SELECTION OF OPTIMAL INVESTMENT STRATEGIES FOR LOW VOLUME ROADS USING STAGE CONSTRUCTION

by

Fred Moavenzadeh

Professor of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

June 1973

Presented At
International Symposium on Optimization in Civil Engineering
Liverpool, England

I. INTRODUCTION

The lack of adequate transportation in many developing countries has been cited in the literature [1, 2, 3] as one of the major factors slowing down the rate of industrialization and general economic development in these countries. One reason for the inadequacy of transportation facilities is the high cost of their construction. If these facilities could be constructed at lower costs per kilometer, through staged construction, then a greater contribution could be made to the economic development of these countries.

The staged construction of a low volume road is the process whereby a road is initially built to a level sufficient to meet the immediate requirements of traffic and at a later date is reconstructed to a higher standard in order to decrease the costs borne by the increased traffic.

The goal of staged construction is to increase the effectiveness of road investments by the closest possible matching of the properties of the road and the needs of the traffic at each point in the analysis horizon.

Some reasons why staged construction can be used advantageously in highway planning are:

1. It permits a lower initial investment in terms of capital, equipment, and manpower in a road, thus permitting those freed (unused) resources to be utilized in other productive endeavors, either within the transport sector or in other sectors of the economy.

2. In cases where expected traffic increases do not occur, an initial low standard road would entail a lower opportunity loss than would a high standard road. Conversely, if traffic should increase more rapidly than anticipated, upgrading would only require moving up the original construction schedule.

3. Finally, staged construction contributes to improved pavement performance, because irregularities that develop -- for example, consolidation of the subgrade -- can be corrected in the next upgrading.

The disadvantages of staged construction include:

1. There may be higher road maintenance and operating costs in the years immediately following construction of the first-stage earth or gravel road than would be experienced if a surface treated or asphalt surface had been built. Because of the high discount rates (10 - 15% per annum) often used in evaluating low volume road projects, these increased costs can have a disproportionately greater effect on the net present worth of the road.
2. The total undiscounted construction costs of roads which are initially constructed to the higher standard will usually be less than the costs of constructing the road in stages because of lost economies of scale.
3. The optimal staging strategy for the road when it is considered by itself will often be quite different from the optimal strategy for the road when it is viewed as one part of a whole network of inter-connected transport systems. Failure to take this into account may cause the improvements to one road to lead to a rerouting of traffic in such a way as to cause either the under or over-use of other parts of the transportation system (4)

Optimal Staging Strategy

Construction staging may be described as a three part problem: selecting a timing strategy, selecting a design, and deciding which projects should be selected for construction in a given time period (5, 6, 7). In choosing certain projects from a large set one can assume that such projects are either mutually independent for ease

in computation , or account for their interdependency in the analyses of staging [8]

Several authors have considered the timing issue with regard to independent projects. Marglin [7] in discussing the timing problems, identifies as the major issue the extent to which costs and benefits vary with the date of construction, and gives a decision algorithm for selecting projects for construction if the time flows of cost and benefits are known. Mori [5] and Gulbrandsen [9] have developed dynamic programming computer programs for finding optimal construction schedules for sets of independent projects.

The approaches of Marglin, Mori, and Gulbrandsen are quite effective with regard to computational efficiency and project mixes. However, they assume that each project is the optimal feasible alternative on any given link, and that the time stream of costs and benefits is known with certainty. The assumption is also made that the preferred alternative on any link remains optimal regardless of the status of the rest of the network. This assumption would imply, for instance, that an access road to a small village would be equally effective whether or not a connecting link was built to the market town. This is quite obviously not true, and signifies the shortcoming of a pure timing approach.

To account for the network effect, Ochoa-Rosso [10] have formulated a multi-period investment model as an integer programming problem. The model is concerned with the investment strategies for networks and considers the relationship between links but does not indicate how one can optimize a single project.

The work by Lack et al. [11] describes a computer program which examines sixteen possible road designs. Models for estimating construction, maintenance, and vehicle operating costs are developed and a dynamic programming algorithm is used to find when and what designs should be implemented. Limitations on expenditures have been incorporated through the use of Lagrangian multipliers. The relatively simple cost estimating routines, however, weigh against its use in developing

nations, especially as the cost models are derived from Australian data and are, in the case of maintenance and user costs, in the form of regression equations, which poses some difficulty in transferring this model intact from area to area.

Pecknold [12] considers both network and project design, and discusses the question of uncertainty. He develops the staging problem as a set of sequential decision trees and then, using various decision rules, prunes branches from the decision trees. The model operates using Bayesian probability techniques to update the tree under uncertainty.

In summary the models for formulations of staged construction which are currently available, are concerned primarily with transportation networks rather than with the design of a single link and the subsequent increase of capacity or cost of that link. The cost components are rather aggregated and are mostly derived from regression analysis rather than causal relationships. The primary concern of this paper is therefore, the allocation of resources to a single road project. It uses a Highway Cost Model which simulates the behavior of low volume road investments over time. The model was designed to be a tool with which planners in developing nations could locate those road projects which would provide optimal return on scarce and constrained resources. The HCM can consider uncertainty in traffic projections, labor versus capital intensive maintenance, and changes in factor prices over time.

II. FRAMEWORK OF THE HIGHWAY COST MODEL (HCM)

Road transportation can be viewed as a production process in which a time stream of inputs are transformed into a time stream of outputs. The inputs are referred to as construction, maintenance, and vehicle operating resources while the outputs are mainly road transportation services. The problem which a highway designer must resolve, and which the HCM was developed to help solve, consists in obtaining the combination of inputs which over time results in the most efficient production

