPE	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20
1	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	0.0
2	20.000	20.000	20.000	15.000	15.000	10.000	10.000	10.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
3	20.000	20.000	20.000	15.000	15.000	10.000	10.000	10.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
4	15.000	15.000	10.000	10.000	10.000	10.000	5.000	5.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
5	40.000	30.000	30.000	30.000	30.000	20.000	20.000	20.000	20.000	20.000
	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000
6	40.000	35.000	30.000	25.000	20.000	20.000	15.000	15.000	10.000	10.000
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

HIGHWAY TYPE= 2

TIME PERIOD

DISTRESS TYPE	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20
1	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
2	20.000	15.000	15.000	10.000	10.000	5.000	5.000	5.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
3	20.000	15.000	15.000	10.000	10.000	5.000	5.000	5.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
4	15.000	10.000	10.000	10.000	10.000	10.000	5.000	5.000	5.000	5.000
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
5	0.020	0.020	0.020	0.020	0.020	0.030	0.030	0.030	20.000	20.000
	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000
6	25.000	20.000	15.000	15.000	10.000	10.000	5.000	5.000	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

SURVIVOR PROBABILITIES FOR DIFFERENT MAINTENANCE STRATEGIES AND DISTRESS TYPES

RUTTING

TIME PERIOD

STRATEGY	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20
1	1.000	1.000	1.000	1.000	0.690	0.670	0.480	0.260	0.170	0.140
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.000	0.930	0.910	0.880	0.780	0.310	0.220	0.150	0.070	0.050
	0.020	0.020	0.020	0.020	0.010	0.010	0.010	0.010	0.010	0.010
3	1.000	1.000	1.000	1.000	0.880	0.780	0.460	0.250	0.250	0.250
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1.000	1.000	1.000	1.000	0.790	0.750	0.750	0.750	0.750	0.750
	0.330	0.250	0.250	0.170	0.080	0.0	0.0	0.0	0.0	0.0
5	1.000	1.000	1.000	1.000	1.000	0.830	0.710	0.660	0.620	0.380
	0.300	0.300	0.300	0.280	0.220	0.170	0.120	0.040	0.040	0.040
6	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	0.670	0.670	0.670	0.670	0.220	0.0	0.0	0.0	0.0	0.0
7	1.000	1.000	1.000	1.000	1.000	0.720	0.670	0.580	0.500	0.500
	0.360	0.330	0.330	0.280	0.170	0.170	0.170	0.170	0.170	0.170
8	1.000	1.000	1.000	1.000	1.000	0.720	0.670	0.580	0.500	0.500
	0.360	0.330	0.330	0.280	0.170	0.170	0.170	0.170	0.170	0.170

ALLIGATOR CRACKING

TIME PERIOD

STRATEGY	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20
1	1.000	1.000	1.000	0.870	0.620	0.500	0.250	0.080	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.000	0.940	0.890	0.890	0.650	0.280	0.240	0.150	0.090	0.070
	0.020	0.010	0.010	0.010	0.0	0.0	0.0	0.0	0.0	0.0
3	1.000	1.000	0.890	0.820	0.730	0.670	0.670	0.670	0.670	0.360
	0.110	0.090	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1.000	1.000	0.950	0.910	0.900	0.610	0.560	0.550	0.510	0.280
	0.170	0.140	0.140	0.140	0.080	0.010	0.0	0.0	0.0	0.0
5	1.000	1.000	1.000	1.000	0.770	0.640	0.580	0.530	0.510	0.380
	0.210	0.190	0.190	0.170	0.150	0.100	0.070	0.060	0.060	0.030
6	1.000	1.000	1.000	1.000	1.000	0.710	0.620	0.440	0.290	0.290
	0.290	0.170	0.140	0.140	0.120	0.0	0.0	0.0	0.0	0.0
7	1.000	1.000	1.000	1.000	1.000	0.490	0.360	0.360	0.360	0.290
	0.270	0.270	0.270	0.270	0.210	0.190	0.190	0.180	0.110	0.090
8	1.000	1.000	1.000	1.000	1.000	0.490	0.360	0.360	0.360	0.290
	0.270	0.270	0.270	0.270	0.210	0.190	0.190	0.180	0.110	0.090

LONGTUD. CRACKING

TIME PERIOD

STRATEGY	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20
1	1.000	1.000	0.790	0.500	0.500	0.210	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.000	0.930	0.880	0.870	0.670	0.370	0.320	0.180	0.090	0.070
	0.020	0.010	0.010	0.010	0.0	0.0	0.0	0.0	0.0	0.0
3	1.000	1.000	1.000	1.000	1.000	0.750	0.500	0.500	0.250	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1.000	1.000	0.930	0.930	0.400	0.140	0.140	0.120	0.070	0.020
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1.000	1.000	1.000	1.000	1.000	0.330	0.110	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1.000	1.000	1.000	1.000	1.000	0.330	0.330	0.280	0.170	0.170
	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170
7	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.650	0.600
	0.600	0.600	0.530	0.400	0.380	0.210	0.200	0.200	0.200	0.200
8	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.650	0.600
	0.600	0.600	0.530	0.400	0.380	0.210	0.200	0.200	0.200	0.200

TRANSVERSE CRACKING

TIME PERIOD

STRATEGY	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20
1	1.000	1.000	0.560	0.530	0.390	0.190	0.060	0.050	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.000	0.920	0.860	0.850	0.670	0.380	0.330	0.180	0.090	0.060
	0.010	0.010	0.010	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1.000	1.000	1.000	1.000	1.000	0.830	0.670	0.670	0.330	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1.000	1.000	0.940	0.940	0.430	0.180	0.180	0.140	0.060	0.010
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1.000	1.000	1.000	1.000	1.000	0.630	0.260	0.220	0.110	0.040
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1.000	1.000	1.000	1.000	1.000	0.330	0.330	0.280	0.170	0.170
	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170
7	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.650	0.600
	0.600	0.600	0.510	0.400	0.380	0.200	0.200	0.200	0.200	0.200
8	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.650	0.600
	0.600	0.600	0.510	0.400	0.380	0.200	0.0	0.0	0.0	0.0

FAILURES/MILE

STRATEGY	TIME PERIOD 1 / 11	2 / 12	3 / 13	4 / 14	5 / 15	6 / 16	7 / 17	8 / 18	9 / 19	10 / 20
1	1.000	1.000	1.000	0.670	0.670	0.330	0.330	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.000	1.000	0.910	0.780	0.470	0.220	0.200	0.100	0.040	0.010
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.330	0.330	0.330
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1.000	1.000	1.000	0.890	0.530	0.230	0.160	0.150	0.130	0.080
	0.020	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1.000	1.000	1.000	1.000	0.770	0.510	0.480	0.360	0.330	0.240
	0.170	0.170	0.170	0.170	0.170	0.170	0.070	0.0	0.0	0.0
6	1.000	1.000	1.000	1.000	1.000	0.750	0.590	0.500	0.500	0.480
	0.250	0.250	0.250	0.250	0.200	0.0	0.0	0.0	0.0	0.0
7	1.000	1.000	1.000	1.000	1.000	0.470	0.360	0.320	0.270	0.270
	0.270	0.200	0.180	0.180	0.150	0.090	0.090	0.090	0.090	0.090
8	1.000	1.000	1.000	1.000	1.000	0.470	0.360	0.320	0.270	0.270
	0.270	0.200	0.180	0.180	0.150	0.090	0.090	0.090	0.090	0.090

SERVICEABILITY INDEX

STRATEGY	TIME PERIOD 1 / 11	2 / 12	3 / 13	4 / 14	5 / 15	6 / 16	7 / 17	8 / 18	9 / 19	10 / 20
1	1.000	0.900	0.700	0.500	0.400	0.300	0.200	0.100	0.100	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.000	0.900	0.700	0.500	0.400	0.300	0.200	0.100	0.100	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1.000	1.000	1.000	0.900	0.800	0.700	0.600	0.500	0.400	0.300
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1.000	1.000	1.000	0.900	0.800	0.700	0.600	0.500	0.400	0.300
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1.000	1.000	1.000	1.000	0.900	0.800	0.700	0.600	0.500	0.500
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1.000	1.000	1.000	1.000	1.000	0.900	0.900	0.800	0.700	0.600
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1.000	1.000	1.000	0.900	0.800	0.700	0.600	0.500	0.400	0.300
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	1.000	1.000	1.000	0.900	0.800	0.700	0.600	0.500	0.400	0.300
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

OVERALL PAVEMENT RATING REQUIREMENT

HIGHWAY TYPE	RATING
1	131.00
2	114.00

APPENDIX D

OUTPUT

FOR THE HIGHWAY

MAINTENANCE PROBLEM

MATRIX OF FEASIBLE STRATEGIES ACCORDING TO THE MINIMUM PAVEMENT RATING REQUIREMENT CONSTRAINT

X(I,J)=0 MEANS THE JTH MAINTENANCE STRATEGY FOR THE ITH HIGHWAY SEGMENT IS INFEASIBLE
X(I,J)=1, MEANS MAINTENANCE STRATEGY J FOR THE ITH HIGHWAY SEGMENT IS IS FEASIBLE

SEGMENT NUMBER	STRATEGY							
	1	2	3	4	5	6	7	8
1	0	0	1	1	1	1	1	1
2	0	0	1	1	1	1	1	1
3	0	0	1	1	1	1	1	1
4	0	0	1	1	1	1	1	1
5	0	0	1	1	1	1	1	1
6	0	0	1	1	1	1	1	1
7	0	0	0	1	1	1	1	1
8	0	0	1	1	1	1	1	1
9	0	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1
14	0	0	0	1	1	1	1	1
15	0	0	1	1	1	1	1	1

MATRIX OF FEASIBLE STRATEGIES ACCORDING TO OVERALL PAVEMENT RATING REQUIREMENT CONSTRAINT

X(I,J)=Ø MEANS THE JTH MAINTENANCE STRATEGY FOR THE ITH HIGHWAY SEGMENT IS INFEASIBLE
X(I,J)=1, MEANS MAINTENANCE STRATEGY J FOR THE ITH HIGHWAY SEGMENT IS IS FEASIBLE

SEGMENT NUMBER	STRATEGY 1	2	3	4	5	6	7	8
1	Ø	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1
3	Ø	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1
7	Ø	Ø	1	1	1	1	1	1
8	Ø	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1
1Ø	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1
14	Ø	Ø	1	1	1	1	1	1
15	Ø	1	1	1	1	1	1	1

X(I,J)=Ø MEANS THE JTH MAINTENANCE STRATEGY FOR THE ITH HIGHWAY SEGMENT IS INFEASIBLE
X(I,J)=1, MEANS MAINTENANCE STRATEGY J FOR THE ITH HIGHWAY SEGMENT IS IS FEASIBLE

SEGMENT NUMBER	STRATEGY 1	2	3	4	5	6	7	8
1	Ø	Ø	1	1	1	1	1	1
2	Ø	Ø	1	1	1	1	1	1
3	Ø	Ø	1	1	1	1	1	1
4	Ø	Ø	1	1	1	1	1	1
5	Ø	Ø	1	1	1	1	1	1
6	Ø	Ø	1	1	1	1	1	1
7	Ø	Ø	Ø	1	1	1	1	1
8	Ø	Ø	1	1	1	1	1	1
9	Ø	1	1	1	1	1	1	1
1Ø	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1
14	Ø	Ø	Ø	1	1	1	1	1
15	Ø	Ø	1	1	1	1	1	1

RESTRICTED SECTION-STRATEGY COMBINATIONS

I	J
1	7
2	7
3	7
9	7
10	7
11	7
12	7
13	7
4	8
5	8
6	8
7	8
8	8
14	8
15	8

COMPLETE STRATEGIES WITHHELD

JOUT
1
3
0

RANKING OF STRATEGIES FOR ALL HIGHWAY SEGMENTS

SEGMENT NUMBER	STRATEGY							
1	4	5	6	8	0	0	0	0
2	4	5	8	0	0	0	0	0
3	4	5	6	8	0	0	0	0
4	4	5	7	6	0	0	0	0
5	4	5	7	6	0	0	0	0
6	4	5	7	6	0	0	0	0
7	7	4	5	6	0	0	0	0
8	4	5	7	6	0	0	0	0
9	2	4	5	8	6	0	0	0
10	4	5	6	8	0	0	2	0
11	4	2	5	8	6	0	0	0
12	2	4	5	8	6	0	0	0
13	4	6	5	8	0	0	2	0
14	4	7	5	6	0	0	0	0
15	4	7	5	6	0	0	0	0

OBJECTIVE FUNCTION COEFFICIENTS

SEGMENT NUMBER	STRATEGY 1	2	3	4	5	6	7	8
1	0.0	0.0	0.0	61569.3	70025.9	80367.0	0.0	67293.4
2	0.0	0.0	0.0	90155.2	152937.7	0.0	0.0	140001.7
3	0.0	0.0	0.0	36231.4	56363.7	62989.7	0.0	56504.9
4	0.0	0.0	0.0	38304.0	66233.9	76299.9	63118.9	0.0
5	0.0	0.0	0.0	11838.3	21285.1	24611.4	19184.4	0.0
6	0.0	0.0	0.0	65715.6	118155.4	136619.7	106494.4	0.0
7	0.0	0.0	0.0	110298.1	237727.4	268479.2	237006.1	0.0
8	0.0	0.0	0.0	28789.4	45254.3	53053.8	42953.7	0.0
9	0.0	16178.2	0.0	32606.1	42472.5	44826.1	0.0	65951.9
10	0.0	0.0	0.0	2810.3	3747.1	4683.9	0.0	2810.3
11	0.0	1078.9	0.0	4362.5	6332.7	7036.4	0.0	7740.0
12	0.0	821.2	0.0	1847.7	2786.2	2932.8	0.0	3959.3
13	0.0	0.0	0.0	1938.6	2423.2	4846.4	0.0	2423.2
14	0.0	0.0	0.0	66499.7	109754.6	124642.0	117031.6	0.0
15	0.0	0.0	0.0	74749.5	110803.7	123927.9	118943.1	0.0

PHASE 1

INITIAL SOLUTION BY THE METHOD OF EFFECTIVE GRADIENT

HIGHWAY SEGMENT 13 EXCHANGE STRATEGY 6 WITH STRATEGY 4
HIGHWAY SEGMENT 13 EXCHANGE STRATEGY 5 WITH STRATEGY 6
HIGHWAY SEGMENT 13 EXCHANGE STRATEGY 8 WITH STRATEGY 5

DROP 13

HIGHWAY SEGMENT 10 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 10 EXCHANGE STRATEGY 6 WITH STRATEGY 5
HIGHWAY SEGMENT 10 EXCHANGE STRATEGY 8 WITH STRATEGY 6

DROP 10

HIGHWAY SEGMENT 11 EXCHANGE STRATEGY 2 WITH STRATEGY 4
HIGHWAY SEGMENT 11 EXCHANGE STRATEGY 5 WITH STRATEGY 2
HIGHWAY SEGMENT 11 EXCHANGE STRATEGY 8 WITH STRATEGY 5
HIGHWAY SEGMENT 11 EXCHANGE STRATEGY 6 WITH STRATEGY 8

DROP 11

HIGHWAY SEGMENT 12 EXCHANGE STRATEGY 4 WITH STRATEGY 2
HIGHWAY SEGMENT 12 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 12 EXCHANGE STRATEGY 8 WITH STRATEGY 5
HIGHWAY SEGMENT 12 EXCHANGE STRATEGY 6 WITH STRATEGY 8

DROP 12

HIGHWAY SEGMENT 6 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 6 EXCHANGE STRATEGY 7 WITH STRATEGY 5
HIGHWAY SEGMENT 5 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 5 EXCHANGE STRATEGY 7 WITH STRATEGY 5
HIGHWAY SEGMENT 2 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 2 EXCHANGE STRATEGY 8 WITH STRATEGY 5

DROP 2

HIGHWAY SEGMENT 4 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 4 EXCHANGE STRATEGY 7 WITH STRATEGY 5
HIGHWAY SEGMENT 8 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 8 EXCHANGE STRATEGY 7 WITH STRATEGY 5
HIGHWAY SEGMENT 9 EXCHANGE STRATEGY 4 WITH STRATEGY 2
HIGHWAY SEGMENT 9 EXCHANGE STRATEGY 5 WITH STRATEGY 4
HIGHWAY SEGMENT 9 EXCHANGE STRATEGY 8 WITH STRATEGY 5
HIGHWAY SEGMENT 9 EXCHANGE STRATEGY 6 WITH STRATEGY 8

DROP 9

HIGHWAY SEGMENT 6 EXCHANGE STRATEGY 6 WITH STRATEGY 7

DROP 6

NO MORE HIGHWAY SEGMENT SHOULD BE DROPPED

INITIAL FEASIBLE SOLUTION

HIGHWAY SEGMENT	STRATEGY	BENEFIT
1	4	61569.
3	4	36231.
4	7	63119.
5	7	19184.
7	7	237006.
8	7	42954.
14	4	66500.
15	4	74750.

FOLLOWING HIGHWAY SEGMENTS WITH THE CORRESPONDING STRATEGIES
REPRESENTS THE INITIAL FEASIBLE SOLUTION

SEGMENT NUMBER	STRATEGY
1	THIN OVERLAY
3	THIN OVERLAY
4	LIGHTDUTY RECONSTRUCTION
5	LIGHTDUTY RECONSTRUCTION
7	LIGHTDUTY RECONSTRUCTION
8	LIGHTDUTY RECONSTRUCTION
14	THIN OVERLAY
15	THIN OVERLAY

THE NET BENEFIT= 601313.