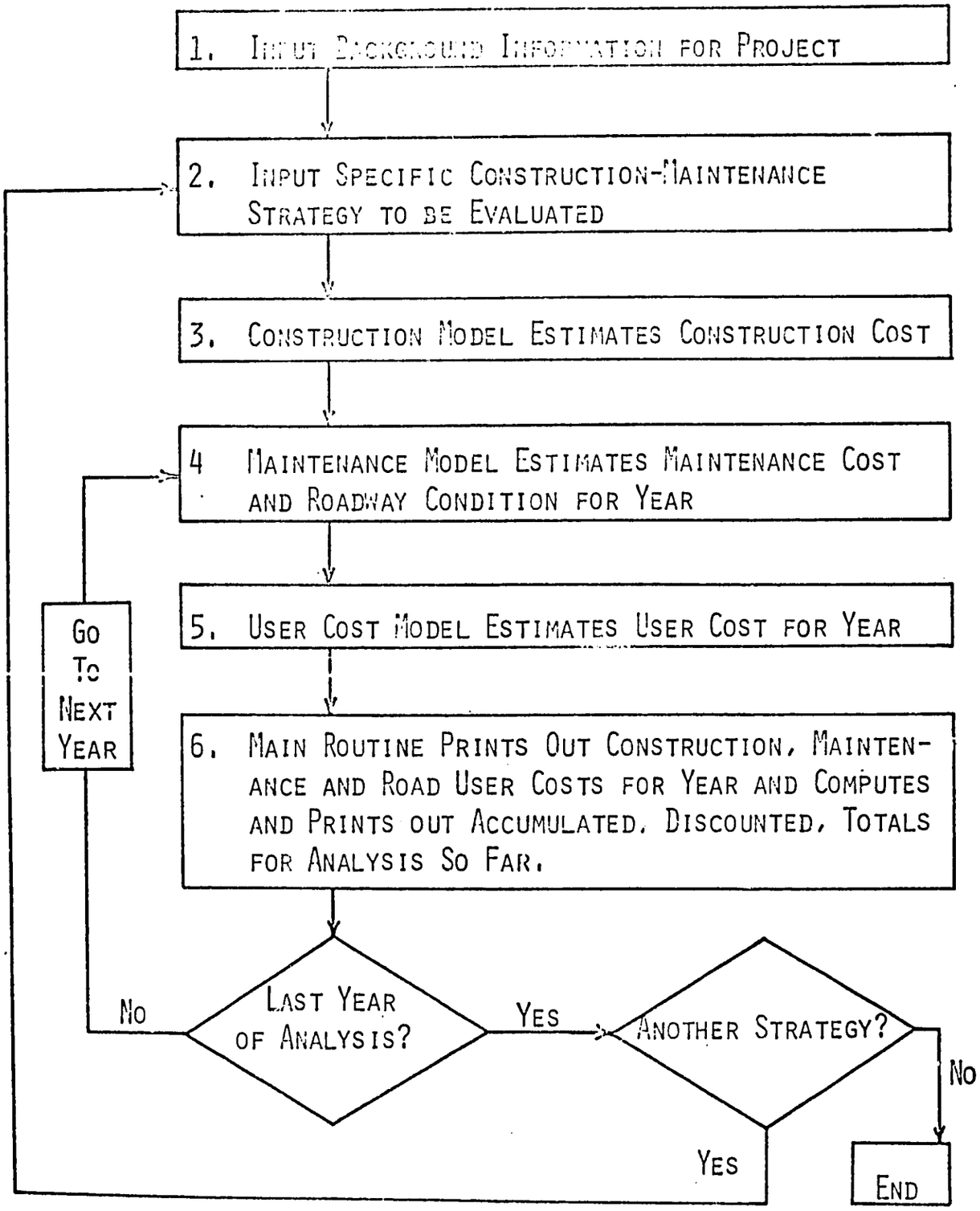

Figure 1: Operation of the Total Cost Model

process. In terms of transportation for developing countries, this may imply capital expansion over time, usually through some form of staging, that is, the upgrading or rebuilding of roads as traffic volume of the demand for raod use increases. Viewed in this context, roadway design can be seen as a problem of selecting the amount, mix, and timing of capital inputs to attain an optimal output of transportation services.

Model Overview

The Highway Cost Model consists of three individual submodels, programmed within the overall model framework [13]. Acting together, these submodels predict the yearly construction, maintenance, and road user costs, which cumulated each year over the design horizon, make up the "total cost" of a roadway.

Since it was anticipated that the model would be used at several stages during the preliminary analysis of a project, the model was designed to be responsive to different levels of information. For example, during the very initial preliminary analysis of a road project, the terrain can be described by the rise and fall of the ground along the path of the road. But, later when a specific alignment is chosen, the model can accept more detailed digital terrain information in the form of stations and elevations for a series of vertical points of intersection (VPI).

The model is designed to provide for a fairly straightforward iteractive time simulation of construction, maintenance and vehicle operating activities. The flow chart shown in Figure 1 illustrates this aspect of the model. Since, this iterative simulation approach is quite flexible in representing physical and economic relations, the approach led to the development of a highly modular model. An important aspect of the iterative approach is the ability of one submodel to rely on information from other submodels in the simulation of physical relationships between construction, maintenance, and the operation of vehicles. In particular, by making estimates of resource consumption, costs, deterioration, and a number of vehicles year by year during the analysis period the submodels are able to base their future predictions partly on information generated by the other submodels.

Using this method, some of the feedback characteristics of the physical system can be simulated. As an example, the estimates of maintenance cost of the deterioration of the road surface for each year is influenced by the volume and type of traffic predicted for that year by the user cost submodel, as well as by the initial description of the roadway from the construction submodel. The user cost submodel in turn estimates individual vehicle costs for each year as a function of the new deteriorated roadway condition predicted by the maintenance model and the physical description of the road. Roadway condition, curvature, and average grade of the roadway are the input variables used by the user cost model to determine the perceived cost of operating each vehicle type. This perceived cost of operation is then used with the specified traffic demand function to predict the traffic volume for the year. Thus, both user costs and traffic volumes are influenced by the predictions of the maintenance model.

In using this sequential simulation procedure, the overall model framework can simulate the major interaction between construction, maintenance and vehicle operation of the road. To do so otherwise, would require independent estimates of the construction, maintenance, and vehicle operation costs for the entire analysis period, which would be highly duplicative.

The HCM is composed of twenty-one individual subroutines. These subroutines, mostly written in FORTRAN, are used to simulate effectively construction, maintenance, and vehicle operating cost for a particular roadway. Each of the cost estimating submodels is composed of two or more subroutines. For a more complete discussion, refer to references (14,15).

Stage Construction

Stage construction of a low volume road is a procedure whereby a road is initially built to a level sufficient to meet the immediate requirements of traffic and at a later date is reconstructed or upgraded to meet the increased demands of traffic. In order to accomodate the increased traffic, staging strategies may include improve-

ments in surface type (for example a road is initially constructed with an earth surface which later is upgraded to gravel and finally to a paved surface), improvements in vertical and horizontal alignment, changes in roadway template, or a combination of these strategies. To make it possible to evaluate these staging strategies, a set of "network routines" were incorporated into the HCM model. Specifically, these routines permit the planner to investigate easily various stage construction strategies by specifying the strategies in the form of decision trees (networks). Also, with the network routines, only one data set is needed to specify up to the 30 strategies possible [14].

Figure 2 is an example of a decision tree that examines the cost due to constructing a road with different surfaces initially, and after a specified time, going through various reconstructions. For this example, only minor modifications in the basic data are needed. The HCM will determine the total discounted cost of each of the seven strategies over the 20 year service life of the road.

Since the main problem associated with stage construction is finding that strategy which will minimize the objective function (present worth of total cost), the network routines incorporated into the HCM make it possible to evaluate an extremely large number of strategies both quickly and cheaply, which using conventional techniques would not have been possible because of the time and money constraints involved. Also, by evaluating such a large number of strategies, the possibility that the optimum strategy will be among them is greatly improved.

Function of the Network Routines

The main function of the network routines can be defined simply as providing the capability of analyzing, in a quick and efficient manner, many alternative staging strategies. In order to expand the HCM to include this capability, five subprograms grouped under the title of "network routines" were added to the model. Although a detailed computerized discussion of these routines will not be included here (see Reference (15)), it is worthwhile to discuss briefly their logic.

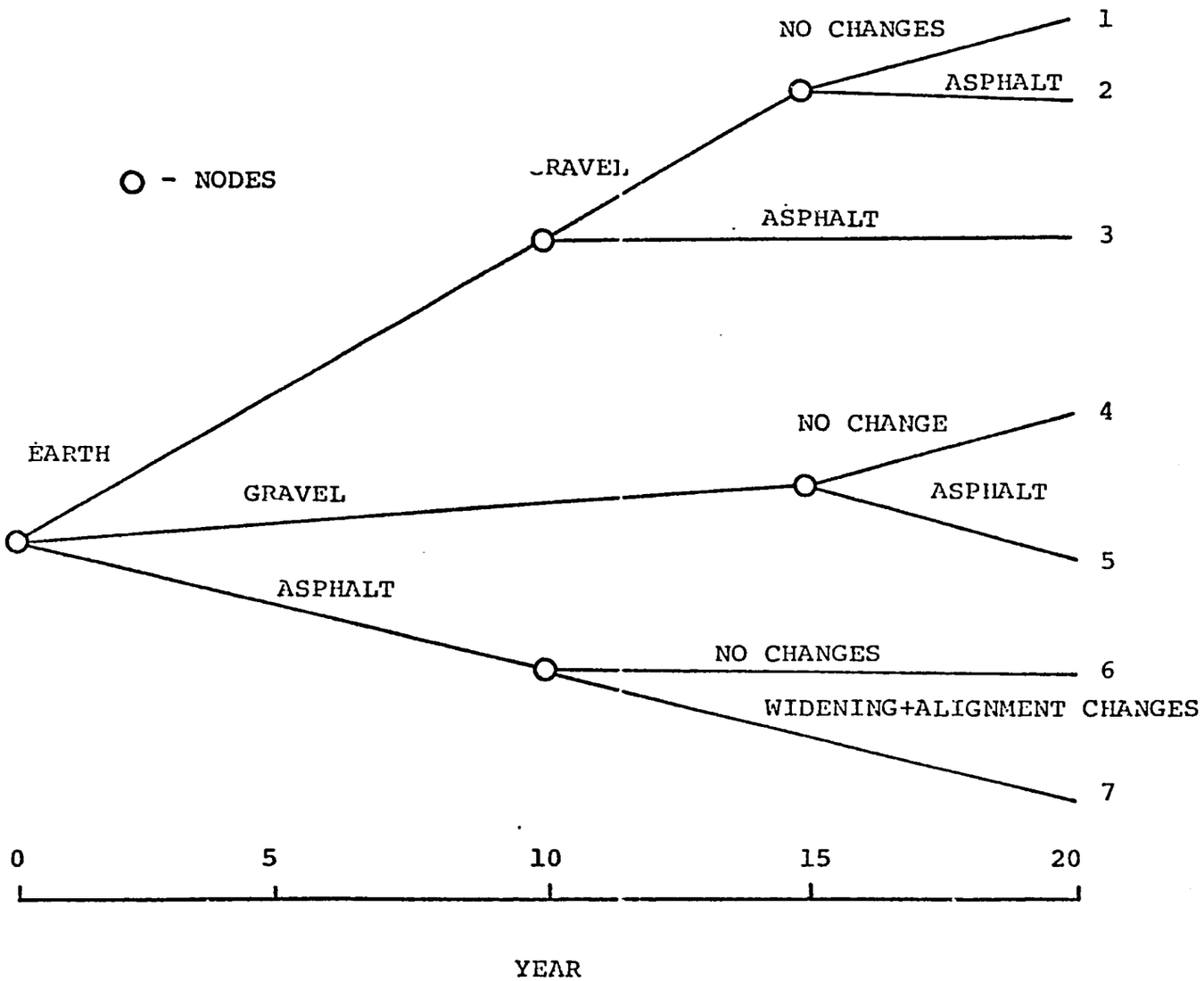
O - NODES
EARTH
GRAVEL
ASPHALT
GRAVEL
NO CHANGES
ASPHALT
ASPHALT
NO CHANGE
ASPHALT
NO CHANGES
WIDENING+ALIGNMENT CHANGES
1
2
3
4
5
6
7
0
5
10
15
20
YEAR

Figure 2

The five subprograms that compose the network routines are the following: MAIN, STRAT, NETWRK, CONSTR, and SAVDAT. The first routine, MAIN, performs only a few introductory functions: It determines what level of construction, maintenance, and operating detail will be presented in the output from the model; this is determined from the information supplied by the model user: It calls a number of other subroutines that perform tasks of reading in the problem description, reading in and analyzing the alternative staging strategies, and stepping through the decision network.

As an example, the first network routine it calls is STRAT, which performs tasks such as reading the number of staging strategies to be examined during the current run. It also determines the number of road designs that will be altered and the number of years in which construction costs and productivities are different from those initially specified. That is, to aid the planner in the very early steps of design, typical templates and pavement cross sections are stored in the model, however, through routine STRAT, the model user has the ability to alter these design variables. The appropriate submodel determines which variables are changed and temporarily stores them to be used later in determining construction quantities and costs.

In addition to being able to alter the initial design variables, the model user, through the network routines, has the ability to change costs and productivities that are expected to be in force sometime during the design horizon. Thus, any increased costs due to inflation and any possibly increased productivities due to experience or new technology can be included in the analysis and in comparing alternative investments.

Probably one of the most important functions of the network routines is their capability of converting investment alternatives supplied by the planner into a form which can be used to step through the decision tree. Briefly, this task consists of the following steps: 1) recognizing nodes in the decision tree, 2) counting the branches from each node, and 3) converting the branch data into symbols defining

SIMPLE DECISION TREE

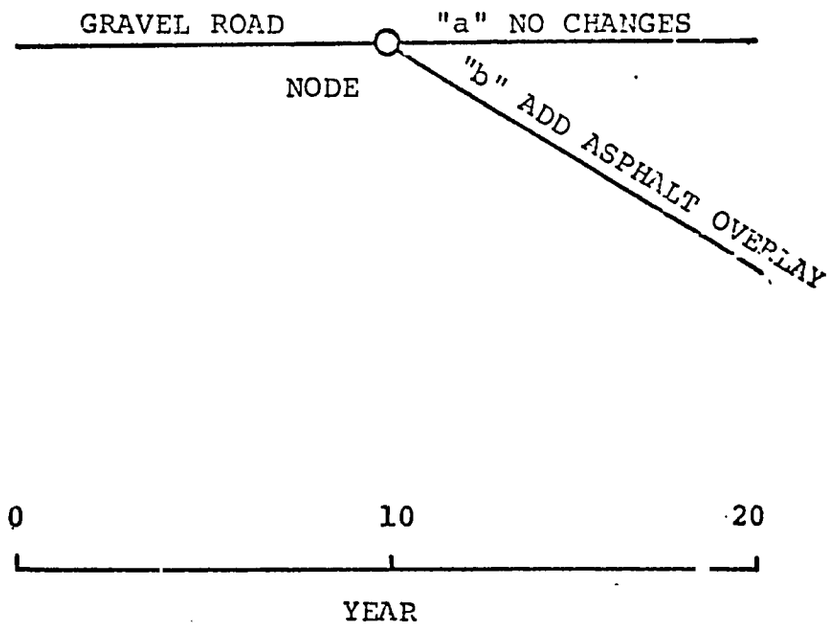

Figure 3

examined.

If the end of the analysis period has been reached, summary costs for the investment are output and the list of construction alternatives is examined for the next strategy. Figure 4 is a macro flow chart for the network routines showing the order in which the model performs the steps mentioned above.

Finally, a function of the network routines that is of considerable importance to planners is their capability to consider explicitly the consequences of uncertainty in traffic projections. The success or failure of a road in a developing country will often depend on the amount of traffic which will use it, and very often, the amount of traffic is not known with certainty. Thus, when there are two or more estimates or projected traffic, the costs accruing to each estimate can be calculated. Then by weighing the estimate with the probability of that estimate occuring, one finds the expected cost of each of the various construction alternatives. It is felt that this procedure predicts a value of total cost that is more likely to represent the conditions that will occur than a process in which total cost is based solely on one "best estimate" of traffic.

Summary

A series of network routines are developed and incorporated into the HCM to allow the model user to specify many alternative road investment strategies in an easily understood format along the lines of a decision tree. With only minor modifications to the standard input data needed for the construction of a roadway, the planner can determine how total cost is affected by a variety of investment strategies ranging from delaying construction to staging a road using various surface types over a gradually improving alignment. The resulting information then allows the planner an opportunity to compare the consequences of numerous investment strategies that could otherwise not have been possible.