CONSTRAINT	PERCENT UTILIZATION	PERCENT UNUTILIZED
SURFACING AGGREGATE	20.49	79.51
ASPHALT CEMENT	12.13	87.87
AGGREGATE(ITEM 340:)	5.93	94.07
AGGREGATE ITEM 290	0.0	100.00
GRADER	18.54	81.46
PICKUP	21.36	78.64
LOADER	19.06	80.94
TRUCK	44.49	55.51
ROLLER	21.43	78.57
SPREADER	19.06	80.94
LAYDOWN MACHINE	5.84	94.16
ASPHALT DISTRIBUTOR	21.98	78.02
GRADER OPERATOR	18.54	81.46
LOADER OPERATOR	19.06	80.94
TRUCK OPERATOR	44.49	55.51
ROLLER OPERATOR	21.43	78.57
SPREADER OPERATOR	19.35	80.65
LAYDOWN MC. OPERATOR	5.84	94.16
ASPHALTDIS. OPERATOR	20.83	79.17
GENERAL LABOR	21.14	78.86
OVERHEAD BUDGET	80.59	19.41

PHASE 2

INCLUSION OF ADDITIONAL HIGHWAY SEGMENTS

SEGMENT NUMBER	STRATEGY	BENEFIT
9	2	16178.
12	2	821.
11	2	1079.

NO MORE HIGHWAY SEGMENT CAN BE INCLUDED

NET BENEFIT= 619391.

CONSTRAINT	PERCENT UTILIZATION
1	41.07
2	15.71
3	5.93
4	0.0
5	18.54
6	21.71
7	19.79
8	45.97
9	21.93
10	19.79
11	5.84
12	22.71
13	18.54
14	19.79
15	45.97
16	21.93
17	20.08
18	5.84
19	21.57
20	21.29
21	90.80

******** 99 ENTERED *******

PHASE 3

FINAL SOLUTION OBTAINED AFTER SEARCHING FOR BETTER STRATEGIES THAN THOSE SELECTED IN PHASE 1 AND PHASE 2

OPTIMUM SOLUTION

HIGHWAY SEGMENT	STRATEGY	BENEFIT
1	4	61569.
3	4	36231.
4	7	63119.
5	7	19184.
7	7	237006.
8	7	42954.
9	2	16178.
11	2	1079.
12	2	821.
14	7	117032.
15	7	118943.
THE NET BENEFIT IS		714117.

CONSTRAINT	PERCENT UTILIZATION
1	51.74
2	15.71
3	2.54
4	0.0
5	28.20
6	29.76
7	29.71
8	62.72
9	30.93
10	29.71
11	2.51
12	30.97
13	28.20
14	29.71
15	62.72
16	30.93
17	30.16
18	2.51
19	30.79
20	30.34
21	91.24

OPTIMAL MAINTENANCE DECISIONS

SEGMENT NO.	NAME	STRATEGY	BENEFIT
1	US 79	THIN OVERLAY	61569.
3	US 190	THIN OVERLAY	36231.
4	SH OSR	LIGHTDUTY RECONSTRUCTION	63119.
5	SH OSR	LIGHTDUTY RECONSTRUCTION	19184.
7	FM 1791	LIGHTDUTY RECONSTRUCTION	237006.
8	FM2821	LIGHTDUTY RECONSTRUCTION	42954.
9	SH 30	SEAL COAT	16178.
11	US 290	SEAL COAT	1079.
12	US 79	SEAL COAT	821.
14	SH OSR	LIGHTDUTY RECONSTRUCTION	117032.
15	FM 908	LIGHTDUTY RECONSTRUCTION	118943.
		NET BENEFIT=	714117.

RESOURCE REQUIREMENTS

MATERIAL REQUIREMENTS IN PERCENTS

SEGMENT NO.	STRATEGY	SURFACING AGGREGATE	ASPHALT CEMENT	AGGREGATE(ITEM 340:)	AGGREGATE ITEM 290
1	THIN OVERLAY	0.0	1.38	1.41	0.0
3	THIN OVERLAY	0.0	1.10	1.13	0.0
4	LIGHTDUTY RECONSTRUCTION	5.29	1.64	0.0	0.0
5	LIGHTDUTY RECONSTRUCTION	1.88	0.58	0.0	0.0
7	LIGHTDUTY RECONSTRUCTION	10.29	3.19	0.0	0.0
8	LIGHTDUTY RECONSTRUCTION	3.03	0.94	0.0	0.0
9	SEAL COAT	6.90	1.20	0.0	0.0
11	SEAL COAT	8.42	1.46	0.0	0.0
12	SEAL COAT	5.27	0.92	0.0	0.0
14	LIGHTDUTY RECONSTRUCTION	5.04	1.56	0.0	0.0
15	LIGHTDUTY RECONSTRUCTION	5.62	1.74	0.0	0.0

EQUIPMENT REQUIREMENTS IN PERCENTS

SEGMENT NO.	STRATEGY	GRADER	PICKUP	LOADER	TRUCK
1	THIN OVERLAY	0.0	0.67	0.0	1.40
3	THIN OVERLAY	0.0	0.54	0.0	1.12
4	LIGHTDUTY RECONSTRUCTION	4.79	4.79	4.92	9.98
5	LIGHTDUTY RECONSTRUCTION	1.70	1.70	1.75	3.54
7	LIGHTDUTY RECONSTRUCTION	9.31	9.31	9.57	19.39
8	LIGHTDUTY RECONSTRUCTION	2.74	2.74	2.82	5.71
9	SEAL COAT	0.0	0.12	0.24	0.49
11	SEAL COAT	0.0	0.14	0.30	0.60
12	SEAL COAT	0.0	0.09	0.19	0.38
14	LIGHTDUTY RECONSTRUCTION	4.56	4.56	4.69	9.51
15	LIGHTDUTY RECONSTRUCTION	5.09	5.09	5.23	10.60

SEGMENT NO.	STRATEGY	ROLLER	SPREADER	LAYDOWN MACHINE	ASPHALT DISTRIBUTOR
1	THIN OVERLAY	0.47	0.0	1.39	0.70
3	THIN OVERLAY	0.38	0.0	1.11	0.56
4	LIGHTDUTY RECONSTRUCTION	5.03	4.92	0.0	4.92
5	LIGHTDUTY RECONSTRUCTION	1.79	1.75	0.0	1.75
7	LIGHTDUTY RECONSTRUCTION	9.77	9.57	0.0	9.57
8	LIGHTDUTY RECONSTRUCTION	2.88	2.82	0.0	2.82
9	SEAL COAT	0.17	0.24	0.0	0.24
11	SEAL COAT	0.20	0.30	0.0	0.30
12	SEAL COAT	0.13	0.19	0.0	0.19
14	LIGHTDUTY RECONSTRUCTION	4.79	4.69	0.0	4.69
15	LIGHTDUTY RECONSTRUCTION	5.34	5.23	0.0	5.23

MANPOWER REQUIREMENTS IN PERCENTS

SEGMENT NO.	STRATEGY	GRADER OPERATOR	LOADER OPERATOR	TRUCK OPERATOR	ROLLER OPERATOR
1	THIN OVERLAY	0.0	0.0	1.40	0.47
3	THIN OVERLAY	0.0	0.0	1.12	0.38
4	LIGHTDUTY RECONSTRUCTION	4.79	4.92	9.98	5.03
5	LIGHTDUTY RECONSTRUCTION	1.70	1.75	3.54	1.79
7	LIGHTDUTY RECONSTRUCTION	9.31	9.57	19.39	9.77
8	LIGHTDUTY RECONSTRUCTION	2.74	2.82	5.71	2.88
9	SEAL COAT	0.0	0.24	0.49	0.17
11	SEAL COAT	0.0	0.30	0.60	0.20
12	SEAL COAT	0.0	0.19	0.38	0.13
14	LIGHTDUTY RECONSTRUCTION	4.56	4.69	9.51	4.79
15	LIGHTDUTY RECONSTRUCTION	5.09	5.23	10.60	5.34

SEGMENT NO.	STRATEGY	SPREADER OPERATOR	LAYDOWN MC. OPERATOR	ASPHALTDIS. OPERATOR	GENERAL LABOR
1	THIN OVERLAY	0.0	1.39	0.35	0.43
3	THIN OVERLAY	0.0	1.11	0.28	0.34
4	LIGHTDUTY RECONSTRUCTION	5.00	0.0	5.00	5.00
5	LIGHTDUTY RECONSTRUCTION	1.77	0.0	1.77	1.77
7	LIGHTDUTY RECONSTRUCTION	9.71	0.0	9.71	9.71
8	LIGHTDUTY RECONSTRUCTION	2.86	0.0	2.86	2.86
9	SEAL COAT	0.25	0.0	0.25	0.05
11	SEAL COAT	0.30	0.0	0.30	0.06
12	SEAL COAT	0.19	0.0	0.19	0.04
14	LIGHTDUTY RECONSTRUCTION	4.76	0.0	4.76	4.76
15	LIGHTDUTY RECONSTRUCTION	5.31	0.0	5.31	5.31

OVERHEAD BUDGET REQUIREMENT IN PERCENTS

SEGMENT NO.	NAME	STRATEGY	OVERHEAD BUDGET
1	US 79	THIN OVERLAY	9.06
3	US 190	THIN OVERLAY	7.24
4	SH OSR	LIGHTDUTY RECONSTRUCTION	11.00
5	SH OSR	LIGHTDUTY RECONSTRUCTION	3.90
7	FM 1791	LIGHTDUTY RECONSTRUCTION	21.37
8	FM2821	LIGHTDUTY RECONSTRUCTION	6.30
9	SH 30	SEAL COAT	3.42
11	US 290	SEAL COAT	4.18
12	US 79	SEAL COAT	2.61
14	SH OSR	LIGHTDUTY RECONSTRUCTION	10.48
15	FM 908	LIGHTDUTY RECONSTRUCTION	11.69

RESOURCE UTILIZATION

CONSTRAINT	PERCENT UTILIZATION
SURFACING AGGREGATE	51.74
ASPHALT CEMENT	15.71
AGGREGATE(ITEM 340:)	2.54
AGGREGATE ITEM 290	0.0
GRADER	28.20
PICKUP	29.76
LOADER	29.71
TRUCK	62.72
ROLLER	30.93
SPREADER	29.71
LAYDOWN MACHINE	2.51
ASPHALT DISTRIBUTOR	30.97
GRADER OPERATOR	28.20
LOADER OPERATOR	29.71
TRUCK OPERATOR	62.72
ROLLER OPERATOR	30.93
SPREADER OPERATOR	30.16
LAYDOWN MC. OPERATOR	2.51
ASPHALTDIS. OPERATOR	30.79
GENERAL LABOR	30.34
OVERHEAD BUDGET	91.24

RESULTS OF UPDATE ROUTINE

RESOURCE UTILIZATION

CONSTRAINT	PERCENT UTILIZATION
SURFACING AGGREGATE	51.74
ASPHALT CEMENT	15.71
AGGREGATE(ITEM 340:)	2.54
AGGREGATE ITEM 290	0.0
GRADER	28.20
PICKUP	29.76
LOADER	29.71
TRUCK	62.72
ROLLER	30.93
SPREADER	29.71
LAYDOWN MACHINE	2.51
ASPHALT DISTRIBUTOR	30.97
GRADER OPERATOR	28.20
LOADER OPERATOR	29.71
TRUCK OPERATOR	62.72
ROLLER OPERATOR	30.93
SPREADER OPERATOR	30.16
LAYDOWN MC. OPERATOR	2.51
ASPHALTDIS. OPERATOR	30.79
GENERAL LABOR	30.34

HIGHWAY SEGMENT NO. 2 HAS BEEN ADDED
THE OVERHEAD BUDGET UTILIZATION NOW BECOMES 97.3861
ADDITIONAL BENEFIT = 11814.8555 TOTAL BENEFIT = 725931.312

THE STRATEGY USED WAS 2

NO MORE SECTIONS CAN BE ADDED

COMMAND?