The analyst can allow the model to specify "typical" design standards in the early stages of planning; later when more specific

MACRO FLOW CHART: NETWORK ROUTINES

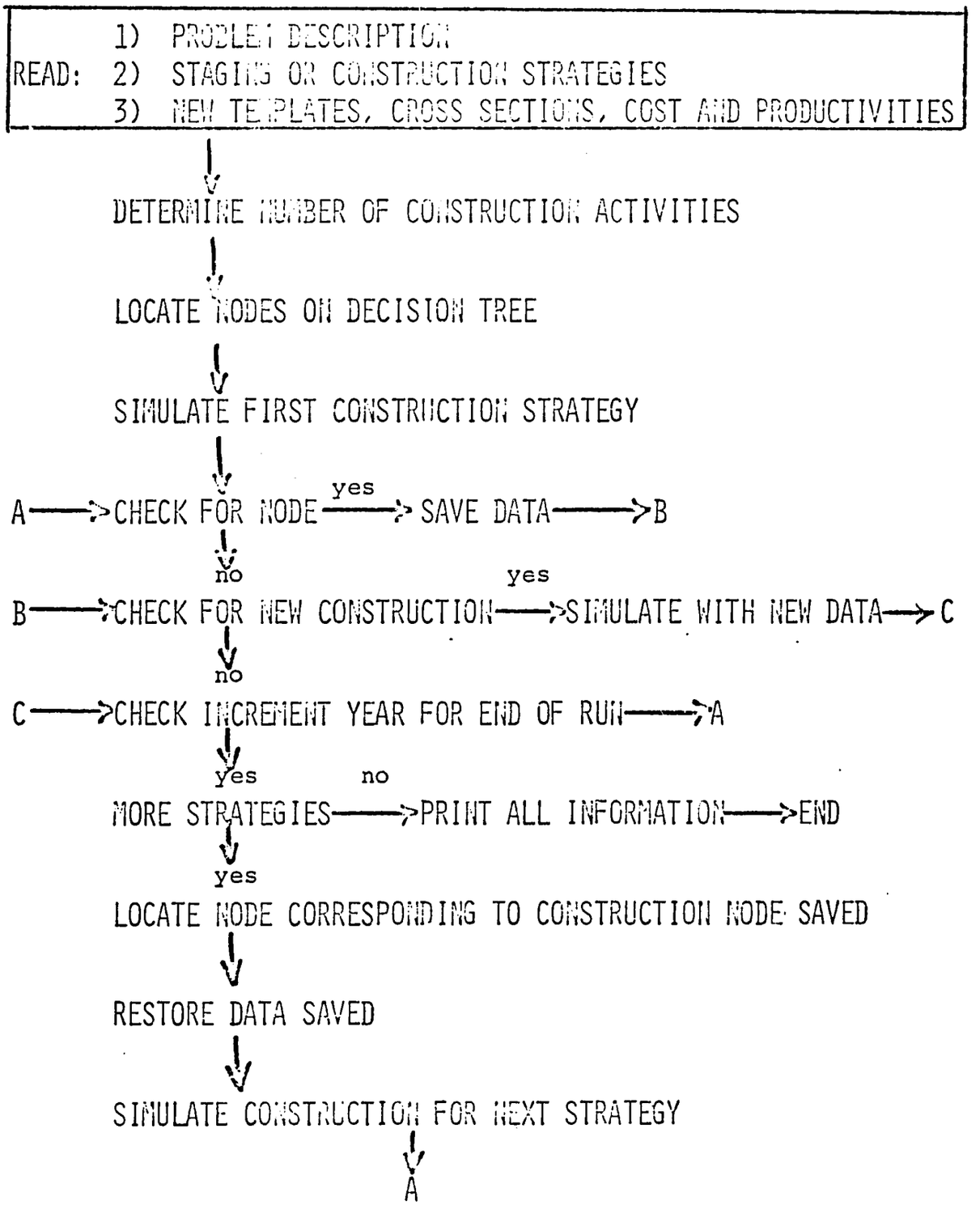

Figure 4

information on the roadway is gathered, the model user can change those standards which he desires. Also because of the inclusion of the network routines, the analyst can change costs and productivities that he feels might be in force in future years. Finally, the network routines allow planners an opportunity to investigate the consequences due to uncertainty in traffic projections.

III. STAGE CONSTRUCTION EXPERIMENT

The capabilities of the model which allow the user to investigate the allocation of resources over time are presented and discussed in this section.

Two basic ways in which highways may be upgraded are through changes in the type of pavement and through improvement in the alignment - both vertical and horizontal. The analyses presented here deal exclusively with pavement upgradings.

Examples of Analysis Under Certainty

The data from a road project in Argentina is used in a staging analysis to find the optimum alternative in terms of minimum total discounted cost. In this analysis each of the twenty-five staging strategies was limited to one pavement upgrading. In Figures 5 and 6 are given the nature of the twenty-five strategies considered and the costs associated with each strategy. For example, strategy number 15 consists of constructing a gravel road and upgrading it to a paved (asphalt) road in year 10; the discounted total cost associated with this strategy is given on the last column of Figure 6. Four sets of initial traffic conditions were used: 40, 200, 400, and 800 vehicles per day, these should be representative of most roads in developing nations. These runs were made using a discount rate of 7%. A similar set of runs were made using a discount rate of 12% and the same initial traffic conditions.

The total discounted costs of the various strategies are presented in Figures 7 and 8. Along the horizontal axis are the strategies along the vertical axis is the total discounted cost. Several conslu-