APPENDIX E

COMPUTER PROGRAM

```
//TRYIT JOB (W106,006A,S10,005,AM),'KNIGHTMOD'
/*JOBPARM R=290,K=0
/*LEVEL        2
// EXEC FORTX,REGION=290K
//SYSPRT DD SYSOUT=A,DCB=(RECFM=FB)
//SOURCE DD *
C
C
C
C         PROGRAM FOR REHABILITATION AND
C         MAINTENANCE OF HIGHWAY SYSTEM
C         AUTHORS: NAZIM UDDIN AHMED
C                  R. L. LYTTON
C                  W. D. YANDELL
C                  D  L. SCHAFER
C                  S. Y. WU
C
C
C
C         THIS PROGRAM IS BASED ON AN
C         0-1 INTEGER LINEAR PROGRAMMING
C         ALGORITHM TO SOLVE FOR THE
C         OPTIMAL MAINTENANCE STRATEGIES,
C         FOR A GIVEN HIGHWAY SYSTEM.
C
C
C
C
C         TEXAS TRANSPORTATION INSTITUTE
C         TEXAS A AND M UNIVERSITY
C         COLLEGE STATION, TEXAS 77843
C
C
C
C         DATE WRITTEN: FEBRUARY,1978
C
C
C
C         THIS PROGRAM WAS WRITTEN IN
C         FORTRAN IV COMPUTER LANGUAGE
C         USING THE WATFIV COMPILER,
C         THEN CONVERTED TO IBM'S
C         FORTRAN H EXTENDED COMPILER
C         IN FEBRUARY, 1979.
C
C
C
C
C         INSTALLATION: AMDHAL 470/V6
C
C
C
C
C
C
C         MAIN PROGRAM
C
C
C
C
      REAL DIST(10,11),P(10,11,20),R(20 ,11),
     1 RMIN(11,20,2),RX(200),JP(200)
      REAL L1(200), L2(200),XL(200)
```

```
      INTEGER T,TDATA,X(20 ,10),G,F,Q,JJ(20 ,10),A(20 ,10
     1 ),INF( 200),HYTYP(20)
      DIMENSION SG(10),SGR(10,10),EF(10),EFR(10,10)
     1,HQ(10),HQR(10,10),CR(10),CO(20 ,10),IP(200),
     2 S(31),PSBR(20,10,10),PHBR(20,10,10),
     4 PEBR(20,10,10),PCR(20,10),WW(20)
      DIMENSION CONSTR(30) ,PCON(30),JFLAG(200)
      DIMENSION  RMAX(11)
      DIMENSION TRAF(20),ENVIR(20)
      DIMENSION  PAR4(50), PAR5(50)
      INTEGER TITLE(20)
      INTEGER PAR1(50,2),PAR2(50,3),PAR3(50,2)
      INTEGER STRAT(15,6),DISTR(15,5)
      INTEGER MAT(10,5),EQUP(10,5),MANP(10,5)
      INTEGER OVHD(5)
      COMMON /AREA1/DIST,P,R,RMIN,WW ,TRAF,ENVIR
      COMMON /AREA2/ NH,NS,T,ND ,NHTYP
      COMMON /IEC1/ IECK
      COMMON /AREA3/X
      COMMON /AREA4/ A
      COMMON /AREA5/ INF
      COMMON /AREA6/ HYTYP
      COMMON /TOY2/SG,HQ,EF,CC
      COMMON /TOY3/ G,F,Q
      COMMON/TOY4/JJ,CO
      COMMON /CHCK1/PSBR,PHBR,PEBR,PCR,S,IP
      COMMON /DATCK1/ L1,L2
      COMMON /DATCK2/ SGR,EFR,HQR ,CR
      COMMON /KNPSK1/ CONSTR,XSUM
      COMMON /DATIN1/ PAR1,PAR2
      COMMON /DATIN2/PAR3,PAR4,PAR5
      COMMON /DATIN3/ STRAT,DISTR
      COMMON /DATIN4/ MAT,EQUP,MANP,OVHD
      COMMON /DATIN5/ TITLE
      COMMON /DATIN6/ RMAX
      COMMON /SERCH1/ PCON
      COMMON /SERCH2/ XXSUM, JFLAG
      COMMON /ADDON/ TDATA
C
C
C
      CALL INPUT(TDATA)
C
C
C
      IF(IECK. EQ. 1) CALL ECOCK
C
C
C
      CALL CALC
C
C
C
      STOP
      END
C
C
```

```
C
C
C
C
C
C
C     *********************************************
C     *                                           *
C     *    S U B R O U T I N E     I N P U T      *
C     *                                           *
C     *********************************************
C
C
C
      SUBROUTINE  INPUT(TDATA)
C
C
C
C        THE PURPOSE OF THIS SUBROUTINE IS TO READ
C        THE INPUT DATA AND PRINT THEM OUT.
C
C
C
C                 INPUT VARIABLE NAMES
C                 --------------------
C
C
C        TITLE= NAME OF THE PROBLEM
C        NH=NUMBER OF HIGHWAY SEGMENTS
C        NS=NUMBER OF STRATEGIES
C        T=NUMBER OF TIME PERIOD IN ANALYSIS
C        TDATA=NUMBER OF YEARS ON INPUT DATA
C        ND=NUMBER OF DISTRESS TYPES
C        NHTYP=NUMBER OF HIGHWAY TYPES
C        G=NUMBER OF MATERIAL TYPES
C        F=NUMBER OF EQUIPMENT TYPES
C        Q=NUMBER OF MANPOWER TYPES
C
C        IECK= AN INDICATOR FOR CALLING THE
C        SUBROUTINE ECOCK. IF IECK=1, THE
C        SUBROUTINE ECOCK WILL BE EXECUTED AND
C        THE OBJECTIVE FUNCTION COEFFICIENTS AND
C        THE CONSTRAINT COEFFICICIENTS WILL BE
C        PRINTED AS IN A REGULAR INTEGER
C        PROGRAMMING PROBLEM
C
C        L1(I)=LENGTH OF ITH HIGHWAY SEGMENT
C        IN MILES
C        L2(I)=WIDTH OF ITH HIGHWAY SEGMENT
C        IN FEET
C        HYTYP(I)=TYPE OF ITH HIGHWAY SEGMENT
C        TRAF(I)=TRAFFIC INDEX OF ITH
C        HIGHWAY SEGMENT
C        ENVIR(I)=ENVIRONMENTAL INDEX OF ITH
C        HIGHWAY SEGMENT
C        PAR1(I)=NAME OF ITH HIGHWAY SEGMENT
C        PAR2(I)=COUNTY NAME OF THE ITH
C        HIGHWAY SEGMENT
C        PAR3(I)= CONTROL SECTION NAME OF THE ITH
C        HIGHWAY SEGMENT
C        PAR4(I)=BEGINNING MILEPOINT OF THE
```

```
C          ITH HIGHWAY SEGMENT
C          PAR5(I)=ENDING MILEPOINT OF THE ITH
C          HIGHWAY SEGMENT
C          STRAT(I)=NAME OF THE ITH STRATEGY
C          DISTR(I)=NAME OF THE ITH DISTRESS TYPE
C          MAT(I)=NAME OF THE ITH MATERIAL TYPE
C          EQUP(I)=NAME OF THE ITH EQUIPMENT TYPE
C          MANP(I)=NAME OF THE ITH MANPOWER TYPE
C          OVHD=OVERHEAD BUDGET NAME
C          SG(I)=AMOUNT OF MATERIAL TYPE I AVAILABLE
C          EF(I)=AMOUNT OF EQUIPMENT TYPE I AVAILABLE
C          HQ(I)=AMOUNT OF MANPOWER TYPE I AVAILABLE
C          CR(I)=OVER HEAD BUDGET REQUIREMENT
C          IF ITH STRATEGY IS APPLIED
C          SGR(J,L)=LTH MATERIAL REQUIREMENT IN
C          TONS PER FT.MILE IF JTH STRATEGY
C          IS APPLIED
C          EFR(J,L)=LTH EQUIPMENT REUIREMENT IN
C          EQUIPMENT-DAYS PER FT.MILE IF
C          JTH STRATEGY IS APPLIED
C          HQR(J,L)=LTH MANPOWER REQUIREMENT
C          IN MAN-DAYS PER FT.MILE IF
C          JTH STRATEGY IS APPLIED
C          DIST(J,K)=POTENTIAL GAINS OF PAVEMENT
C          RATING FOR KTH DISTRESS TYPE
C          IF JTH STRATEGY IS APPLIED
C          R(I,K)=CURRENT PAVEMENT RATING
C          FOR ITH HIGHWAY SEGMENT IF KTH DISTRESS
C          IS PRESENT
C          RMIN(K,L,II)=MINIMUM PAVEMENT RATING
C          REQIUREMENT FOR LTH TIME PERIOD AND
C          KTH DISTRESS TYPE IF THE HIGHWAY SEGMENT
C          IS OF TYPE II
C          P(J,K,L)=PROBABILITY OF SURVIVAL FOR LTH
C          TIME PERIOD IF KTH DISTRESS TYPE IS
C          PRESENT AND STRATEGY J IS APPLIED
C          WW(I)=OVERALL PAVEMENT RATING REQUIRMENT
C          OF THE ITH HIGHWAY TYPE
C          RMAX(K)=MAXIMUM POSSIBLE RATING
C          FOR KTH DISTRESS TYPE
C          CC=TOTAL OVERHEAD BUDGET AVAILABLE
C
C
C
C
C
       REAL DIST(10,11),P(10,11,20),R(20,11),
     1  RMIN(11,20,2)
       REAL L1(200),L2(200)
       INTEGER T,TDATA,G,F,Q,HYTYP(20),TITLE(20)
       DIMENSION SG(10),SGR(10,10),EF(10),EFR(10,10)
     1,HQ(10),HQR(10,10),CR(10),WW(20),RMAX(11)
       DIMENSION TRAF(20),ENVIR(20)
       DIMENSION PAR4(50),PAR5(50)
       INTEGER PAR1(50,2),PAR2(50,3),PAR3(50,2)
       INTEGER STRAT(15,6),DISTR(15,5)
       INTEGER MAT(10,5),EQUP(10,5),MANP(10,5)
       INTEGER OVHD(5)
       COMMON /AREA1/ DIST,P,R,RMIN,WW,TRAF,ENVIR
```

```
      COMMON /AREA2/ NH,NS,T,ND,NHTYP
      COMMON /IEC1/ IECK
      COMMON /AREA6/ HYTYP
      COMMON /TOY2/ SG,HQ,EF,CC
      COMMON /TOY3/ G,F,Q
      COMMON /DATCK1/ L1,L2
      COMMON /DATCK2/ SGR,EFR,HQR,CR
      COMMON /DATIN1/ PAR1,PAR2
      COMMON /DATIN2/ PAR3,PAR4,PAR5
      COMMON /DATIN3/ STRAT,DISTR
      COMMON /DATIN4/ MAT,EQUP,MANP,OVHD
      COMMON /DATIN5/ TITLE
      COMMON / DATIN6/ RMAX
C
C
C
C
C
      READ (5,106)(TITLE(I),I=1,20)
  106 FORMAT(20A4)
      READ(5,101) NH,NS,TDATA,T,ND,NHTYP,G,F,Q ,IECK
  101 FORMAT(16I5)
      WRITE(6,700) (TITLE(I),I=1,20)
  700     FORMAT( '1',  T30,20A4,////)
      WRITE(6,800)
  800 FORMAT(29X,'THE FOLLOWING REPRESENTS THE INPU'
     1 ,'T FOR THE PROBLEM',//)
      WRITE(6,801) NH,NS,T,ND,NHTYP,IECK,TDATA
  801 FORMAT(15X,'NO. OF HIGHWAY SEGMENTS=', I5,5X,
     1 'NO. OF STRATEGIES=',I4,3X,'NO. OF ANALYSIS'
     2,' PERIOD=',I4,/,15X,'NO. OF DISTRESS TYPES='
     3,I4,5X,' NO. OF HIGHWAY TYPES=',I3,/,
     4 15X,'IECK=',I4,/,15X,'YEARS OF INPUT DATA=',I4,/)
      WRITE(6,802) G,F,Q
  802 FORMAT(15X,'NO. OF MATERIAL TYPES=',I3,5X,
     1'NO. OF EQUIPMENT TYPES=',I3,5X,'NO. OF ',
     2 'MANPOWER TYPES= ',I3,//)
C
C
C
C
```

```
C
C
      DO 91 I=1,NH
      READ(5,103) L1(I),L2(I),HYTYP(I),TRAF(I),
     1 ENVIR(I),(PAR1(I,J),J=1,2),(PAR2(I,J),J=1,3),
     3 (PAR3(I,J),J=1,2),PAR4(I),
     2 PAR5(I)
   91 CONTINUE
  103 FORMAT(2F8.3,I4,2F8.3,2A4,3A4,2A4,2F8.3)
      WRITE(6,803)
  803 FORMAT(2X,'SEGMENT',3X,'TYPE',4X,'HIGHWAY',5X
     1,'COUNTY',8X,'CONTROL',7X,'LENGTH',5X,'WIDTH'
     2, 5X,'BEGINNING',5X,'ENDING',5X,'TRAFFIC',5X,
     4'ENVIRONMENTAL',/,2X,'NUMBER',T47,'SECTION',
     5T81,'MILE POINT',T93,'MILE POINT',T106,'INDE'
     6,'X',8X,'INDEX',//)
      DO 1 I=1,NH
      WRITE(6,804) I,HYTYP(I),(PAR1(I,J),J=1,2),
     1 (PAR2(I,J),J=1,3),(PAR3(I,J),J=1,2),L1(I),L2(I),
     2 PAR4(I),PAR5(I),TRAF(I),ENVIR(I)
    1 CONTINUE
  804 FORMAT(3X,I3,6X,I3,5X,2A4,4X,3A4,1X,2A4,4X,
     1 F8.3,4X,F8.3,2X,F9.3,4X,F8.3,T106,F6.3,
     2 T120,F6.3)
C
C
C
C
C
C
      READ(5,104)  ((STRAT(I,J),J=1,6),I=1,NS)
  104 FORMAT( 18A4)
      WRITE(6,701)
  701 FORMAT('1',   T50,'STRATEGY NO.',5X,'NAME',//
     1 )
      DO 21 IK=1,NS
      WRITE(6,702) IK,(STRAT(IK,J),J=1,6)
   21 CONTINUE
  702 FORMAT (53X,I4,7X,6A4)
C
C
C
C
```

```
C
C
      READ(5,105) ((DISTR(I,J),J=1,5),I=1,ND)
  105 FORMAT( 20A4)
      WRITE(6,703)
  703 FORMAT(/////,49X,'DISTRESS TYPE',8X,'NAME',//
     1 )
      DO 22 IJ=1,ND
      WRITE(6,704) IJ,(DISTR(IJ,K),K=1,5)
   22 CONTINUE
  704 FORMAT(55X,I3, 6X,5A4)
C
C
C
C
C
C
      READ(5,105) ((MAT(I,J),J=1,5),I=1,G)
      READ(5,108)(SG(I),I=1,G)
      DO 11 J=1,NS
   11 READ(5,108)(SGR(J,L),L=1,G)
  107 FORMAT( 8F10.3)
  108 FORMAT( 8F10.3)
      WRITE(6,705)
  705 FORMAT( '1', T50,'MATERIAL REQUIREMENT ',
     1 'AND AVAILABILITY',///,50X,'MATERIAL TYPE',
     2 8X,'NAME',//)
      DO 23 IL=1,G
      WRITE(6,704)IL,(MAT(IL,K),K=1,5)
   23 CONTINUE
      WRITE(6,805) (I,I=1,G)
  805 FORMAT(////,25X,'MATERIAL TYPE',//,5X,
     1'STRATEGY',5X,10(I5,5X),//)
      WRITE(6,599)
  599 FORMAT(/)
      DO 2 J=1,NS
      WRITE(6,806) J,(SGR(J,L),L=1,G)
    2 CONTINUE
  806 FORMAT(8X,I2,8X,10(F7.3,3X))
      WRITE(6,807)
  807 FORMAT(18X,'--------------------------------',
     1 '------------------------------------------',
     2 '------------------------------------',//  )
      WRITE(6,808) (SG(I),I=1,G)
  808 FORMAT(4X,'AVAILABLE',4X,10(F8.3,2X))
C
C
```

```
C
C
C
C
      READ(5,105) ((EQUP(I,J),J=1,5),I=1,F)
      READ(5,107)(EF(I),I=1,F)
      DO 860 J=1,NS
  860 READ(5,108)(EFR(J,L),L=1,F)
      WRITE(6,706)
  706 FORMAT('1',48X,'EQUIPMENT REQUIREMENT AND ',
     1 'AVAILABILITY',////,50X,'EQUIPMENT TYPE',
     2 8X,'NAME',//)
      DO 24 IH=1,F
      WRITE(6,704) IH,(EQUP(IH,K),K=1,5)
   24 CONTINUE
C
C
C
C
C
C
      WRITE(6,809) (I,I=1,F)
  809 FORMAT(////,42X,'EQUIPMENT TYPE',//,5X,
     1 'STRATEGY',5X,10(I5,5X),//)
      WRITE(6,599)
      DO 3 J=1,NS
      WRITE(6,806) J,(EFR(J,L),L=1,F)
    3 CONTINUE
      WRITE(6,807)
      WRITE(6,808) (EF(I),I=1,F)
C
C
C
C
```

```
C
C
      READ(5,105) ((MANP(I,J),J=1,5),I=1,Q)
      READ(5,107)(HQ(I),I=1,Q)
      DO 861 J=1,NS
  861 READ(5,108)(HQR(J,L),L=1,Q)
      WRITE(6,707)
  707 FORMAT('1',50X,'MANPOWER REQUIREMENT AND ',
     1 'AVAILABILITY',///,50X,'MANPOWER TYPE',8X,
     2   'NAME',//)
      DO 25 IM=1,Q
      WRITE(6,704)IM,(MANP(IM,K),K=1,5)
   25 CONTINUE
      WRITE(6,810) (I,I=1,Q)
  810 FORMAT(40X,'MANPOWER TYPE',//,5X,'STRATEGY',
     1  5X,10(I5,5X),//)
      WRITE(6,599)
      DO 4 J=1,NS
      WRITE(6,806)J,(HQR(J,L),L=1,Q)
    4 CONTINUE
      WRITE(6,807)
      WRITE(6,808) (HQ(I),I=1,Q)
C
C
C
C
C
C
      READ(5,105) (OVHD(I),I=1,5)
      READ(5,107)(CR(I),I=1,NS)
      READ (5,109) CC
  109 FORMAT (F20.2)
      WRITE(6,811)
  811 FORMAT('1',30X,'OVERHEAD BUDGET REQUIREMENT',
     1 ' AND AVAILABILITY',///,36X,
     1  'STRATEGY',20X,'REQUIREMENT',//)
      DO 5 J=1,NS
      WRITE(6,828) (STRAT(J,K),K=1,6) ,CR(J)
  828 FORMAT(32X,6A4,8X,F8.3)
    5 CONTINUE
      WRITE(6,812) CC
  812 FORMAT(// ,32X,'AVAILABLE',T58,F16.1)
C
C
C
C
C
C
```

```
      READ(5,107) (RMAX(K),K=1,ND)
      WRITE(6,813) (I,I=1,ND)
  813 FORMAT('1', 29X,'GAIN OF RATING MATRIX',//,
     1 34X,'DISTRESS TYPE',//,8X,'STRATEGY',5X,
     2 10(I3,6X),//)
      WRITE(6,599)
      DO 6 J=1,NS
      WRITE(6,814) J,(DIST(J,K),K=1,ND)
    6 CONTINUE
  814 FORMAT( 8X,I4,7X,10(F7.3,2X))
      WRITE(6,713)
  713 FORMAT      (//////,25X,'MAXIMUM GAIN OF ',
     1 'RATING',//,20X,'DISTRESS TYPE',5X,
     2 'GAIN OF RATING',/)
      DO 61 II=1,ND
   61 WRITE(6,714) II,RMAX(II)
  714 FORMAT(25X,I3,11X,F10.3)
C
C
C
      DO 88 I=1,NH
   88 READ(5,107)(R(I,K),K=1,ND)
      WRITE(6,815) (I,I=1,ND)
  815 FORMAT('1',30X,'CURRENT RATING ',
     $/,20X,'FOR DIFFERENT HIGHWAY SEGMENTS AND ',
     2'DISTRESS TYPES',//,33X,'DISTRESS TYPE',//,5X
     3 ,'SEGMENT NUMBER',2X,10(I3,6X),//)
      WRITE(6,599)
      DO 7 I=1,NH
      WRITE(6,814)I,(R(I,K),K=1,ND)
    7 CONTINUE
C
```

```
C
C
      DO 13 II =1,NHTYP
      DO 13 K=1,ND
      READ(5,107) (RMIN(K,L,II),L=1,TDATA)
   13 CONTINUE
      WRITE(6,816)
  816 FORMAT('1',25X,'MINIMUM PAVE',
     $ 'MENT  RATING REQUIREMENT FOR DIFFERENT ',
     2 'HIGHWAY TYPES',//)
      DO 8 II=1,NHTYP
      WRITE(6,817) II
  817 FORMAT(//,48X,'HIGHWAY TYPE=',I3,//)
      WRITE (6,818) (K,K=1,TDATA)
  818 FORMAT(50X,'TIME PERIOD',/,5X,'DISTRESS TYPE'
     1 ,I6,9I9,(/17X,10I9))
      DO 8 K=1,ND
      WRITE(6,8180) K, (RMIN(K,L,II),L=1,TDATA)
 8180 FORMAT(/,8X,I4,5X,10F9.3,(/19X,10F9.3))
    8 CONTINUE
C
C
C
C
      DO 14 K=1,ND
      DO 14 J=1,NS
   14 READ(5,107)(P(J,K,L),L=1,TDATA)
      READ(5,107)(WW(I),I=1,NHTYP)
      WRITE(6,819)
  819 FORMAT('1',10X ,'SURVIVOR PROBABILITIES FOR '
     1 ,'DIFFERENT MAINTENANCE STRATEGIES AND ',
     2 'DISTRESS TYPES',///)
      DO 9 K=1,ND
      WRITE (6,820) (DISTR(K,J),J=1,5), (I,I=1,TDATA)
  820 FORMAT(//,43X,5A4,//,43X,'TIME PERIOD',/,2X,
     1 'STRATEGY',I5,9I9,(/9X,10I9))
      DO 9 J=1,NS
      WRITE(6,821) J, (P(J,K,L),L=1,TDATA)
  821 FORMAT(/,5X,I3,10F9.3,(/10X,10F9.3))
    9 CONTINUE
      WRITE(6,822)
  822 FORMAT(//////,5X,'OVERALL PAVEMENT RATING ',
     1 'REQUIREMENT',// ,8X,'HIGHWAY TYPE',4X,
     2 'RATING',/)
      DO 10 I=1,NHTYP
      WRITE(6,823) I,WW(I)
   10 CONTINUE
  823 FORMAT(10X,I5,6X,F8.2)
      RETURN
      END
C
C
C
```

```
C
C
C
C
C
C      *******************************************
C      *                                         *
C      *     S U B R O U T I N E   E C O C K     *
C      *                                         *
C      *******************************************
C
C
C
       SUBROUTINE ECOCK
C
C
C
C
C         THIS SUBROUTINE PROVIDES THE PRINTOUT OF
C         THE OBJECTIVE FUNCTION COEFFICIENTS AND
C         THE CONSTRAINT COEFFICIENTS.
C
C
C
       DIMENSION SG(10),EF(10),HQ(10),CO( 20,10),
     1 S(31),IP(200)
       DIMENSION PSBR(20,10,10),PEBR(20,10,10),
     1 PHBR(20,10,10),PCR(20,10)
       INTEGER X(20,10),T,G,F,Q,JJ(20,10)
       COMMON /AREA2/NH,NS,T,ND ,NHTYP
       COMMON /AREA3/X
       COMMON /TOY2/SG,HQ,EF,CC
       COMMON /TOY3/G,F,Q
       COMMON /TOY4/ JJ,CO
       COMMON/CHCK1/PSBR,PHBR,PEBR,PCR,S,IP
       DO 4 I=1,NH
       DO 4 J=1,NS
       IF(X(I,J).EQ.1) GO TO 4
       DO 1 II=1,G
     1 PSBR(I,J,II) =0.
       DO 2 II=1,F
     2 PEBR(I,J,II)=0.
       DO 3 II=1,Q
     3 PHBR(I,J,II)=0.
       PCR(I,J)=0.
       CO(I,J)=0.
     4 CONTINUE
       WRITE(6,1001) (SG(II),II=1,G)
  1001 FORMAT('1',50X,'THESE ARE THE VALUES OF SG',/
     1   ,5X,10(2X,F10.2),//)
       WRITE(6,1002) (EF(II),II=1,F)
```

```
 1002 FORMAT( 5X,'THESE ARE THE VALUES OF EF',/,5X,
     1   10(2X,F10.2),//)
      WRITE(6,1003) (HQ(II),II=1,F)
 1003 FORMAT( 5X,'THESE ARE THE VALUES OF HQ',/,5X,
     1 10(2X,F10.2),//)
      WRITE(6,1004) CC
 1004 FORMAT(20X,'THE VALUE OF CC IS ',5X,F16.2,//)
      DO 5 II=1,G
      WRITE(6,1005) II
 1005 FORMAT(55X,'MATERIAL TYPE',I4,//)
      DO 5 I=1,NH
      WRITE(6,1006) I
 1006 FORMAT(15X,'HIGHWAY SEGMENT',I4)
      WRITE(6,1007)(PSBR(I,J,II),J=1,NS)
 1007 FORMAT(5X,10(2X,F10.2))
    5 CONTINUE
      DO 6 II=1,F
      WRITE(6,1008) II
 1008 FORMAT(55X,'EQUIPMENT TYPE',I4,//)
      DO 6 I=1,NH
      WRITE(6,1011) I
      WRITE(6,1009) (PEBR(I,J,II),J=1,NS)
 1009 FORMAT(5X,10(2X,F10.2))
    6 CONTINUE
      DO 7 II=1,Q
      WRITE(6,1010) II
 1010 FORMAT(55X,'MANPOWER TYPE',I4,//)
      DO 7 I=1,NH
      WRITE(6,1011) I
 1011 FORMAT(15X,'HIGHWAY SEGMENT',I4)
      WRITE(6,1009) (PMBR(I,J,II),J=1,NS)
    7 CONTINUE
      WRITE(6,1012)
 1012 FORMAT(5X,'THE VALUES OF BUDGET CONSTRAINT',
     1 ' COEFFICIENTS ARE ',//)
      DO 8 I=1,NH
      WRITE(6,1009) (PCR(I,J),J=1,NS)
    8 CONTINUE
      WRITE(6,1014)
 1014 FORMAT('1',40X,'THES ARE THE OBJECTIVE ',
     1 'FUNCTION COEFFICIENTS',//)
      DO 9 I=1,NH
      WRITE(6,1015) (CO(I,J),J=1,NS)
 1015 FORMAT(5X,10(2X,F10.1))
    9 CONTINUE
      RETURN
      END
C
C
```

```
C
C       *********************************************
C       *                                           *
C       *      S U B R O U T I N E   S O R T        *
C       *                                           *
C       *********************************************
C
C
C
C
        SUBROUTINE SORT(XG,NN,KP)
C
C
C          THIS SUBROUTINE SORTS AN ARRAY IN
C          ASCENDING ORDER.
C
C
        INTEGER START
        DIMENSION XG(200),KP(200)
CCCC     ARRANGE FOR (NN-1) COMPARISON SETS
        LIM=NN-1
        DO 4 I=1,LIM
C
C
C          ARRANGE STARTING POINT FOR EACH SET.
C
C
        START=I+1
C
C
C          BEGIN COMPARISON SET
C
C
        DO 4 J=START,NN
        IF(XG(I)-XG(J))4,4,2
C
C
C          INTERCHANGE POSITION IN STORAGE
C
C
      2 SAVE=XG(I)
        XG(I)=XG(J)
        XG(J)=SAVE
        ISAVE=KP(I)
        KP(I)=KP(J)
        KP(J)=ISAVE
      4 CONTINUE
        RETURN
        END
C
C
```

```
C
C      *****************************************
C      *                                       *
C      *     S U B R O U T I N E   S O R T 1   *
C      *                                       *
C      *****************************************
C
C
C
       SUBROUTINE SORT1(YG,NX,KX)
C
C
C         THIS SUBROUTINE SORTS AN ARRAY IN
C         DESCENDING ORDER.
C
C
C
       INTEGER BEGIN
       DIMENSION YG(NX ),KX(NX )
C
C
C         ARRANGE FOR (NX-1) COMPARISON SETS
C
C
       LIMT=NX-1
       DO 4 I=1,LIMT
C
C
C         ARRANGE STARTING POINT FOR EACH SET
C
C
       BEGIN=I+1
C
C
C         BEGIN COMPARISON SET
C
C
       DO 4 J=BEGIN,NX
       IF(YG(I)-YG(J))2,2,4
C
C
C         INTERCHANGE POSITION IN STORAGE
C
C
     2 SAVE=YG(I)
       YG(I)=YG(J)
       YG(J)=SAVE
       ISAVE=KX(I)
       KX(I)=KX(J)
       KX(J)=ISAVE
     4 CONTINUE
       RETURN
       END
C
C
```

```
C
C      ********************************************
C      *                                          *
C      *     S U B R O U T I N E   M I N D I S    *
C      *                                          *
C      ********************************************
C
C
C
       SUBROUTINE MINDIS
C
C
C
C         THIS  SUBROUTINE FINDS THE FEASIBLE
C         STRATEGIES FOR ALL HIGHWAY SEGMENTS
C         ACCORDING TO THE MINIMUM PAVEMENT RATING
C         REQUIREMENT CONSTRAINT.
C
C
       REAL DIST(10,11),P(10,11,20),R(20 ,11),
     1 RMIN(11,20,2),WW(20)
       INTEGER T,X(20 ,10),A(20,10),HYTYP(20)
       DIMENSION TRAF(20),ENVIR(20)
       COMMON /AREA1/DIST,P,R,RMIN,WW ,TRAF,ENVIR
       COMMON /AREA2/ NH,NS,T,ND ,NHTYP
       COMMON /AREA3/X
       COMMON /AREA4/ A
       COMMON /AREA6/ HYTYP
C
C
       DO 4 I=1,NH
       DO 3 J=1,NS
       DO 1 K=1,ND
       L=1
       SUM=R(I,K)+DIST(J,K)
       IF(SUM.LT.RMIN(K,L,HYTYP(I))) GO TO 3
    1  CONTINUE
       DO 2 JJ=J,NS
     2 X(I,JJ)=1
       GO TO 4
     3 X(I,J)=0
     4 CONTINUE
C
C
C
       WRITE (6,601)
   601 FORMAT('1',45X,           //,15X,'MATRIX OF',
      2 ' FEASIBLE STRATEGIES ACCORDING TO THE '
      2 ,'MINIMUM PAVEMENT RATING REQUIREMENT ',
      3 'CONSTRAINT',//)
       WRITE(6,602)(J,J=1,NS)
```

```
      602 FORMAT(17X,'X(I,J)=0 MEANS THE JTH ',
         1'MAINTENANCE STRATEGY FOR THE ITH HIGHWAY ',
         2'SEGMENT IS INFEASIBLE',/,17X,'X(I,J)=1,',
         3' MEANS MAINTENANCE STRATEGY J FOR THE ITH',
         4'  HIGHWAY SEGMENT IS IS FEASIBLE',//,10X,
         5 'SEGMENT NUMBER',35X,'STRATEGY',//,28X,
         6  10(6X,I4),//)
          WRITE(6,599)
      599 FORMAT(/)
C
C
C
          DO 5 I=1,NH
        5 WRITE(6,603)I,(X(I,J),J=1,NS)
      603 FORMAT(14X,I4,10X,10(6X,I4))
C
C
C
          RETURN
          END
C
C
C
C         *********************************************
C         *                                           *
C         *     S U B R O U T I N E   A L L D I S     *
C         *                                           *
C         *********************************************
C
C
C
          SUBROUTINE ALLDIS
C
C
C
C            THIS SUBROUTINE FINDS THE FEASIBLE
C            STRATEGIES FOR ALL HIGHWAY SEGMENTS
C            ACCORDING TO OVERALL PAVEMENT RATING
C            REQUIREMENT CONSTRAINT.
C
C
          INTEGER T,X(20 ,10),A(20 ,10) ,HYTYP(20)
          DIMENSION WW(20 ),DIST(10,11),P(10,11,20),
        1 R(20,11), RMIN(11,20,2)
          DIMENSION TRAF(20),ENVIR(20)
          COMMON /AREA1/DIST,P,R,RMIN,WW,TRAF,ENVIR
          COMMON /AREA2/ NH,NS,T,ND ,NHTYP
          COMMON /AREA3/X
          COMMON /AREA4/A
          COMMON /AREA6/ HYTYP
C
C
          CALL MINDIS
C
```

```
C
      DO 11 I=1,NH
C
C
C        CHECKING WHETHER THE OVERALL RATING
C        REQUIREMENT CONSTRAINT IS NECESSARY FOR A
C        PARTICULAR  HIGHWAY SEGMENT.
C
C
      DO 2 L=1,T
      SUMY=0.
      DO 1 K=1,ND
    1 SUMY=SUMY+RMIN(K,L,HYTYP(I))
      IF(SUMY-WW(HYTYP(I))) 4,2,2
    2 CONTINUE
C
C
C        THIS MEANS OVERALL RATING REQUIREMENT
C        CONSTRAINT IS NOT NECESSARY AND ALL THE
C        STRATEGIES FOR THIS HIGHWAY SEGMENT
C        IS FEASIBLE.
C
C
      DO 3 J=1,NS
      A(I,J)=1
    3 CONTINUE
      GO TO 11
C
C
C        THIS MEANS THAT THE CONSTRAINT IS
C        NECESSARY AND THE INDIVIDUAL STRATEGIES
C        FOR EACH HIGHWAY SEGMENT SHOULD BE CHECKED
C        TO FINDOUT WHETHER THE STRATEGIES ARE
C        FEASIBLE OR NOT.
C
C
    4 DO 9 J=1,NS
      L=1
      SUMZ=0.
      DO 5 K=1,ND
    5 SUMZ=SUMZ+R(I,K)+DIST(J,K)
      IF(SUMZ-WW(HYTYP(I)))7,6,6
    6 CONTINUE
      GO TO 8
    7 A(I,J)=0
      X(I,J)=0
      GO TO 9
    8 A(I,J)=1
C
C
C
    9 CONTINUE
   11 CONTINUE
C
```

```
C
C
      WRITE (6,701)
  701 FORMAT('1',                //,18X,'MATRIX OF',
     1 ' FEASIBLE STRATEGIES ACCORDING TO OVERALL',
     2' PAVEMENT RATING REQUIREMENT CONSTRAINT',//)
C
C
      WRITE(6,702) (J,J=1,NS)
  702 FORMAT(18X,'X(I,J)=0 MEANS THE JTH ',
     1'MAINTENANCE STRATEGY FOR THE ITH HIGHWAY ',
     2'SEGMENT IS INFEASIBLE',/,18X,'X(I,J)=1,',
     3' MEANS MAINTENANCE STRATEGY J FOR THE ITH',
     4'  HIGHWAY SEGMENT IS IS FEASIBLE',//,10X,
     5 'SEGMENT NUMBER',34X,'STRATEGY',//,28X,
     6  10(6X,I4),//)
      WRITE(6,599)
  599 FORMAT(/)
C
C
      DO 10 I=1,NH
   10 WRITE(6,703)I,(A(I,J),J=1,NS)
  703 FORMAT(14X,I4,10X,10(6X,I4))
      RETURN
      END
C
C
C
C     *******************************************
C     *                                         *
C     *     S U B R O U T I N E   C A L C       *
C     *                                         *
C     *******************************************
C
C
C
      SUBROUTINE  CALC
C
C
C        THIS SUBROUTINE CONVERTS THE INPUT DATA
C        INTO CONVENIENT FORM
C
C
      REAL DIST(10,11),P(10,11,20),R(20 ,11),
     1 RMIN(11,20,2),RX(200),JP(200)
      REAL L1(200), L2(200),XL(200)
      INTEGER T,TDATA,X(20,10),G,F,Q,JJ(20 ,10),A( 20,10)
     1    ,INF(200) ,HYTYP(20)
      DIMENSION SG(10),SGR(10,10),EF(10),EFR(10,10)
     1 ,HQ(10),HQR(10,10),CR(10),CO(20 ,10),IP(200)
     2 ,S(31),PSBR(20,10,10),PHBR(20,10,10),
     3 PEBR(20,10,10),PCR(20,10),WW(20)
      DIMENSION CONSTR(30)
      DIMENSION  RMAX(11)
```

```
      DIMENSION TRAF(20),ENVIR(20)
      COMMON /AREA1/DIST,P,R,RMIN,WW ,TRAF,ENVIR
      COMMON /AREA2/ NH,NS,T,ND ,NHTYP
      COMMON /AREA3/X
      COMMON /AREA4/ A
      COMMON /AREA5/ INF
      COMMON /AREA6/ HYTYP
      COMMON /TOY2/SG,HQ,EF,CC
      COMMON /TOY3/ G,F,Q
      COMMON/TOY4/JJ,CO
      COMMON /CHCK1/PSBR,PHBR,PEBR,PCR,S,IP
      COMMON /DATCK1/ L1,L2
      COMMON /DATCK2/ SGR,EFR,HQR ,CR
      COMMON /ADDON/ TDATA
      COMMON/NETG/ PRES(20,20),RATIMP(20,20),NLIF(20),IX(20),
     1RATNOD(1000,10),CCO(20)
      COMMON /KNPSK1/ CONSTR,XSUM
      COMMON /DATIN6/ RMAX
C
C
C
C
      CALL ALLDIS
C
C
C
C      WRITE (6,501)
C  501 FORMAT('1',                  //,45X,'MATRIX OF',
C     1 ' FEASIBLE STRATEGIES',//)
      WRITE (6,201)(J,J=1,NS)
  201 FORMAT(20X,'X(I,J)=0 MEANS THE JTH ',
     1'MAINTENANCE STRATEGY FOR THE ITH HIGHWAY ',
     2'SEGMENT IS INFEASIBLE',/,20X,'X(I,J)=1,',
     3' MEANS MAINTENANCE STRATEGY J FOR THE ITH',
     4'  HIGHWAY SEGMENT IS IS FEASIBLE',//,10X,
     5 'SEGMENT NUMBER',28X,'STRATEGY',//,28X,
     6  10(6X,I4),//)
      WRITE(6,599)
  599 FORMAT(/)
      DO 5 I=1,NH
      INF(I)=0
    5 WRITE(6,202)I,(X(I,J),J=1,NS)
  202 FORMAT(14X,I4,10X,10(6X,I4))
C
C
C
C* WITHHOLD SECTION-STRATEGY
C* NUM=0 FOR NO MODIFICATIONS
C
C
      WRITE(6,301)
  301 FORMAT('1',//,50X,'RESTRICTED SECTION-STRATEGY COMBINATIONS',
     $ //,65X,'I',10X,'J',//)
      NU=0
```

```
  161 READ (5,159)NUM
  159 FORMAT(I4)
      IF(NUM) 164,164,163
  163 READ (5,160) I,J,X(I,J)
  160 FORMAT (3I5)
      IF (X(I,J).EQ.1) GO TO 304
      WRITE(6,302)I,J
  302 FORMAT(/,60X,I5,5X,I5)
 304  NU=NU+1
      IF (NUM-NU) 164,164,163
  164 CONTINUE
C
C
C*  TO WITHHOLD COMPLETE STRATEGIES LIST
C*  EQUIVALENT J NUMBERS AS JOUT WITH 0 AT
C*  END OF LIST
C
C
      WRITE(6,303)
  303 FORMAT(/////,50X,'COMPLETE STRATEGIES WITHHELD',
     $//,60X,'JOUT',//)
  168 READ(5,166)JOUT
  166 FORMAT(I5)
      IF(JOUT)167,167,165
 165  WRITE(6,305)JOUT
  305 FORMAT(/,60X,I5)
      DO 169 I=1,NH
  169 X(I,JOUT)=0
      GO TO 168
  167 CONTINUE
C
C
      WRITE(6,901)
  901 FORMAT('1',     //,39X,'RANKING OF ',
     1 'STRATEGIES FOR ALL HIGHWAY SEGMENTS',/)
C
C
      XXL=0.
      DO 20 I=1,NH
      XL(I)=L1(I)*L2(I)
      XXL=XXL+XL(I)
   20 CONTINUE
      DO 21 II=1,G
   21 SG(II)=SG(II)*XXL
      DO 22 II=1,F
   22 EF(II)=EF(II)*XXL
      DO 23 II=1,Q
   23 HQ(II)=HQ(II)*XXL
      WRITE(6,931)
  931 FORMAT(10X,'SEGMENT NUMBER ',31X,'STRATEGY')
C
```

```
C
C
      DO 14 I=1,NH
      INDEX=0
      DO 13 J=1,NS
      IF(X(I,J).EQ. 0) GO TO 11
      SUM=0.0
      DO 225 K=1,ND
      L=0
      IT=T
      DDIST=DIST(J,K)
      IF((R(I,K)+DIST(J,K))-RMAX(K))31,31,32
 32   DDIST=RMAX(K)-R(I,K)+0.1
   31 CONTINUE
      L=L+1
      PP=1-TRAF(I)*ENVIR(I)*(1-P(J,K,L))
      IF(PP.LE.0.) PP=0.
      PP=PP*(RMAX(K))
      RR=R(I,K)+DDIST
      IF(RR.LT.PP)GO TO 223
C      IF(R(I,K).LT.RMIN(K,L,HYTYP(I))) GO TO 228
C      SUM=SUM+PP-RMIN(K,L,HYTYP(I))
C      IF(SUM.LE.0.)SUM=0.
C      GO TO 224
  228  IF(PP-R(I,K))225,222,222
 222  SUM=SUM+PP-R(I,K)
      IF(SUM.LE.0.)SUM=0.
      GO TO 226
  223 IT=IT+1
  226 IF(IT-TDATA)224,225,225
  224 IF(L-IT)31,225,225
  225 CONTINUE
C
C
C          CO(I,J) IS THE OBJECTIVE FUNCTION
C          COEFFICIENT.
C
C
      CO(I,J)=SUM*XL(I)
      XSGR=0.
      DO 8 II=1,G
      PSBR(I,J,II)=XL(I)*SGR(J,II)/SG(II)*100.
      IF(PSBR(I,J,II).GT.100.) GO TO 12
    8 XSGR=XSGR+PSBR(I,J,II)
C
C
      XHQR=0.
      DO 9 II=1,Q
      PHBR(I,J,II)=XL(I)*HQR(J,II)/HQ(II)*100.
      IF(PHBR(I,J,II).GT.100.) GO TO 12
    9 XHQR=XHQR+PHBR(I,J,II)
C
```

```
C
      XEFR=0.
      DO 10 II=1,F
      PEBR(I,J,II)=XL(I)*EFR(J,II)/EF(II)*100.
      IF(PEBR(I,J,II).GT.100.) GO TO 12
   10 XEFR=XEFR+PEBR(I,J,II)
      PCR(I,J)=XL(I)*CR(J)/CC*100.
      IF(PCR(I,J).GT.100.)  GO  TO 12
C     RX(J)=CO(I,J)/(XHQR+XEFR+XSGR+PCR(I,J))
      RX(J)=CO(I,J)/((XHQR+XEFR+XSGR)*.20+
     1    PCR(I,J))
C
C
C        RX IS THE RANKING RATIO
C
C
C        STRATEGIES ARE TO BE SORTED ACCORDING
C        TO THE VALUES OF RX IN ASCENDING ORDER.
C
C
      JP(J)=J
      GO TO 13
   12 X(I,J)=0
   11 JP(J)=J
      RX(J)=0.
      CO(I,J)=0.
      INDEX=INDEX+1
      IF(INDEX-NS)13,17,13
   17 INF(I)=I
      WRITE(6,203)I
  203 FORMAT(/,15X,'NO FEASIBLE STRATEGY EXISTS ',
     1 'FOR HIGHWAY SEGMENT NO.=',I4,'***',/)
   13 CONTINUE
      CALL SORT(RX,NS,JP)
      DO 15 K=1,NS
      JJ(I,K)=JP(NS-K+1)
      IF(X(I,JP(NS-K+1)).EQ.0) JJ(I,K)=0
   15 CONTINUE
      WRITE(6,206) I,(JJ(I,K),K=1,NS)
C
  206 FORMAT(//,14X,I4,10X,10(4X,I4))
   14 CONTINUE
      WRITE(6,204)
  204 FORMAT('1',41X,'OBJECTIVE FUNCTION COEFFICIE'
     1 ,'NTS',//,7 X,'SEGMENT NUMBER',34X,
     2  'STRATEGY',//)
      WRITE(6,207) (J,J=1,NS)
  207 FORMAT(21X,10(I3,8X),//)
      WRITE(6,599)
      DO 16 I=1,NH
      WRITE(6,205)I,(CO(I,J),J=1,NS)
  205 FORMAT(10X,I5,10(1X,F10.1))
   16 CONTINUE
C
```

```
C
C
      CALL GRAD
C
C
C
      RETURN
      END
C
C
C
C     ********************************************
C     *                                          *
C     *       S U B R O U T I N E   G R A D      *
C     *                                          *
C     ********************************************
C
C
C
      SUBROUTINE GRAD
C
C
C
C        THIS SUBROUTINE GENERATES THE INITIAL
C        FEASIBLE SOLUTION BY CALCULATING THE
C        EFFECTIVE GRADIENT FOR THE HIGHWAY
C        SEGMENTS.
C
C
      DIMENSION SG(10),S(31),HQ(10),EF(10),H(20,31)
     1 ,CO(20,10),JJ(20,10),XG(200),PSBR(20,10,10),
     2 PHBR(20,10,10),PEBR(20,10,10),PCR(20,10),
     3 SX(31),CONSTR(30),RLEFT(30)
      INTEGER G,F,Q ,IP(200),IK(200),LFLAG(200),
     1 KFLAG(200),TOP,INF(200),X(20,10)
      INTEGER RES(30,6)
      INTEGER STRAT(15,6),DISTR(15,5)
      INTEGER MAT(10,5),EQUP(10,5),MANP(10,5)
      INTEGER OVHD(5)
      DATA BLANK/'    '/
      COMMON /AREA2/ NH,NS,T,ND ,NHTYP
      COMMON /AREA3/X
      COMMON /TOY2/SG,HQ,EF,CC
      COMMON /TOY3/ G,F,Q
      COMMON/TOY4/JJ,CO
      COMMON /AREA5/ INF
      COMMON /CHCK1/PSBR,PHBR,PEBR,PCR,S,IP
      COMMON /KNPSK1/CONSTR,XSUM
      COMMON /PICK1/ KFLAG,LFLAG
      COMMON /DATIN3/ STRAT,DISTR
      COMMON /DATIN4/ MAT, EQUP, MANP, OVHD
      EQUIVALENCE(IK(1),IP(1))
C
```

```
C
      WRITE(6,301)
  301 FORMAT('1',50X,'PHASE 1',/50X,'-------',//,
     1 30X,'INITIAL SOLUTION BY THE METHOD OF ',
     2 'EFFECTIVE GRADIENT',//)
C
C
      NRES=G+F+Q+1
C
C
C          KFLAG IS THE HIGHWAY INDICATOR
C          LFLAG IS THE STRATEGY INDICATOR
C
C
C          INITIALLY ALL THE HIGHWAY SEGMENTS ARE
C          ASSUMED TO HAVE THE BEST FEASIBLE STRATEGY
C
C
      DO 5 I=1,NH
      KFLAG(I)=0
      IF(I.EQ.INF(I)) KFLAG(I)=I
      LFLAG(I)=1
    5 CONTINUE
      TOP=NH
  100 DO 7 II=1,G
      XSBR=0
      DO 6 I=1,NH
      IF(I-KFLAG(I))51,6,51
C
C
C          THIS IS TO CHECK WHETHER A HIGHWAY SEGMENT
C          HAS ALREADY BEEN DROPPED.
C
C
   51 YSBR=PSBR(I,JJ(I,LFLAG(I)),II)
      XSBR=XSBR+YSBR
    6 CONTINUE
      S(II)=XSBR-100.
      SX(II)=S(II)
      IF(S(II).LE.0.)S(II)=0.
    7 CONTINUE
C
C
C
C
      DO 9 II=1,F
      XEFR=0.
      DO 8 I=1,NH
      IF(I-KFLAG(I))52,8,52
   52 YEBR=PEBR(I,JJ(I,LFLAG(I)),II)
      XEFR=XEFR+YEBR
```

```fortran
    8 CONTINUE
      S(II+G)=XEFR-100.
      SX(II+G)=S(II+G)
      IF(S(II+G).LE.0.) S(II+G)=0.
    9 CONTINUE
C
C
C
      DO 11 II=1,Q
      XHQR=0.
      DO 10 I=1,NH
      IF(I-KFLAG(I))53,10,53
   53 YHBR=PHBR(I,JJ(I,LFLAG(I)),II)
      XHQR=XHQR+YHBR
   10 CONTINUE
      S(II+G+F)=XHQR-100.
      SX(II+G+F)=S(II+G+F)
      IF(S(II+G+F).LE.0.)S(II+G+F)=0.
   11 CONTINUE
C
C
C
      XCR=0.
      DO 12 I=1,NH
      IF(I-KFLAG(I))54,12,54
   54 YCR=PCR(I,JJ(I,LFLAG(I)))
      XCR=XCR+YCR
   12 CONTINUE
      S(NRES)=XCR-100.
      SX(NRES)=S(NRES)
      IF(S(NRES).LE.0.) S(NRES)=0.
C
C
C
      COUNT=0
      DO 91 NK=1,NRES
      IF(S(NK).EQ.0) COUNT=COUNT+1
      IF(COUNT.EQ.NRES) GO TO 101
   91 CONTINUE
C
C
C         THIS CALCULATES THE SUMMATION OF H(I,J)
C         FOR A PARTICULAR HIGHWAY SEGMENT FOR
C         ALL ACTIVE CONSTRAINTS.
C
C
      DO 16 I=1,NH
      DO 13 II=1,G
      IF(I-KFLAG(I))55,13,55
   55 H(I,II)=PSBR(I,JJ(I,LFLAG(I)),II)
   13 CONTINUE
C
C
```

```
C
      DO 14 II=1,F
      IF(I-KFLAG(I))56,14,56
   56 H(I,II+G)=PEBR(I,JJ(I,LFLAG(I)),II)
   14 CONTINUE
C
C
C
      DO 15 II=1,Q
      IF(I-KFLAG(I))57,15,57
   57 H(I,II+G+F)=PHBR(I,JJ(I,LFLAG(I)),II)
   15 CONTINUE
C
C
C
      IF(I-KFLAG(I))58,16,58
   58 H(I,NRES)=PCR(I,JJ(I,LFLAG(I)))
   16 CONTINUE
C
C
C         CALCULATION OF EFFECTIVE GRADIENT
C
C
      TOP=0
      DO 18 I=1,NH
      XN=0.
      IF(I-KFLAG(I))59,18,59
   59 DO 17 IJ=1,NRES
   17 XN=XN+H(I,IJ)*S(IJ)
      TOP=TOP+1
      XG(TOP)=CO(I,JJ(I,LFLAG(I)))/XN
      IP(TOP)=I
   18 CONTINUE
C
C
C
      CALL SORT (XG,TOP,IK)
C
C
C
      KST=IP(1)
      LFLAG(IP(1))=LFLAG(KST)+1
      IF(LFLAG(IP(1)).EQ.(NS+1)) GO TO 19
      IF(JJ(IP(1),LFLAG(IP(1))))99,19,99
   99 KKK=LFLAG(IP(1))-1
      WRITE(6,71) IP(1) ,JJ(IP(1),LFLAG(IP(1))),
     1    JJ(IP(1),KKK)
   71 FORMAT(25X,'HIGHWAY SEGMENT',I4,4X,
     1 'EXCHANGE STRATEGY',I4,1X,'WITH STRATEGY',
     2 I4)
      GO TO 100
   19 NN=IP(1)
      KFLAG(NN)=IP(1)
      WRITE(6,304)IP(1)
  304 FORMAT(/,50X,'DROP',1X,I3,/)
      GO TO 100
```

```
  101 WRITE(6,305)
  305 FORMAT(/,30X,' NO MORE HIGHWAY SEGMENT ',
     1 'SHOULD BE  DROPPED',/)
C
C
      WRITE(6,306)
  306 FORMAT('1',40X,'INITIAL FEASIBLE SOLUTION',//)
      WRITE(6,308)
  308 FORMAT(33X,'HIGHWAY SEGMENT',5X,'STRATEGY',5X,
     1 'BENEFIT',/)
C
C
C
      XSUM=0.
      DO 61 I=1,NH
      IF(I-KFLAG(I))60,61,60
   60 WRITE(6,307)I,JJ(I,LFLAG(I)),CO(I,JJ(I,LFLAG(
     1 I)))
  307 FORMAT(37X,I4,13X,I3,9X,F9.0)
      XSUM=XSUM+CO(I,JJ(I,LFLAG(I)))
   61 CONTINUE
C
C
C
      WRITE( 6,310)
  310 FORMAT('1',25X,'FOLLOWING HIGHWAY SEGMENTS ',
     1 'WITH THE CORRESPONDING STRATEGIES',/,30X,
     3 'REPRESENTS THE INITIAL FEASIBLE SOLUTION',
     4 //,35X,'SEGMENT NUMBER',10X,'STRATEGY',/)
      DO 63 I=1,NH
      IF(I-KFLAG(I)) 62,63,62
   62 M=JJ(I,LFLAG(I))
      WRITE(6,311) I,(STRAT(M,N),N=1,6)
   63 CONTINUE
  311 FORMAT(40X,I4,15X,6A4)
C
C
C
      DO 70 II=1,NRES
      IF(II-G)64,64,65
   64 DO 644 K=1,5
      RES(II,K)=MAT(II,K)
  644 CONTINUE
      RES(II,6)=BLANK
      GO TO 70
   65 IF(II-(G+F))66,66,67
   66 DO 666 K=1,5
      RES(II,K)=EQUP(II-G,K)
  666 CONTINUE
      RES(II,6)=BLANK
      GO TO 70
   67 IF(II-NRES) 68,69,69
   68 DO 688 K=1,5
      RES(II,K)=MANP((II-G-F),K)
```

```
  688 CONTINUE
      RES(II,6)=BLANK
      GO TO 70
   69 DO 699 K=1,5
      RES(II,K)=OVHD(K)
  699 CONTINUE
      RES(II,6)=BLANK
   70 CONTINUE
C
C
C
      WRITE(6,309) XSUM
  309 FORMAT(/,37X,'THE NET BENEFIT=',F16.0)
      DO 80 II=1,NRES
   80 CONSTR(II)=0.
C
C
C
      DO 84 I=1,NH
      IF(I-KFLAG(I))82,84,82
   82 DO 81 II=1,NRES
      IF(II.LE.G)CONSTR(II)=CONSTR(II)+
     1    PSBR(I,JJ(I,LFLAG(I)),II)
      IF(II.GT.G.AND.II.LE.(G+F))CONSTR(II)=
     1  CONSTR(II) +PEBR(I,JJ(I,LFLAG(I)),II-G)
      IF(II.GT.(G+F).AND.II.LE.(G+F+Q))CONSTR(II)=
     1 CONSTR(II)+ PHBR(I,JJ(I,LFLAG(I)),(II-G-F))
      IF(II.GT.(G+F+Q))CONSTR(II)=CONSTR(II)+
     1 PCR(I,JJ(I,LFLAG(I)))
   81 CONTINUE
   84 CONTINUE
C
C
C
      WRITE(6,74)
   74 FORMAT('1',35X,'CONSTRAINT',15X,'PERCENT',10X
     1,'PERCENT',/,59X,'UTILIZATION',
     2 7X,'UNUTILIZED',/)
      DO 83 II=1,NRES
      IF(CONSTR(II).GT.100.)CONSTR(II)=100.
      RLEFT(II)=100.-CONSTR(II)
C
C
C        RLEFT(II)=RESOURCE LEFT IN IITH CONSTRAINT
C
C
      WRITE(6,75) (RES(II,K),K=1,6),CONSTR(II),RLEFT(II)
   75 FORMAT(33X,6A4,4X,F6.2,11X,F6.2)
   83 CONTINUE
C
C
C
      CALL PICKUP
C
C
C
      RETURN
      END
C
```

```
C
C
C      **********************************************
C      *                                            *
C      *      S U B R O U T I N E   P I C K U P     *
C      *                                            *
C      **********************************************
C
C
C
       SUBROUTINE  PICKUP
C
C
C
C         THE PURPOSE OF THIS SUBROUTINE IS TO
C         PICKUP ADDITIONAL HIGHWAY SEGMENTS INTO
C         THE SOLUTION SET AFTER THE INITIAL
C         SOLUTION IS OBTAINED BY THE METHOD OF
C         EFFECTIVE GRADIENT.
C
C
C
       DIMENSION PSBR(20,10,10),PHBR(20,10,10),
     1 PEBR(20 ,10,10), PCR(20 ,10)
       DIMENSION CO(20,10),S(31),IP(200)
       INTEGER X(20,10),A(20,10),G,F,Q,JJ(20,10),T
       DIMENSION XXG(20),RR(20),RATIO(20,10),
     1 RLEFT(30),ICON(30),CONSTR(30),PCON(30),
     2 LFLAG(200),KFLAG(200),INF(200),JP(20),
     3 TONSTR(30)
       COMMON /AREA2/ NH,NS,T,ND ,NHTYP
       COMMON /TOY3/ G,F,Q
       COMMON /TOY4/JJ,CO
       COMMON /AREA5/ INF
       COMMON /CHCK1/PSBR,PHBR,PEBR,PCR,S,IP
       COMMON /KNPSK1/ CONSTR,XSUM
       COMMON /AREA3/X
       COMMON /PICK1/ KFLAG,LFLAG
       COMMON /SERCH1/ PCON
C
C
C
       NRES=G+F+Q+1
       WRITE(6,100)
   100 FORMAT('1',//,50X,'PHASE 2',/,50X,'-------',/
     1 /,34X,'INCLUSION OF ADDITIONAL HIGHWAY ',
     2 'SEGMENTS',//)
       WRITE(6,101)
   101 FORMAT(35X,'SEGMENT NUMBER',5X,'STRATEGY',3X,
     1  'BENEFIT',/)
       DO 122 I=1,NH
        NKS=0
       DO 121 J=1,NS
       IF(CO(I,J))121,120,121
```

```
  120 NKS=NKS+1
      A(I,J)=0
  121 CONTINUE
      IF(NKS.EQ.NS) INF(I)=I
  122 CONTINUE
C
C
C
   99 DO 1 II=1,NRES
      ICON(II)=II
      PCON(II)=CONSTR(II)
    1 CONTINUE
C
C
C
      CALL SORT1(CONSTR,NRES,ICON)
C
C
C
C         SORTING THE CONSTRAINTS IN POSITIVE ORDER
C         ACCORDING TO THEIR UTILIZATION.
C
C
C
      DO 2 II=1,NRES
      IF(CONSTR(ICON(II))-100. )2,2,999
    2 CONTINUE
C
C
C
C         CHECKS WHETHER ALL THE CONSTRAINTS ARE
C         SATISFIED OR NOT.
C
C
C
      INTEX=0
      DO 49 I=1,NH
      IF(I-INF(I))47,46,47
   46 INTEX=INTEX+1
      GO TO 49
   47 IF(I-KFLAG(I))48,50,48
   48 INTEX=INTEX+1
   49 CONTINUE
C
C
C
      IF(INTEX.EQ.NH)  GO TO 999
C
C
C
C         THIS IS TO CHECK WHETHER ALL THE FEASIBLE
C         HIGHWAY SEGMENTS ARE ALREADY IN THE
C         SOLUTION OR NOT.
C
C
```

```
C
   50 DO 60 I=1,NH
      IF(I.EQ.INF(I)) GO TO 60
      IF(I-KFLAG(I))60,3,60
    3 INDEX=0
C
C
C
      DO 13 J=1,NS
      IF ( CO(I,J) .LE. 0.) GO TO 12
      IF(X(I,J))4,12,4
C
C
C
    4 DO 43 JX=1,NRES
      IF(ICON(JX)-G)5,5,6
   5  TONSTR(ICON(JX))=  PCON(ICON(JX))+
     1  PSBR(I,J,ICON(JX))
      GO TO 11
    6 IF(ICON(JX)-(G+F))7,7,8
    7 TONSTR(ICON(JX))=  PCON(ICON(JX))+
     1  PEBR(I,J,ICON(JX)-G)
      GO TO 11
    8 IF(ICON(JX)-(G+F+Q))9,9,10
    9 TONSTR(ICON(JX))=  PCON(ICON(JX))+
     1   PHBR(I,J,ICON(JX)-G-F)
      GO TO 11