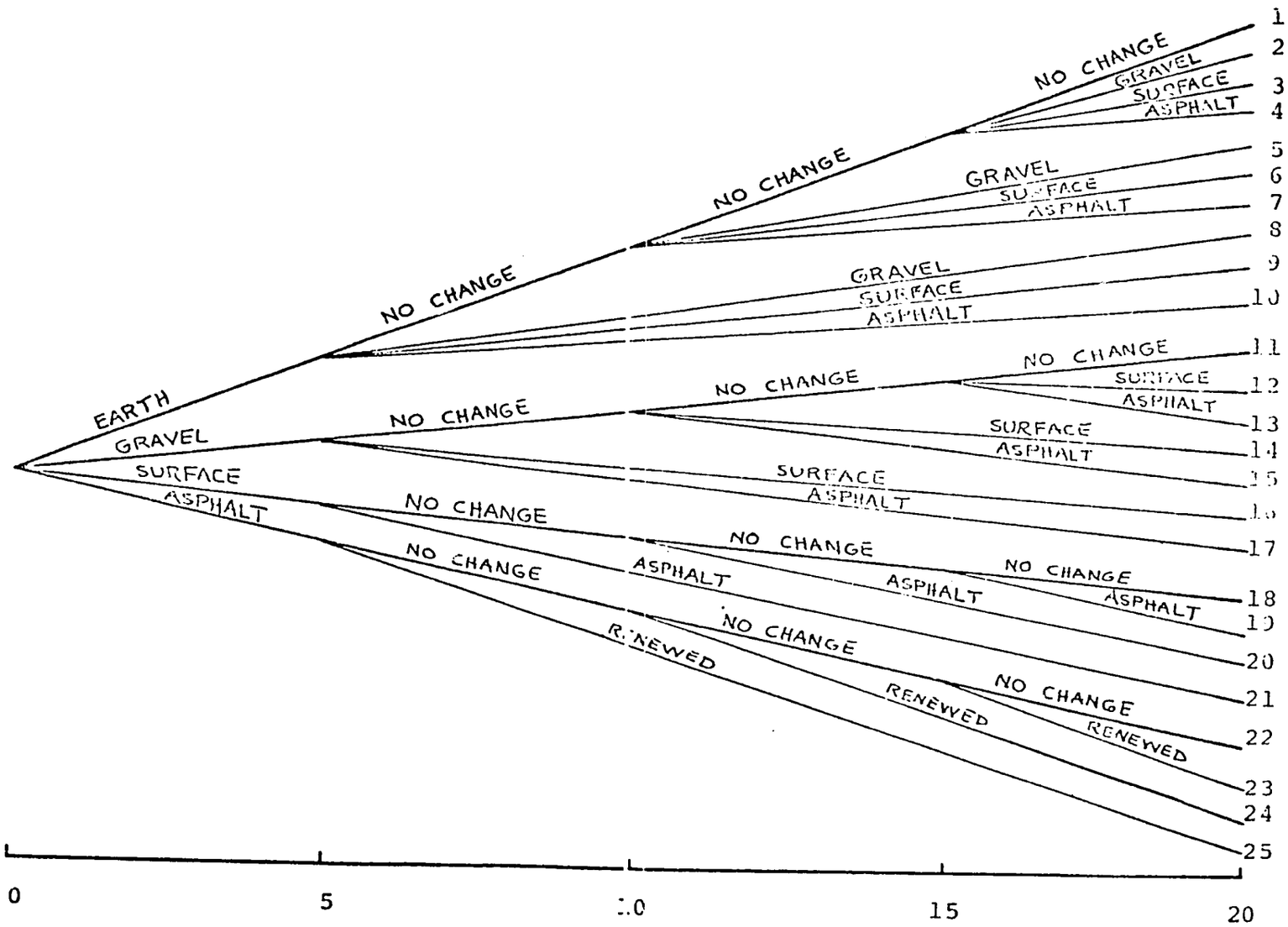

Figure 5: Staging Strategies for Argentina Route 14

COSTS FOR THIS RUN ARE

STRATEGY	UNDISCOUNTED CONSTRUCTION	UNDISCOUNTED MAINTENANCE	UNDISCOUNTED OPERATING	UNDISCOUNTED TOTAL	DISCOUNTED CONSTRUCTION	DISCOUNTED MAINTENANCE	DISCOUNTED OPERATING	DISCOUNTED TOTAL
1	1161914.	36687.	3608310.	4807111.	1085901.	16855.	1590256.	2693012.
2	1231467.	39014.	2718051.	3988532.	1111110.	17498.	1310157.	2438764.
3	1524642.	29928.	2543396.	4097966.	1217372.	14700.	1257579.	2489651.
4	1610530.	29398.	2543396.	4183324.	1248502.	14550.	1257579.	2520630.
5	1231467.	40253.	2270149.	3541869.	1121258.	18023.	1110813.	2250093.
6	1524642.	38563.	2000425.	3563630.	1270294.	16932.	1016988.	2304213.
7	1610530.	36663.	2000425.	3647617.	1313956.	16394.	1016988.	2347256.
8	1231467.	41187.	1986207.	3258861.	1135491.	18539.	931166.	2085196.
9	1524642.	65599.	1654727.	3244969.	1344522.	26235.	799742.	2170499.
10	1610530.	60086.	1654727.	3325342.	1405758.	24428.	799742.	2229926.
11	1221977.	41787.	1839512.	3103275.	1142035.	18946.	802064.	1963045.
12	1575617.	32309.	1655220.	3263145.	1270212.	16029.	746239.	2032479.
13	1661504.	31764.	1655220.	3348487.	1301342.	15875.	746239.	2063454.
14	1575617.	39756.	1562229.	3177601.	1321809.	17733.	705025.	2044567.
15	1661504.	37815.	1562229.	3261547.	1365470.	17143.	705025.	2087637.
16	1575617.	66047.	1503613.	3145276.	1394176.	26577.	668146.	2088898.
17	1661504.	60490.	1503613.	3225607.	1455413.	24755.	668146.	2148314.
18	1604747	92339.	1474670.	3171755.	1398572.	38587.	642988.	2080145.
19	1645997.	52873.	1474670.	3173539.	1429091.	26178.	642988.	2098256.
20	1645997.	43533.	1474670.	3164199.	1456945.	20734.	642988.	2120665.
21	1645997.	61196.	1474670.	3181863.	1496012.	25329.	642988.	2164328.
22	1540977.	93407.	1474670.	3109053.	1440166.	37947.	642988.	2121100.
23	1690634.	49890.	1474670.	3215193.	1494409.	24797.	642988.	2162193.
24	1690634.	42300.	1474670.	3207604.	1516244.	20171.	642988.	2179402.
25	1690634.	65324.	1474670.	3230627.	1546870.	26923.	642988.	2216779.