   10 TONSTR(ICON(JX))=  PCON(ICON(JX))+PCR(I,J)
   11 IF(TONSTR(ICON(JX))-100.)  43,43,12
   43 CONTINUE
C
C
C
C
   45 A(I,J)=1
      GO TO 13
   12 A(I,J)=0
      INDEX=INDEX+1
   13 CONTINUE
C
C
C
      IF(INDEX.EQ.NS) INF(I)=I
   60 CONTINUE
      NHH=0
C
C
C
      DO 65 I=1,NH
      IF(I-INF(I))61,70,61
   61 IF(I-KFLAG(I))70,65,70
   70 NHH=NHH+1
   65 CONTINUE
C
```

```
C
C
      IF(NHH.EQ.NH) GO TO 999
C
C
C
C
      DO 3Ø I=1,NH
      IF(I-INF(I))14,3Ø,14
   14 IF(I-KFLAG(I))3Ø,15,3Ø
   15 LFLAG(I)=1
C
C
C
      DO 28 J=1,NS
      DENOM=Ø.
      IF(A(I,J))16,25,16
C
C
C
   16 DO 24 KK=1,NRES
      IF(PCON(ICON(KK))-5Ø.)24,24,17
   17 IF(ICON(KK)-G)18,18,19
   18 DENOM=DENOM+PSBR(I,J,ICON(KK))
      GO TO 24
   19 IF(ICON(KK)-(G+F))2Ø,2Ø,21
   2Ø DENOM=DENOM+PEBR(I,J,ICON(KK)-G)
      GO TO 24
   21 IF(ICON(KK)-(G+F+Q))22,22,23
   22 DENOM=DENOM+PHBR(I,J,ICON(KK)-G-F)
      GO TO 24
   23 DENOM=DENOM+PCR(I,J)
   24 CONTINUE
C
C
C
      GO TO 26
   25 RATIO(I,J)=Ø.
      GO TO 27
   26 RATIO(I,J)=CO(I,J)/DENOM
   27 JP(J)=J
      RR(J)=RATIO(I,J)
   28 CONTINUE
C
C
C
      CALL SORT1(RR,NS,JP)
C
C
C
C      SORTING IN POSITIVE ORDER
C
C
```

```
C
      DO 29 K=1,NS
   29 JJ(I,K)=JP(K)
   30 CONTINUE
C
C
C
      DO 34 I=1,NH
      IP(I)=I
      IF(I-INF(I))31,32,31
   31 IF(I-KFLAG(I))32,33,32
   32 XXG(I)=0.
      GO TO 34
   33 XXG(I)=RATIO(I,JJ(I,LFLAG(I)))
   34 CONTINUE
C
C
C
      CALL SORT1(XXG,NH,IP)
C
C
C
      KFLAG(IP(1))=0
      LFLAG(IP(1)) =1
      WRITE(6,107) IP(1),JJ(IP(1),LFLAG(IP(1))),
     1 CO(IP(1),JJ(IP(1),LFLAG(IP(1))))
  107 FORMAT(40X,I4,11X,I3,4X,F10.0)
       XSUM=XSUM+CO(IP(1),JJ(IP(1),LFLAG(IP(1))))
C
C
C
      DO 57 II=1,NRES
      IF(II-G)51,51,52
   51 CONSTR(II)=PCON(II)+PSBR(IP(1),JJ(IP(1),
     1 LFLAG(IP(1))),II)
      GO TO 57
   52 IF(II-G-F)53,53,54
   53 CONSTR(II)=PCON(II)+PEBR(IP(1),JJ(IP(1),
     1 LFLAG(IP(1))),II-G)
      GO TO 57
   54 IF(II-G-F-Q)55,55,56
   55 CONSTR(II)=PCON(II)+PHBR(IP(1),JJ(IP(1),
     1  LFLAG(IP(1))),II-G-F)
      GO TO 57
   56 CONSTR(II)=PCON(II)+PCR(IP(1),JJ(IP(1),
     1  LFLAG(IP(1))))
   57 CONTINUE
C
C
C
      GO TO 99
  999 WRITE(6,188)XSUM
  188 FORMAT(/,35X,'NO MORE HIGHWAY SEGMENT CAN B',
     1'E INCLUDED',//,41X,'NET BENEFIT=',F14.0,//)
```

```
      WRITE(6,189)
  189 FORMAT('1',45X,'CONSTRAINT',15X,'PERCENT',/,
     1  69X,'UTILIZATION',//)
      DO 83 II=1,NRES
      CONSTR(II)=PCON(II)
      WRITE(6,190) II,PCON(II)
   83 CONTINUE
C
C
C
  190 FORMAT(48X,I4,19X,F6.2)
C
C
C
      CALL SEARCH
C
C
C
      RETURN
      END
C
C
C
C     ********************************************
C     *                                          *
C     *     S U B R O U T I N E   S E A R C H    *
C     *                                          *
C     ********************************************
C
C
      SUBROUTINE  SEARCH
C
C
C        THE PURPOSE OF THIS SUBROUTINE IS TO
C        IMPROVE THE CURRENT SOLUTION BY
C        SEARCHING THE STRATEGIES WITHIN THE
C        HIGHWAY SEGMENTS ALREADY IN SOLUTION.
C
C
      DIMENSION PSBR(20,10,10), PHBR(20,10,10),
     1 PEBR(20,10,10),PCR(20,10),XX(200),KX(200)
      DIMENSION CO(20,10),S(31),IP(200),INF(200),
     1 CCO(200),CONSTR(30),PCON(30),LFLAG(200),
     2 KFLAG(200),TCON(30)
      INTEGER G,F,Q,JJ(20 ,10),T,MFLAG(200),
     1  JFLAG(200)
C
C
C
      COMMON /AREA2/ NH,NS,T,ND,NHTYP
      COMMON /TOY3/ G,F,Q
      COMMON /TOY4/ JJ,CO
      COMMON /AREA5/ INF
      COMMON /CHCK1/ PSBR,PHBR,PEBR,PCR,S,IP
      COMMON/KNPSK1/CONSTR,XSUM
```

```
      COMMON /PICK1/ KFLAG,LFLAG
      COMMON /SERCH1/ PCON
      COMMON /SERCH2/ XXSUM, JFLAG
C
C
C
      NRES=G+F+Q+1
C
C
      DO 229 I=1,NH
      CCO(I)=0.
      IP(I)=I
      IF(I- KFLAG(I)) 228,229,228
  228 MFLAG(I)= JJ(I,LFLAG(I))
      JFLAG(I)=MFLAG(I)
  229 CONTINUE
C
C
    1 DO 10 I=1,NH
C**   NEXT 2 STATEMENTS ADDED BY DALE SCHAFER
      CCO(I)=0
      IP(I)=I
      IF( KFLAG(I).EQ. -1) GO TO 10
      IF( I-KFLAG(I)) 2,10,2
    2 DO 3 J=1,NS
      XX(J)= CO(I,J)
      KX(J)=J
    3 CONTINUE
C
C
C         PICKS THE BEST  OBJECTIVE FUNCTION
C         COEFFICIENT IN EACH HIGHWAY SEGMENT
C         IN SOLUTION.
C
C
      CALL SORT1 (XX,NS,KX)
      XNUM= CO(I,JFLAG(I))
      IF( CO(I,KX(1)).LE. XNUM) GO TO 5
C
C
C
      DO 9 J=1,NS
      IF( CO(I,KX(J)) -XNUM) 10,10,6
C
C
    6 DO 7 II=1,NRES
      IF(II-G) 21,21,22
   21 TCON(II)= PCON(II)+ PSBR(I,KX(J), II) -
     1   PSBR(I,MFLAG(I),II)
      GO TO 27
   22 IF(II-G-F) 23,23,24
   23 TCON(II) =PCON(II) + PEBR(I,KX(J),II-G) -
     1 PEBR(I,MFLAG(I),II-G)
      GO TO 27
```

```
   24 IF(II-G-F-Q) 25,25,26
   25 TCON(II)= PCON(II) + PHBR(I,KX(J), II-G-F)-
     1  PHBR(I,MFLAG(I),II-G-F)
      GO TO 27
   26 TCON(II)=PCON(II)+ PCR(I,KX(J))-
     1  PCR(I,MFLAG(I))
   27 IF( TCON(II) -100.) 7,7,9
    7 CONTINUE
C
C
      CCO(I)= CO(I,KX(J))- XNUM
      MFLAG(I)= KX(J)
      GO TO 10
    9 CONTINUE
    5 KFLAG(I)= -1
   10 CONTINUE
C
C
C
      CALL SORT1( CCO,NH,IP)
C
C
C
      IF(ABS(CCO(1)).LT.1.E-4) GO TO 77
      KFLAG(IP(1)) =-1
      DO 88 II=1,NRES
      IF(II-G) 35,35,36
   35 PCON(II)= PCON(II)+ PSBR( IP(1), MFLAG(IP(1))
     1,II)-PSBR(IP(1),JJ(IP(1),LFLAG(IP(1))),II)
      GO TO 88
   36 IF(II-G-F) 37,37,38
   37 PCON(II)=PCON(II)+ PEBR(IP(1),MFLAG(IP(1)),
     1 II-G)-PEBR(IP(1),JJ(IP(1),LFLAG(IP(1))),II-G
     2 )
      GO TO 88
   38 IF( II-G-F-Q) 39,39,40
   39 PCON(II)=PCON(II)+ PHBR(IP(1),MFLAG(IP(1)),
     1 II-G-F)-PHBR(IP(1),JJ(IP(1),LFLAG(IP(1))),
     2II-G-F)
      GO TO 88
   40 PCON(II)= PCON(II)+ PCR(IP(1), MFLAG(IP(1)))
     1  - PCR(IP(1),JJ(IP(1),LFLAG(IP(1))))
      IF( PCON(II) -100.) 88,88,99
   88 CONTINUE
      JFLAG(IP(1))=MFLAG(IP(1))
      GO TO 1
C
C
 99   WRITE(6,1234)
 1234 FORMAT(1H ,'******** 99 ENTERED *******')
      DO 15 II=1,NRES
      IF(II-G) 41,41,42
   41 PCON(II)=PCON(II)-PSBR(IP(1),MFLAG(IP(1)),II)
     2+PSBR(IP(1),JJ(IP(1),LFLAG(IP(1))),II)
      GO TO 15
```

```
   42 IF(II-G-F) 43,43,44
   43 PCON(II)=PCON(II) -PEBR(IP(1), MFLAG(IP(1)),
     1   II-G) +PEBR(IP(1),JJ(IP(1),LFLAG(IP(1))),II-G)
      GO TO 15
   44 IF(II-G-F-Q) 45,45,46
   45 PCON(II)= PCON(II)- PHBR(IP(1), MFLAG(IP(1)),
     1  II-G-F)+PHBR(IP(1),JJ(IP(1),LFLAG(IP(1))),II-G-F)
      GO TO 15
   46 PCON(II)=PCON(II)- PCR(IP(1), MFLAG(IP(1)))
     2+PCR(IP(1),JJ(IP(1),LFLAG(IP(1))))
   15 CONTINUE
C
C
   77 WRITE(6,100)
  100 FORMAT('1',//,50X,'PHASE 3 ',/,50X,'--------',
     1//,20X,'FINAL SOLUTION OBTAINED AFTER ',
     2  'SEARCHING FOR BETTER STRATEGIES THAN THOSE'
     3 ,/,20X,'SELECTED IN PHASE 1  AND PHASE 2',//
     4 )
      WRITE(6,101)
  101 FORMAT(// ,35X,'    OPTIMUM SOLUTION   ', //,
     1 25X,' HIGHWAY SEGMENT',4 X,'STRATEGY', 3X,
     2 'BENEFIT',/)
      XXSUM=0.
      DO 17 I=1,NH
      IF( I-KFLAG(I))16,17,16
   16 WRITE(6,102) I,JFLAG(I),CO(I,JFLAG(I))
      XXSUM=XXSUM+ CO(I, JFLAG(I))
   17 CONTINUE
  102 FORMAT(31X,I4,12X,I3,4X,F10.0)
      WRITE(6,103)XXSUM
  103 FORMAT(/,29X,'THE NET BENEFIT IS ',F16.0,///)
      WRITE(6,104)
  104 FORMAT(///,33X,'CONSTRAINT',8X,'PERCENT',
     1 /,49X,'UTILIZATION',/)
      DO 18 II=1,NRES
      WRITE(6,105) II, PCON(II)
   18 CONTINUE
  105 FORMAT( 35X,I4,12X,F6.2)
C
C
C
      CALL RPRINT
      RETURN
      END
C
C
```

```
C
C     ********************************************
C     *                                          *
C     *     S U B R O U T I N E   I P R I N T    *
C     *                                          *
C     ********************************************
C
C
C
      SUBROUTINE IPRINT(MAT,STRAT,JFLAG,PSBR,NH,G)
C
C
C
C        THIS SUBROUTINE IS USED AS INPUT TO THE
C        SUBROUTINE  RPRINT.
C
C
C
      INTEGER MAT(10,5),STRAT(15,6)
      DIMENSION PSBR(20,10,10), JFLAG(200),KFLAG(20
     10),LFLAG(200)
      INTEGER G
      COMMON /PICK1/ KFLAG,LFLAG
C
C
C
      IF(G-4) 5,5,6
    5 K=G
      GO TO 7
    6 K=4
    7 WRITE(6,107) ((MAT(II,M),M=1,5),II=1,K)
  107 FORMAT(///,5X,'SEGMENT NO.',3X,'STRATEGY',17X
     1   ,4(2X,5A4),/)
C
C
      DO 9 I=1,NH
      IF(I-KFLAG(I))8,9,8
    8 WRITE(6,108) I,(STRAT(JFLAG(I),M),M=1,6),(PSBR(I,
     1JFLAG(I),II),II=1,K)
  108 FORMAT(8X,I4,6X,6A4,T50,4(F7.2,13X))
    9 CONTINUE
C
C
      IF( G.LE. 4) GO TO 25
      IF ( G-8) 10,10,11
   10 KK=G
      GO TO 12
   11 KK=8
   12 WRITE(6,107) ((MAT(II,M),M=1,5),II=5,KK)
C
C
C
      DO 14 I=1,NH
      IF(I-KFLAG(I)) 13,14,13
   13 WRITE(6,108) I,(STRAT(JFLAG(I),M),M=1,6),(PSBR(I,
     1 JFLAG(I),II),II=5,KK)
   14 CONTINUE
C
```

```
C
C
      IF( G.LE. 8) GO TO 25
      IF(G-12 )15,15,16
   15 KK=G
      GO TO 17
   16 KK=12
   17 WRITE(6,107) ((MAT(II,M),M=1,5),II=1,KK)
C
C
C
      DO 19 I=1,NH
      IF(I-KFLAG(I))18,19,18
   18 WRITE(6,108) I,(STRAT(JFLAG(I),M),M=1,6),(PSBR(I,
     1JFLAG(I),II),II=9,KK)
   19 CONTINUE
C
C
C
      IF (G.LE. 12) GO TO 25
      IF (G-16) 20,20,21
   20 KK=G
      GO TO 22
   21 KK=16
   22 WRITE(6,107) ((MAT(II,M),M=1,5),II=13,KK)
C
C
C
      DO 24 I=1,NH
      IF(I- KFLAG(I))23,24,23
   23 WRITE(6,108) I,(STRAT(JFLAG(I),M),M=1,6),(PSBR(I,
     1 JFLAG(I),II),II=13,KK)
   24 CONTINUE
   25 RETURN
      END
C
C
C
C
C     ********************************************
C     *                                          *
C     *     S U B R O U T I N E   R P R I N T    *
C     *                                          *
C     ********************************************
C
C
C
      SUBROUTINE  RPRINT
C
C
C
C        THIS SUBROUTINE  PRINTS THE OPTIMAL
C        MAINTENANCE DECISIONS, AND THE RESOURCE
C        REQUIREMENTS ASSOCIATED WITH THE
C        OPTIMAL MAINTENANCE DECISIONS.
C
```

```
C
C
      DIMENSION PSBR(20,10,10), PHBR(20,10,10),TOTR(20),IEX(20),
     1 PEBR(20,10,10), PCR(20,10),R(20,11),CR(10),XL(200)
      REAL*4 L1(200),L2(200)
      DIMENSION CO(20,10), S(31), IP(200), PCON(30)
     1 ,LFLAG(200),KFLAG(200) ,CONSTR(30),COST(20,10)
      INTEGER G,F,Q, JJ(20,10), T,MFLAG(200),
     1 JFLAG(200),TDATA
      INTEGER PAR1(50,2),STRAT(15,6),
     1 MAT(10,5),EQUP(10,5),MANP(10,5),
     2 OVHD(5),PAR2(50,3)
      INTEGER DISTR(15,5)
C
C
C
      COMMON /AREA2/ NH,NS,T,ND,NHTYP
      COMMON /DATIN1/PAR1,PAR2
      COMMON /DATIN4/ MAT,EQUP,MANP,OVHD
      COMMON /TOY4/ JJ,CO
      COMMON /CHCK1/ PSBR,PHBR,PEBR,PCR,S,IP
      COMMON /TOY3/ G,F,Q
      COMMON /KNPSK1/ CONSTR,XSUM
      COMMON /PICK1/ KFLAG,LFLAG
      COMMON /SERCH1/ PCON
      COMMON /SERCH2/ XXSUM, JFLAG
      COMMON /DATIN3/STRAT,DISTR
      COMMON /AREA1/DIST(10,11),P(10,11,20),R,
     1RMIN(11,20,2),WW(20),TRAF(20),ENVIR(20)
      COMMON /TOY2/SG(10),HQ(10),EF(10),CC
      COMMON /DATCK1/ L1,L2
      COMMON /DATCK2/ SGR(10,10),EFR(10,10),HQR(10,10),CR
      COMMON /ADDON/ TDATA
      COMMON /DATIN6/ RMAX(11)
C
C
C
      WRITE(6,101)
  101 FORMAT( '1', 41X,'OPTIMAL MAINTENANCE DECIS',
     1  'IONS',///)
      WRITE(6,102)
  102 FORMAT(20X,'SEGMENT NO.',6X,'NAME',10X,
     1 'STRATEGY',21X,'BENEFIT',//)
C
C
C
      DO 2 I=1,NH
      IF(I-KFLAG(I)) 1,2,1
    1 WRITE(6,103) I, (PAR1(I,J),J=1,2),(STRAT(JFLAG(I),K),K=1,6),
     1  CO(I,JFLAG(I))
    2 CONTINUE
  103 FORMAT(23X,I4,9X,2A4,2X,6A4,2X,F15.0)
C
C
      WRITE(6,104) XXSUM
  104 FORMAT( /, T60,'NET BENEFIT=', F16.0)
C
```

```
C
      WRITE(6,105)
  105 FORMAT( '1', 45X,'RESOURCE REQUIREMENTS',///)
C
C
      WRITE(6,106)
  106 FORMAT(41X,'MATERIAL REQUIREMENTS IN ',
     1 'PERCENTS')
C
C
C
      CALL IPRINT( MAT,STRAT, JFLAG,PSBR,NH,G)
C
C
      WRITE(6,107)
  107 FORMAT('1', 41X,'EQUIPMENT REQUIREMENTS ',
     1 'IN PERCENTS',/)
C
C
      CALL IPRINT(EQUP,STRAT,JFLAG,PEBR,NH,F)
C
C
      WRITE(6,108)
  108 FORMAT('1', 41X,'MANPOWER REQUIREMENTS ',
     1 'IN PERCENTS')
C
C
      CALL IPRINT( MANP,STRAT,JFLAG,PHBR,NH,Q)
C
C
      WRITE(6,109)
  109 FORMAT('1', 34X,'OVERHEAD BUDGET REQUIREMENT'
     1 ,' IN PERCENTS',//)
      WRITE(6,110)
  110 FORMAT(20X,'SEGMENT NO.',7X,'NAME',10X,
     1 'STRATEGY',10X,'OVERHEAD BUDGET',//)
C
C
      DO 197 II=1,NH
      TOTR(II)=0.
  197 CONTINUE
      IE=0
      DO 4 I=1,NH
      IF(I-KFLAG(I))3,200,3
    3 WRITE(6,111) I,(PAR1(I,J),J=1,2),(STRAT(JFLAG(I),K),K=1,6),
     1 PCR(I,JFLAG(I))
  111 FORMAT(23X,I4,9X,2A4,2X,6A4,6X,F6.2)
      GO TO 4
  200 IE=IE+1
      IEX(IE)=I
    4 CONTINUE
      IET=IE
C
C
```

```
C
      NRES=G+F+Q+1
      WRITE(6,112)
  112 FORMAT( '1',////,29X,'RESOURCE UTILIZATION',
     1 //,25X,'CONSTRAINT',12X,'PERCENT',/,45X,
     2 'UTILIZATION',/)
C
C
C
      DO 11 II=1,NRES
      IF(II-G)5,5,6
    5 WRITE(6,113) (MAT(II,M),M=1,5),PCON(II)
      GO TO 11
    6 IF(II-(G+F)) 7,7,8
    7 WRITE(6,113) (EQUP((II-G),M),M=1,5), PCON(II)
      GO TO 11
    8 IF(II-(G+F+Q))  9,9,10
    9 WRITE(6,113) (MANP((II-G-F),M),M=1,5), PCON(II)
  113 FORMAT(23X,5A4,4X,F6.2)
      GO TO 11
   10 WRITE(6,113) (OVHD(M),M=1,5), PCON(II)
   11 CONTINUE
      J=2
      RTOTM=1.E20
      DO 201 IE=1,IET
      IEXNOW=IEX(IE)
      DO 202 K=1,ND
  202 TOTR(IEXNOW)=TOTR(IEXNOW) + R(IEXNOW,K)
      XL(IEXNOW)=L1(IEXNOW) * L2(IEXNOW)
  201 COST(IEXNOW,J)=XL(IEXNOW) * CR(J)
      DO 215 I=1,IET
  211 DO 203 IE=1,IET
      IF (TOTR(IEX(IE)).GE.RTOTM) GO TO 203
      RTOTM=TOTR(IEX(IE))
      IEM=IEX(IE)
  203 CONTINUE
      COST2=CC*PCON(21)/100. + COST(IEM,J)
      COST2=CC - COST2
      IF (COST2.LT.0.) GO TO 2065
      PBUSD=(CC-COST2)/CC * 100.
      SUM=0.0
      DO 725 K=1,ND
      L=0
      IT=T
      DDIST=DIST(J,K)
      IF ((R(IEM,K) + DIST(J,K)) - RMAX(K))731,731,732
  732 DDIST=RMAX(K) - R(IEM,K) + 0.1
  731 CONTINUE
      L=L + 1
      PP=1-TRAF(IEM)*ENVIR(IEM)*(1.-P(J,K,L))
      IF (PP.LE.0.) PP=0.
      PP=PP*(RMAX(K))
      RR=R(IEM,K) + DDIST
      IF (RR.LT.PP) GO TO 723
  728 IF (PP-R(IEM,K)) 725,722,722
```

```
  722 SUM=SUM + PP - R(IEM,K)
      IF (SUM.LE.0.) SUM=0.
      GO TO 726
  723 IT=IT + 1
  726 IF (IT-TDATA) 724,725,725
  724 IF (L-IT) 731,725,725
  725 CONTINUE
      ADBNF=SUM*XL(IEM)
      XXSUM=XXSUM + ADBNF
      IGG=0
      IGF=0
      IGQ=0
      WRITE(6,712)
  712 FORMAT(1H1,30X,'RESULTS OF UPDATE ROUTINE',/1H-,
     129X,'RESOURCE UTILIZATION',//25X,'CONSTRAINT',12X,'PERCENT',
     2/45X,'UTILIZATION',/)
      DO 701 II=1,G
      PCON(II)=PCON(II) + PSBR(IEM,J,II)
      WRITE(6,113) (MAT(II,M),M=1,5),PCON(II)
      IF (PCON(II).GT.100.) IGG=1
  701 CONTINUE
C
      DO 702 II=1,F
      III=II+G
      PCON(III)=PCON(III) + PEBR(IEM,J,II)
      WRITE(6,113) (EQUP(II,M),M=1,5),PCON(III)
      IF (PCON(III).GT.100.) IGF=1
  702 CONTINUE
C
      DO 703 II=1,Q
      III=II+G+F
      PCON(III)=PCON(III) + PMBR(IEM,J,II)
      WRITE(6,113) (MANP(II,M),M=1,5),PCON(III)
      IF (PCON(III).GT.100.) IGQ=1
  703 CONTINUE
C
      IF ((IGG.EQ.1).OR.(IGF.EQ.1).OR.(IGQ.EQ.1)) WRITE(6,714)
  714 FORMAT(1H-,'***** NOTE:  ONE OR MORE PERCENTS ARE',
     1'GREATER THAN 100 *****')
      WRITE(6,1210) IEM,PBUSD,ADBNF,XXSUM
 1210 FORMAT(1H0,'HIGHWAY SEGMENT NO. ',I3,1X,'HAS BEEN ADDED',
     1/1H0,'THE OVERHEAD BUDGET UTILIZATION NOW BECOMES ',F12.4,
     2/1H0,'ADDITIONAL BENEFIT = ',F12.4,10X,'TOTAL BENEFIT = ',F12.4)
      WRITE(6,1213) J
 1213 FORMAT(1H+,90X,'THE STRATEGY USED WAS ',I3)
      PCON(21)=(CC-COST2)/CC * 100.
 2065 TOTR(IEM)=1.E21
      RTOTM=1.E20
  215 CONTINUE
      WRITE(6,1214)
 1214 FORMAT(1H-,'NO MORE SECTIONS CAN BE ADDED ')
      WRITE(6,699)
  699 FORMAT(1H1)
      RETURN
      END
```

```
//SYSIN DD *
          TEST PROBLEM   FOR THE STATE OF TEXAS
    15     8   20   10    6     2     4    8     8
   4.53    26.0       1  1.0    1.0    US 79    MILAM          0204-050.0      0.0
  12.32  28.00        1  1.0    1.0    US 77    MILAM          0209-05
   3.62    26.0       1  1.0    1.0    US 190   MILAM          0815-02
  7.00     20.0       2  1.0    1.0    SH OSR   MADISON        0475-04
  2.260    22.0       2  1.0    1.0    SH OSR   MADISON        0475-03
  13.80    20.0       2  1.0    1.0    FM1696   WALKER         1809-02
   12.37  22.00       2  1.0    1.0    FM 1791  WALKER         1706-01
   3.34   24.00       2  1.0    1.0    FM2821   WALKER         2805-01
   7.39   26.0        1  1.0    1.0    SH 30    WALKER         0212-02
   12.01    26.0      1  1.0    1.0    SH 36    BURLESON       0816-03
   9.021    26.0      1  1.0    1.0    US 290   WASHINGTON     0114-09
   5.64     26.0      1  1.0    1.0    US 79    MILAM          0204-08
   9.32     26.0      1  1.0    1.0    SH 36    BURLESON       0186-02
   6.67   20.0        2  1.0    1.0    SH OSR   BRAZOS         0475-02
   7.44   20.0        2  1.0    1.0    FM 908   MILAM          0858-02
FOG SEAL                  SEAL COAT               OGPMS
THIN OVERLAY              MODERATE OVERLAY        HEAVY OVERLAY
LIGHTDUTY RECONSTRUCTIONHEAVY DUTY RECONSTRT.
RUTTING                 ALLIGATOR CRACKING  LONGTUD. CRACKING   TRANSVERSE CRACKING
FAILURES/MILE           SERVICEABILITY INDEX
SURFACING AGGREGATE ASPHALT CEMENT      AGGREGATE(ITEM 340:)AGGREGATE ITEM 290
    9.5         4.6         87.7      87.7
     0.          0.4        0.        0.
    9.5        0.8         0.0       0.0
     0.0       3.0         20.0       0.0
    0.0        1.5         29.3      0.0
    0.0        4.1         80.5      0.0
     0.0       8.1         29.3     132.0
    10.0       1.5         0.0       0.0
     0.0      1.50        29.30     143.00
GRADER                  PICKUP                  LOADER                  TRUCK
ROLLER                  SPREADER                LAYDOWN MACHINE         ASPHALT DISTRIBUTOR
     .70         .70         .34         .84        1.0         .34         .17         .34
    0.0        0.008        0.0       0.017       0.0         0.0         0.0       0.008
    0.0        0.012      0.012       0.060       0.024     0.012       0.0         0.012
    0.0        0.111        0.0       0.278       0.111     0.          0.056       0.056
   0.          0.111        0.0       0.278       0.111       0.0       0.056       0.056
    0.0        0.222        0.0       0.556       0.222       0.0       0.111       0.111
    0.0        0.333        0.0       0.834       0.333     0.0         0.168       0.168
   0.667     0.667       0.333      1.667       1.0       0.333       0.0         0.333
    1.0        0.778      0.333       3.611       1.111     0.          0.056       &
GRADER OPERATOR         LOADER OPERATOR         TRUCK OPERATOR          ROLLER OPERATOR
SPREADER OPERATOR       LAYDOWN MC. OPERATORASPHALTDIS. OPERATORGENERAL LABOR
     .70         .34         .84        1.0        1.34         .85         .67        1.66
    0.         0.          0.017      0.          0.          0.          0.016       0.008
    0.         0.012       0.060      0.024       0.048       0.0         0.024       0.012
    0.         0.          0.278      0.111       0.          0.280       0.056       0.168
    0.         0.          0.278      0.111       0.0         0.280       0.056       0.168
    0.         0.          0.556      0.222       0.0         0.560       0.111       0.336
    0.0        0.0         0.834      0.333       0.          0.840       0.168       0.504
   0.667      0.333       1.667        1.0       1.332       0.           0.666       1.65
    1.0        0.333      3.611       1.111      0.          0.280        0.056       1.818
```

2370.	OVERHEAD BUDGET							
2371.	56.	214.	950.	925.	2000.	3549.	944.	2600.
2372.	1202000.							
2373.	0.	5.	5.	5.	2.	2.		
2374.	0.	15.	15.	15.	10.	2.		
2375.	13.	19.	19.	19.	24.	45.		
2376.	13.	20.	20.	20.	25.	45.		
2377.	15.	25.	25.	20.	30.	50.		
2378.	15.	25.	25.	20.	35.	50.		
2379.	15.	25.	25.	20.	40.	50.		
2380.	15.0	25.0	25.0	20.0	40.0	50.		
2381.	15.	25.	25.	20.	40.	50.		
2382.	10.	5.	20.	17.	20.	10.		
2383.	10.	15.	25.	20.	40.	3.		
2384.	10.	10.	15.	13.	40.			
2385.	10.	20.	20.	20.	40.			
2386.	10.	25.	25.	20.	40.			
2387.	10.	25.	25.	20.	40.			
2388.	8.	0.	10.	20.	10.			
2389.	10.	15.	25.	20.	20.			
2390.	15.	25.	5.	5.	40.	42.		
2391.	15.	25.	25.	20.	40.	47.		
2392.	15.	25.	25.	17.	40.	47.		
2393.	15.	25.	25.	17.	40.	49.		
2394.	13.	25.	25.	20.	40.	50.		
2395.	8.	5.	0.	17.	20.			
2396.	10.	10.	10.	8.	20.			
2397.	5.	5.	5.	5.	5.	5.	5.	5.
2398.	5.	5.	5.	5.	5.	5.	5.	5.
2399.	5.	5.	5.					
2400.	20.	20.	20.	15.	15.	10.	10.	10.
2401.	5.	5.	5.	5.	5.	5.	5.	5.
2402.	5.	5.	5.	5.				
2403.	20.	20.	20.	15.	15.	10.	10.	10.
2404.	5.	5.	5.	5.	5.	5.	5.	5.
2405.	5.	5.	5.	5.				
2406.	15.	15.	10.	10.	10.	10.	5.	5.
2407.	5.	5.	5.	5.	5.	5.	5.	5.
2408.	5.	5.	5.	5.				
2409.	40.	30.	30.	30.	30.	20.	20.	20.
2410.	20.	20.	20.	20.	20.	20.	20.	20.
2411.	20.	20.	20.	20.				
2412.	40.	35.	30.	25.	20.	20.	15.	15.
2413.	10.	10.						
2414.								
2415.	5.	5.	5.	5.	5.	5.	5.	5.
2416.	5.	5.	5.	5.	5.	5.	5.	5.
2417.	5.	5.	5.	5.				
2418.	20.	15.	15.	10.	10.	5.	5.	5.
2419.	5.	5.	5.	5.	5.	5.	5.	5.
2420.	5.	5.	5.	5.				
2421.	20.	15.	15.	10.	10.	5.	5.	5.
2422.	5.	5.	5.	5.	5.	5.	5.	5.
2423.	5.	5.	5.	5.				
2424.	15.	10.	10.	10.	10.	10.	5.	5.