Figure 6: Costs of the 25 Staging Strategies

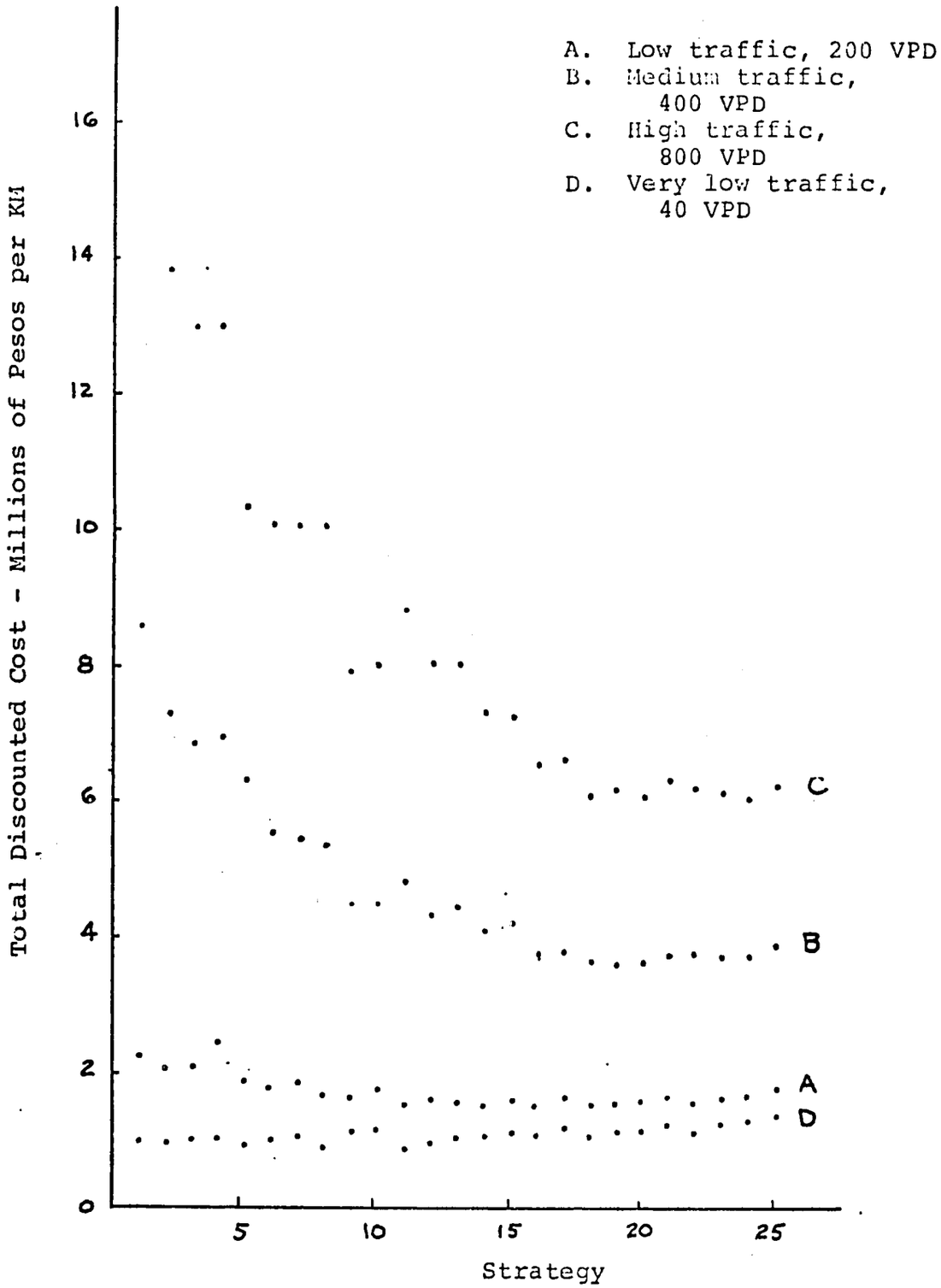

Figure 7: Effect Traffic Levels have on Total Discounted Cost for Argentina Rte. 14 with Discount Rate of 7%

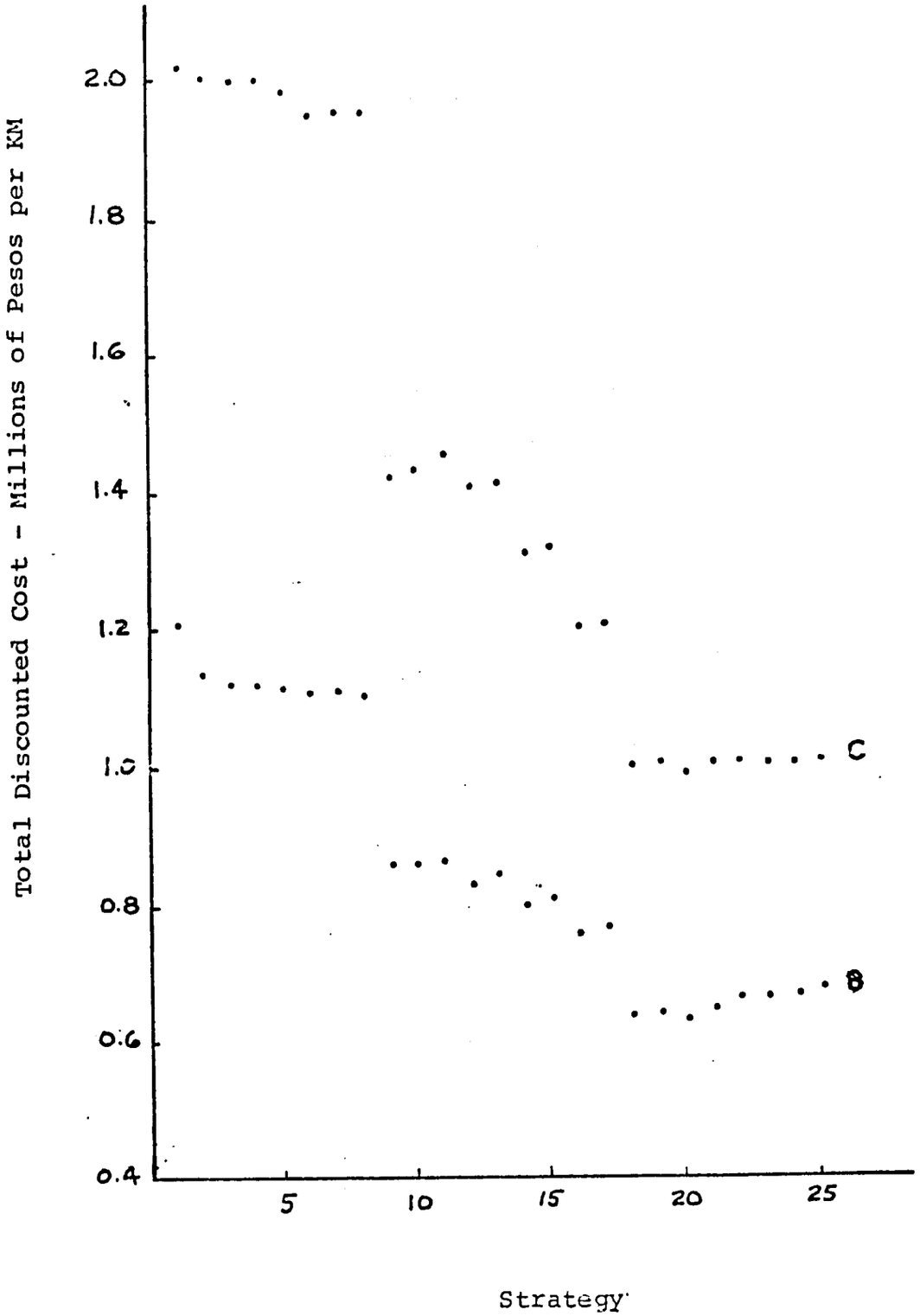

Figure 8: Effect Traffic Levels have on Total Discounted Cost for Argentina Rte. 14 with Discount Rate of 12%

sions can be drawn from these figures the most pertinent being that strategies nineteen and twenty are preferred for medium and high traffic volumes while strategies eleven is preferred for low and very low traffic.

As the figures show, the total discounted costs fall into three groups for the medium and high traffic levels. These groupings are related to the choice of design in year one. Thus strategies one thru ten all start with an earth road in year one which is upgraded at various years to several distinct desings, i.e. gravel, surface treated, and asphalt.

The cause of the clusterings is due to the fact that per kilometer operating costs on earth roads are significantly higher than on gravel or paved roads. As the traffic demand curve is fairly inelastic traffic levels do not vary significantly as a function of per kilometer operating costs. The clustering is even more pronounced when a twelve percent discount rate is used because the costs in the early years of the road are weighted significantly more than the costs in the latter years.

The clustering of costs is less pronounced for the low levels of traffic. In these cases construction and maintenance costs are a larger fraction of total costs (from fifty to eighty percent) than in the case of higher levels of traffic. Thus as traffic volumes are fairly similar on all four riding surfaces, differences in total discounted costs at low traffic levels are less significant than those differences that occur at higher traffic levels. (See Figure 7).

These results are conditional upon the growth rates of the various vehicle classes, and upon the elasticities of demand. Simulations with higher demand elasticities or growth rates would be expected to yield different results.

Example of Analysis Under Uncertainty

To illustrate how the HCM can be used to analyze staging alternatives when neither the initial traffic volume nor its rate of growth

are known. three initial volumes of traffic and two rates of growth were used in the simulation. These six sets of conditions are shown in Table 1; a different value of elasticity of demand was used for each of the two rates of growth.

The six sets of conditions were assigned equal probabilities, and with each of these conditions was associated the same decision network of strategies (see Figures 9 and 10). The decision network of strategies consists of a decision node at year zero with four possible choice branches; at year fifteen, for two of the four branches there are decision nodes with two branches bending from each. Of course, the model may be used to simulate situations with more elaborate decision networks as well as with a greater variety of sets of conditions.