2425.	5.	5.	5.	5.	5.	5.	5.	5.
2426.	5.	5.	5.	5.				
2427.	.02	.02	.02	.02	.02	.03	.03	.03
2428.	20.	20.	20.	20.	20.	20.	20.	20.
2429.	20.	20.	20.	20.				
2430.	25.	20.	15.	15.	10.	10.	5.	5.
2431.								
2432.								
2433.	1.0	1.0	1.0	1.0	0.69	0.67	0.48	0.26
2434.	0.17	0.14						
2435.								
2436.	1.0	0.93	0.91	0.88	0.78	0.31	0.22	0.15
2437.	0.07	0.05	0.02	0.02	0.02	0.02	0.01	0.01
2438.	0.01	0.01	0.01	0.01				
2439.	1.	1.0	1.0	1.0	0.88	0.78	0.46	0.25
2440.	0.25	0.25						
2441.								
2442.	1.0	1.0	1.0	1.0	0.79	0.75	0.75	0.75
2443.	0.75	0.75	0.33	0.25	0.25	0.17	0.08	
2444.								
2445.	1.0	1.0	1.0	1.0	1.0	0.83	0.71	0.66
2446.	0.62	0.38	0.30	0.30	0.30	0.28	0.22	0.17
2447.	0.12	0.04	0.04	0.04				
2448.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2449.	1.0	1.0	0.67	0.67	0.67	0.67	0.22	
2450.								
2451.	1.0	1.0	1.0	1.0	1.0	0.72	0.67	0.58
2452.	0.50	0.50	0.36	0.33	0.33	0.28	0.17	0.17
2453.	0.17	0.17	0.17	0.17				
2454.	1.0	1.0	1.0	1.0	1.0	0.72	0.67	0.58
2455.	0.50	0.50	0.36	0.33	0.33	0.28	0.17	0.17
2456.	0.17	0.17	0.17	0.17				
2457.	1.0	1.0	1.0	0.87	0.62	0.50	0.25	0.08
2458.								
2459.								
2460.	1.0	0.94	0.89	0.89	0.65	0.28	0.24	0.15
2461.	0.09	0.07	0.02	0.01	0.01	0.01		
2462.								
2463.	1.0	1.0	0.89	0.82	0.73	0.67	0.67	0.67
2464.	0.67	0.36	0.11	0.09				
2465.								
2466.	1.0	1.0	0.95	0.91	0.90	0.61	0.56	0.55
2467.	0.51	0.28	0.17	0.14	0.14	0.14	0.08	0.01
2468.								
2469.	1.00	1.0	1.0	1.0	0.77	0.64	0.58	0.53
2470.	0.51	0.38	0.21	0.19	0.19	0.17	0.15	0.10
2471.	0.07	0.06	0.06	0.03				
2472.	1.0	1.0	1.0	1.0	1.0	0.71	0.62	0.44
2473.	0.29	0.29	0.29	0.17	0.14	0.14	0.12	
2474.								
2475.	1.0	1.0	1.0	1.0	1.0	0.49	0.36	0.36
2476.	0.36	0.29	0.27	0.27	0.27	0.27	0.21	0.19
2477.	0.19	0.18	0.11	0.09				
2478.	1.0	1.0	1.0	1.0	1.0	0.49	0.36	0.36
2479.	0.36	0.29	0.27	0.27	0.27	0.27	0.21	0.19
2480.	0.19	0.18	0.11	0.09				
2481.	1.0	1.0	0.79	0.50	0.50	0.21		