In Tables 2 (a) and (b) are given the volumes in year twenty and, at two different rates of discount, the costs associated with each of the thirty six possible combinations of sets of conditions and strategies. For each rate of discount used, the rankings of the six alternatives for each of the sets of conditions used are shown; lowest total (discounted) cost is the criterion used to rank the alternatives. In Table 2 (b) are also given the average or expected costs for each strategy and the rankings of strategies, for each rate of discount.

In Table 3 is shown the frequency with which each strategy is ranked in each of the six orders of preference. For example, at interest rate 7%, strategy number 3 is ranked first twice, second and third once each, and fourth twice.*

The expected Minimum Cost is

$$\sum_i \sum_j \left\{ P(\text{Set } i) \times \left[\text{Min}(C_{ij}) \right] \right\}$$

* Adding the number of 1's in each column, one does not always get six because there were several ties, and two strategies in the same set were sometimes ranked the same.

Set	# of Vehicles/Day	Elasticity of Demand %	Rate of Growth %/Yr
1	25 light 25 heavy	3 3	5 5
2	50 50	3 3	5 5
3	100 100	3 3	5 5
4	25 25	1 1	2.5 2.5
5	50 50	1 1	2.5 2.5
6	100 100	1 1	2.5 2.5

Vehicles Descriptions

Typical Vehicle	Gross Weight Kg.
Light Vehicle - Pickup Truck	3,000
Heavy Vehicle - Medium Van	10,000

Table 1: Initial Traffic Conditions for Analysis of Stage Construction

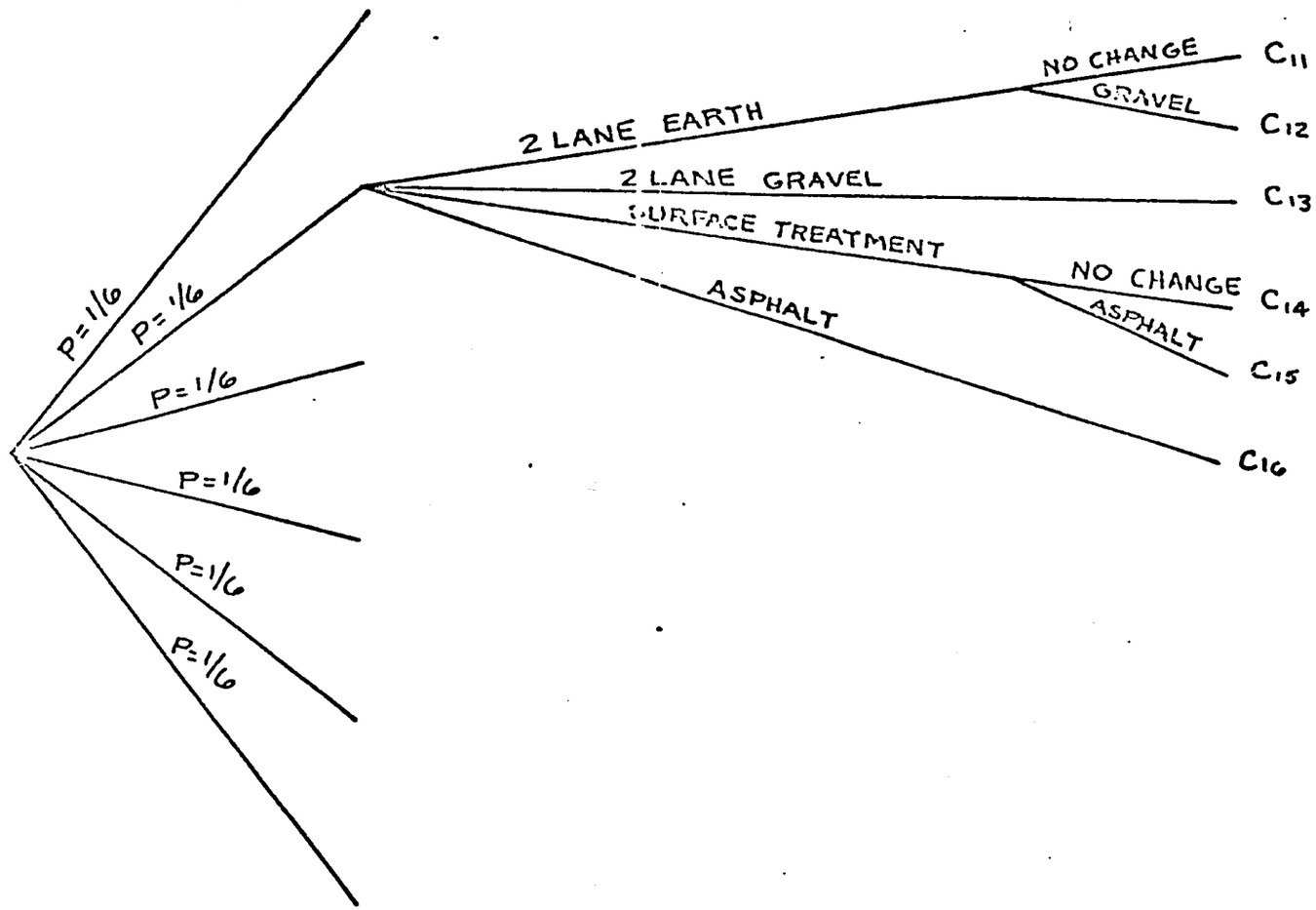

Figure 9: The Expected Minimum Cost is -- $\sum_i \sum_j \{P(\text{Set } i) \times [\text{Min}(C_{ij})]\}$