2482.								
2483.								
2484.	1.0	0.93	0.88	0.87	0.67	0.37	0.32	0.18
2485.	0.09	0.07	0.02	0.01	0.01	0.01		
2486.								
2487.	1.0	1.0	1.0	1.0	1.0	0.75	0.50	0.50
2488.	0.25							
2489.								
2490.	1.0	1.0	0.93	0.93	0.40	0.14	0.14	0.12
2491.	0.07	0.02						
2492.								
2493.	1.0	1.0	1.0	1.0	1.0	0.33	0.11	
2494.								
2495.								
2496.	1.0	1.0	1.0	1.0	1.0	0.33	0.33	0.28
2497.	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
2498.	0.17	0.17	0.17	0.17				
2499.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2500.	0.65	0.60	0.60	0.60	0.53	0.40	0.38	0.21
2501.	0.20	0.20	0.20	0.20				
2502.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2503.	0.65	0.60	0.60	0.60	0.53	0.40	0.38	0.21
2504.	0.20	0.20	0.20	0.20				
2505.	1.0	1.0	0.56	0.53	0.39	0.19	0.06	0.05
2506.								
2507.								
2508.	1.0	0.92	0.86	0.85	0.67	0.38	0.33	0.18
2509.	0.09	0.06	0.01	0.01	0.01			
2510.								
2511.	1.0	1.0	1.0	1.0	1.0	0.83	0.67	0.67
2512.	0.33							
2513.								
2514.	1.0	1.0	0.94	0.94	0.43	0.18	0.18	0.14
2515.	0.06	0.01						
2516.								
2517.	1.0	1.0	1.0	1.0	1.0	0.63	0.26	0.22
2518.	0.11	0.04						
2519.								
2520.	1.0	1.0	1.0	1.0	1.0	0.33	0.33	0.28
2521.	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
2522.	0.17	0.17	0.17	0.17				
2523.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2524.	0.65	0.60	0.60	0.60	0.51	0.40	0.38	0.20
2525.	0.20	0.20	0.20	0.20				
2526.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2527.	0.65	0.60	0.60	0.60	0.51	0.40	0.38	0.20
2528.								
2529.	1.0	1.0	1.0	0.67	0.67	0.33	0.33	
2530.								
2531.								
2532.	1.0	1.0	0.91	0.78	0.47	0.22	0.20	0.10
2533.	0.04	0.01						
2534.								
2535.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.33
2536.	0.33	0.33						
2537.								
2538.	1.0	1.0	1.0	0.89	0.53	0.23	0.16	0.15
2539.	0.13	0.08	0.02					

```

1.0    1.0    1.0    1.0    0.77   0.51   0.48   0.36
0.33   0.24   0.17   0.17   0.17   0.17   0.17   0.17
0.07
1.0    1.0    1.0    1.0    1.0    0.75   0.59   0.50
0.50   0.48   0.25   0.25   0.25   0.25   0.20

1.0    1.0    1.0    1.0    1.0    0.47   0.36   0.32
0.27   0.27   0.27   0.20   0.18   0.18   0.15   0.09
0.09   0.09   0.09   0.09
1.0    1.0    1.0    1.0    1.0    0.47   0.36   0.32
0.27   0.27   0.27   0.20   0.18   0.18   0.15   0.09
0.09   0.09   0.09   0.09
 1.0    0.9    0.7    0.5    0.4    0.3    0.2    0.1
 0.1

 1.0    0.9    0.7    0.5    0.4    0.3    0.2    0.1
 0.1

 1.0    1.0    1.0    0.9    0.8    0.7    0.6    0.5
 0.4    0.3

 1.0    1.0    1.0    0.9    0.8    0.7    0.6    0.5
 0.4    0.3

 1.0    1.0    1.0    1.0    0.9    0.8    0.7    0.6
 0.5    0.5

 1.0    1.0    1.0    1.0    1.0    0.9    0.9    0.8
 0.7    0.6

 1.0    1.0    1.0    0.9    0.8    0.7    0.6    0.5
 0.4    0.3

 1.0    1.0    1.0    0.9    0.8    0.7    0.6    0.5
0.4     0.3

131.     114.
15
 1    7    0
 2    7    0
 3    7    0
 9    7    0
10    7    0
11    7    0
12    7    0
13    7    0
 4    8    0
 5    8    0
 6    8    0
 7    8    0
 8    8    0
14    8    0
15    8    0
 1
 3
 0
/*END


```

APPENDIX F

GRAPHICAL DESCRIPTION OF THE COMPONENTS

OF THE OBJECTIVE FUNCTION

APPENDIX F

GRAPHICAL DESCRIPTIONS OF THE COMPONENTS OF THE OBJECTIVE FUNCTION

Figure F1 shows five diagramatic plots all with abscisa as representing time. Figure F1(A) shows some sample relationships P(J, K, L) which estimate the probability of rating survival for particular strategies (e.g. fog seal, thin overlay, etc.) for particular distress types (e.g. alligator cracking, rutting, etc.) and for particular time periods T (which have a maximum TDATA).

Figure F1(B) shows examples of characteristic plots of:

$$\left[1 - Traf(I)*Envir(I)*\left(1 - P(J, K, L)\right)\right] * RMAX(I)$$

which are the distributions of rating decline with time each for a given distress type (e.g. rutting) after being subjected to a given strategy (e.g. seal coating). It will be noted that each of these curves is scaled by the maximum possible rating of the particular distress type at T = 0. The detrimental effects of excess traffic and environment as specified by Traf(I) and Envir(I) are taken into account in the curves also. Figure F1(B) has plotted also two-typical distributions with time of the minimum acceptable ratings for given distress (K) and highway types (II). These can range from being constant to non-linear with time.

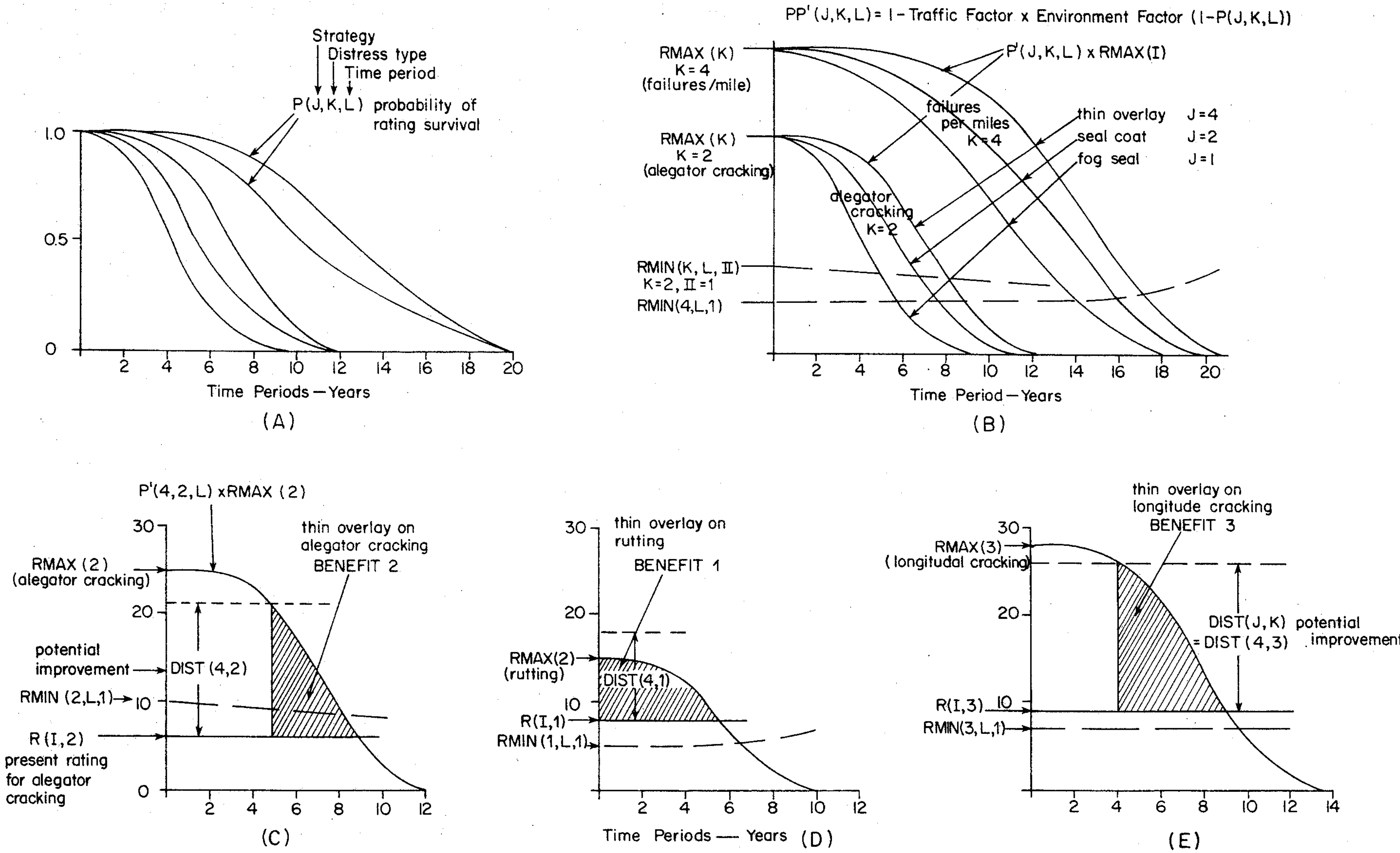
Figures F1(C), (D), and (E) demonstrate how benefit contributions from three rating type improvements (e.g. alligator cracking, rutting, longitudinal cracking) resulting from the application of a particular strategy (e.g. thin overlay) to a section (I) of the highway are calculated by the program. It will be noted in Figure F1(C) that the program calculates benefit down to the present rating level (R(I, K)) which in this case is below the minimum acceptable rating (RMIM (K, L, II)). That portion of the survival curve that bounds the benefit area is dictated by the relative magnitude of the maximum possible rating and the rating that the improvement (DIST (J, K)) raises the pavement to at T = 0. In Figure F1(C) the maximum possible rating is greater than the improved level, so benefit starts at a time instant on the diagram when the survival curve has dropped to the improved level of rating. That particular instant is then considered by the program to be the present so that the life of the improvement in this case is 8.8 - 4.8 = 4 years.

Figure F1(D) shows the case where the potential improvement (DIST (J, K)). achieveable by the strategy (thin overlay) is <u>more</u> than sufficient to take the present rating to the maximum possible level (RMAX (K)).

Benefit is calculated down to the present rating level whether it is above or below the minimum. This means that for a given strategy those sections in initial low rating states will have greater benefit/cost ratios and hence will be more likely to be chosen for treatment by the integer program.

The total benefit wrought on a particular road section is equal to the sum of six or so hatched areas (three of which are shown), each of which represent improvement contributions to an individual rating type from the treatment.

In previous subroutines of the program those strategies which fail to bring a rating of to the minimum (RMIN (K, L, II)) of <u>any</u> distress type are considered infeasible. Those treatments which fail to give an



Total Benefit of thin overlay on road section (I) = BENEFIT 1 + BENEFIT 2 + BENEFIT 3 + - - + BENEFIT (K)

Figure F1.

overall rating, to a pavement section, at least equal to the recommended minimum (WW (HYTYP(I))) are also considered infeasible and are not considered by the integer program. The program also has the facility of withholding any section-strategy combination or withholding complete strategies from the solution.