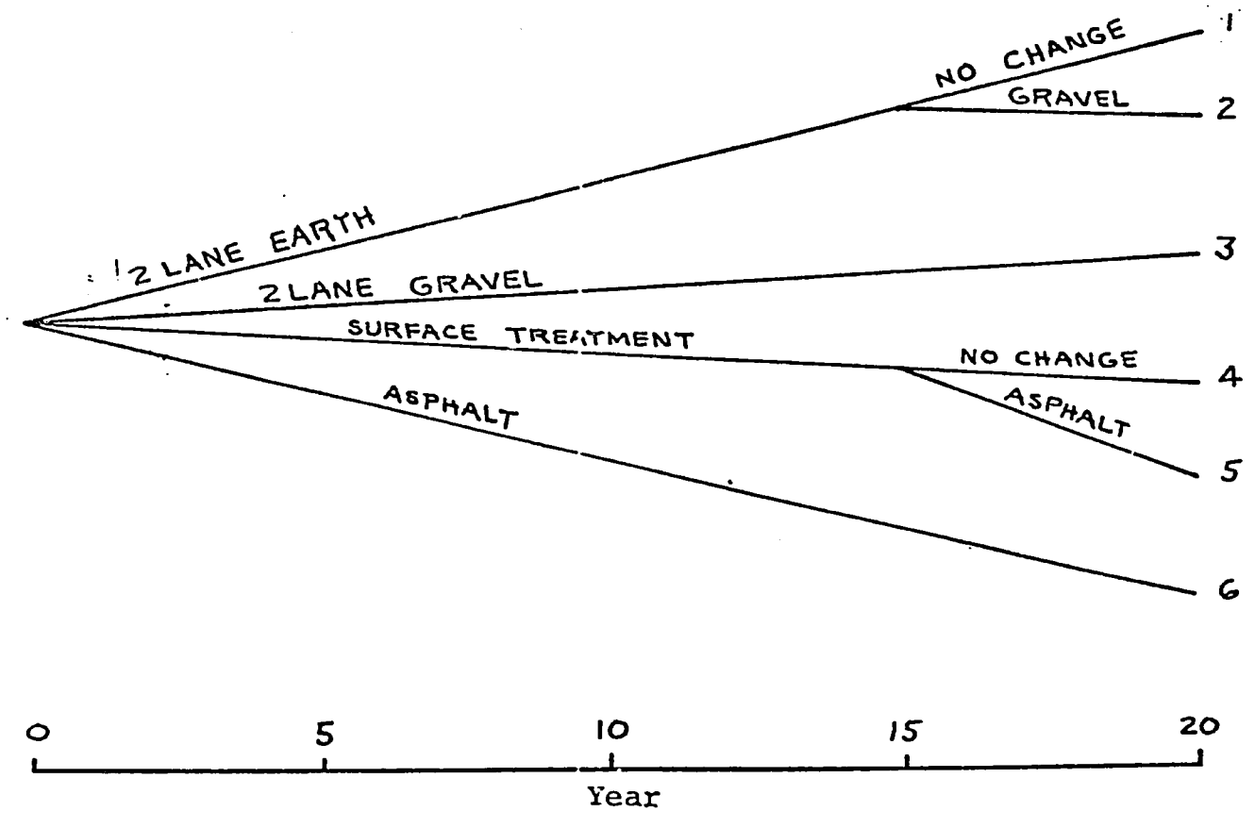

Figure 10: Decision Network of Strategies

Initial Conditions Set #	Strategy #	Vehicle/Day Year 20 Type	Vehicle/Day Year 20 Type	7% COSTS Const.	7% COSTS Maint.	7% COSTS Operational	7% COSTS Total	10% COSTS Const.	10% COSTS Maint.	10% COSTS Operational	10% COSTS Total	RANK 7%	RANK 10%
1	1	61	61	103	16	240	357	100	12	184	296	3	2
	2	64	67	129	16	210	355	117	12	166	296	2	2
	3	73	83	152	20	144	316	148	15	109	272	1	1
	4	83	92	247	29	96	372	240	21	72	330	4	4
	5	84	93	260	19	94	372	249	14	71	334	4	5
	6	83	92	270	25	96	393	263	19	72	354	6	6
2	1	121	122		29	478	610		22	369	492	6	6
	2	128	133		30	420	580		23	333	474	5	5
	3	146	167		37	288	477		28	219	395	3	1
	4	166	185		32	192	471		23	145	408	2	3
	5	167	185		20	187	467		15	142	407	1	2
	6	166	185		28	192	491		21	145	428	4	4
3	1	242	245		56	957	1115		43	737	831	6	6
	2	255	266		65	841	1035		48	666	832	5	5
	3	334	334		89	575	816		66	437	651	4	4
	4	332	369		33	384	664		24	289	554	2	2
	5	334	371		23	375	658		17	284	550	1	1
	6	332	370		31	385	686		22	290	575	0	0

Table 2(a): Costs of Strategies as a Function of Initial Conditions, Discount Rates

Initial Conditions Set #	Strategy #	Vehicle/Day Year 20 Type	Vehicle/Day Year 20 Type	7% COSTS Const.	7% COSTS Maint.	7% COSTS Operational	7% COSTS Total	10% COSTS Const.	10% COSTS Maint.	10% COSTS Operational	10% COSTS Total	RANK 7%	RANK 10%
4	1	39	40				313				266	3	2
	2	40	41				219				271	1	3
	3	42	42				276				245	2	1
	4	44	45				345				315	4	4
	5	44	45				347				317	5	5
	6	44	45				367				337	6	6
5	1	79	79				521				429	6	6
	2	80	81				507				422	5	5
	3	84	88				397				340	1	1
	4	88	91				417				371	2	3
	5	88	91				417				370	2	2
	6	88	91				438				392	4	4
6	1	158	158				936				756	6	6
	2	160	163				883				724	5	5
	3	168	175				640				530	4	4
	4	175	182				560				482	2	2
	5	176	182				557				481	1	1
	6	175	182				581				503	3	3
AVERAGE OR EXPECTED COSTS													
	1			103	30	503	636	100	24	392	515	6	6
	2			128	33	447	607	116	25	356	498	5	5
	3			150	40	291	482	146	31	224	401	3	1
	4			244	30	192	467	238	22	147	406.1	2	3
	5			257	20	187	465	246	15	144	405.6	1	2
	6			268	28	191	488	260	20	147	427	4	4

Table 2(b)

	RANK											
	7%						10%					
Preference / Strategy	1	2	3	4	5	6	1	2	3	4	5	6
1			II			IIII		II				IIII
2	I	I			IIII			I	I		IIII	
3	II	I	I	II			IIII			II		
4		IIII		II				II	II	II		
5	III	I		I	I		II	II			II	
6			II	II		II			II	II		II

Table 3: Cumulative Rank of Strategies by Total Discounted Costs

At r = 7%, the expected minimum cost is 435.7, and at r = 10% the expected minimum cost is 380.5.

The user can use the capabilities of the model to investigate possible staging alternatives even in the face of uncertainty with respect to traffic characteristics and other factors. If probabilities can be estimated, principles of decision theory may be used in conjunction with the model to analyze various staging alternatives.

IV. SUMMARY

The main purpose of this paper was to examine the performance of the HCM model and to illustrate how the capabilities of the model can be used to analyze staging alternatives.

The model has been found to perform satisfactorily, and has shown that it can be used to investigate the possibilities of upgrading the road at intervals rather than to construct it initially to serve the projected long range traffic demand.

REFERENCES

1. Steiner, H.M., Criteria for Planning Rural Roads in a Developing Country: The Case of Mexico, Stanford Program on Engineering Economic Systems, Report Ee 17, August 1965.

2. Odier, L., The Economic Benefits of Road Construction and Improvement, Estoup, Paris, 1967.

3. Soberman, R.M., Transport Technology for Developing Regions, M.I.T. Press, Cambridge, 1966.

4. Manheim, M.L., and Ruiter and Bhatt, Search and Choice in Transport Systems Planning: Summery Report, M.I.T. Department of Civil Engineering, Report #R68-40, 1968.

5. Mori, Yasuo, "A Highway Investment Planning Model: An Application of Dynamic Programming", Unpublished M.S. Thesis, Department of Civil Engineering, M.I.T., Cambridge, Mass. 1968.

6. Stafford, Joseph H., and de Neufville, Richard, Engineering Systems Analysis, Chapter 9: "Choosing Among Investment Alternatives",

7. Marglin, Stephen A, Approaches to Dynamic Investment Planning, North Holland Publishing Company, Amsterdam, 1963.

8. Alexander, J.A., "An Approach for Integrating Highway Maintenance Into the Design Process", Ph.D. Thesis, M.I.T. Department of Civil Engineering, 1970.

9. Gulbrandsen, Odd, "Optimal Priority Rating of Resource Allocation by Dynamic Programming", Institute of Transport Economy, Royal Norwegian Council for Scientific, Industrial Research, Oslo.

10. Ochoa-Rosso, Felipe, "Application of Discrete Optimization Techniques to Capital Investment and Network Synthesis Problems", Sc.D. Thesis, M.I.T., Cambridge, Mass.

11. Same as Reference Number 4.

12. Same as Reference Number 8.

13. Moavenzadeh, F. et al., Highway Design Study: Final Report, CLM? Systems Inc., Cambridge, Mass., 1970.

14. Moavenzadeh, F., "Investment Strategies for Developing Areas: Analytic Model for Choice of Strategies in Highway Transportation", M.I.T. Report R72-68, June 1972.

15. Moavenzadeh, F., "Highway Cost Model: Operating Instruction and Program Documentation", M.I.T. Report R72-69, June 1972.