SELECTION OF OPTIMAL INVESTMENT STRATEGIES FOR LOW VOLUME ROADS

by

MARK ARNOLD BECKER
SB, Massachusetts Institute of Technology

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Signature of Author

Department of Civil Engineering
March 17, 1972

Certified by
Thesis Supervisor

Accepted by
Chairman, Departmental Committee on Graduate Students of the Department of Civil Engineering
ABSTRACT

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Submitted to the Department of Civil Engineering on February 20, 1972, in partial fulfillment of the requirements for the degree of Master of Science.

This thesis presents the Highway Cost Model, a set of twenty computer routines written in FORTRAN IV which model 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.
Acknowledgments

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Chapter One

Introduction

The lack of adequate transportation in many developing countries has been cited by Haefele (48), Soberman (58), and Steiner (42), among others, as one of the factors slowing down the rate of industrialization and general economic development in those countries. Transportation brings raw materials to factories, workers to jobs, finished goods to market, food to urban areas, and health and educational services to the outlying population in much the same way that arteries move vital resources through the human body, thus making possible a complexity of function far beyond the capacity of any single isolated organ. It is clear that an underdeveloped country with rich natural resources and a populace eager for progress must have such a means of collating its own particular energies and materials if it is to fulfill its highest potential for industrialization.

One reason for the inadequacy of transportation facilities in countries with scarce capital resources is the high cost of constructing roads, railroads, and similar basic components of the transport system. If these facilities could be constructed at lower costs per kilometer, then for any given investment more kilometers of road or rail could be constructed, and so a greater contribution could be made to the economic development of the country.
1. Maximizing Value: Modes of Approach

One obvious method that could be used to extend the mileage made available per investment dollar would be the construction of lower quality, cheaper roads. However, this policy by itself is shortsighted, since it can lead to increased costs (gasoline consumption, vehicle deterioration, driver salaries) for the individual user, so that ultimately no real economy has been achieved. Another disadvantage of this form of construction is the maintenance expenditure required each year to keep the road in adequate condition. If many roads in an area require a high maintenance effort in order to keep the roadway passable, resources needed for other projects would be unduly tied up, and so new construction would necessarily be restricted. Since many developing countries have comparatively little capital equipment, this drawback can be regarded as a critical one.

On the other side of the spectrum is the alternative of building an expensive-to-construct but easy-to-maintain heavy duty highway system, which would have the advantage of providing low user costs and needing very little maintenance and repair. But this alternative also will provide an unsatisfactory return on investment, because a government with limited capital resources will not be able to construct enough miles of road to meet the needs of the area.

How, then, can the various desirable qualities of these two extremes be combined at an acceptable cost? The
research reported in this thesis indicates that in many cases the best approach is to initiate a long-range highway construction plan with relatively many miles of low quality road and then to improve those roads as traffic on them increases. This is known as staged construction.

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. Staged construction may include changes in surface type, changes in alignment, an increase in the number of lanes, and other changes to the road or its environs.

The reason that the stage construction strategy is most appropriate to developing areas is that when a road is built through an underdeveloped area it is at first not very heavily used. The explanation is quite simple. Since there never has been a road from point A to point B, people in A and B have not established a social or economic reliance on one another. After the slow start, however, it has been found (Haefele (48)) that as people take advantage of the opportunities the new road provides, commerce between the vertices—and thus traffic—increases rapidly. Since there will be few vehicles traveling the road in these first slow years, the total road user costs and the maintenance expenses will be relatively low. Later traffic increases will
permit relatively lower construction expenditures in terms of unit costs of transport.

2. Problems of Staged Construction

Staged construction has been used in almost every road now in existence, but this construction has not followed any carefully analyzed long-range plan. The costs of analyzing staged construction alternatives are too high; too many skilled man-hours are required to do an adequate job. Few engineering feasibility reports even mention the possibility of planned staging, and when they do it is often in the context of suggesting the upgrading of a previously constructed road.

Another reason for the lack of long-range construction planning may be that there does not exist sufficient fiscal stability in many developing countries to permit planning intervals of any great length. If this is so, then the role of staged construction will necessarily be minimal. However, the development of techniques to find low cost staging strategies is likely to increase the interest of international lending agencies (such as A.I.D. and the World Bank) in staged construction, and the stability provided by these agencies should be sufficient to produce the confidence necessary for long-term planning to be undertaken.

3. Economic Issues in Staging

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 a road, thus permitting those freed (unused) funds to be utilized in other productive endeavors, either within the transport sector or in other sectors of the economy. For instance, the funds thus freed could be used to construct several roads in an area rather than just one. Thus a limited amount of money could be spent over a comparatively large mileage of low type, but adequately designed, highways (Taylor (59)).

2. It reduces the initial requirements for other scarce resources such as skilled manpower and equipment, and permits the use of these resources on other projects. This savings of resources is due to the shorter time required to build a lower standard road and the lessened need for specialized (i.e. expensive and imported) equipment and labor to construct the simpler road.

3. 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 because of the smaller investment in the low standard
surface. Conversely, if traffic should increase more than was anticipated, upgrading would only require moving up the original construction schedule, rather than a redesign of the road.

4. Finally, staged construction contributes to improved pavement performance (in the case of asphalt and surface-treated roads) because irregularities that develop—for example, consolidation of the subgrade—can be incorporated as improvements in the next upgrading. In general, this would be cheaper than performing the type of major maintenance which would normally be required if these defects appeared in an "original" surface.

But staged construction also has several disadvantages. Among these are:

1. There may be higher road maintenance 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.

2. User operating costs on the lower quality roads would be greater. This is due to the speedier deterioration of these types of roads and the consequently higher roughness values (Moavenzadeh (38)). 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 great effect on the net present worth of the road.

3. The total undiscounted construction costs of roads which were 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.

4. Use of Staged Construction in Project and Systems Analysis

One problem in finding an optimal construction staging strategy is that when performing project, as opposed to system analysis, the planner often assumes that the project is an isolated road, forgetting that it is really a link in a larger transportation network. 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 interconnected 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 (Manheim (37)).

The model developed in this thesis can be used to examine the impact of changes in the demand equations on all road-related costs; as network effects are most often expressed as changes in the demand equations, the method
presented here for investigating staged construction alternatives should prove to be an aid to highway and network planners, even though it is primarily a tool for project analysis.

5. Determining Optimal Staging Strategies

One of the difficulties associated with determining the optimal staging strategy is the high cost of examining enough alternatives to be reasonably sure that the optimal strategy has been included in the solution space. Unfortunately, this is a situation where it is hard for rules-of-thumb such as common sense or previous experience on similar projects to approximate the answers required.

What is needed, then, is a relatively accurate, but relatively inexpensive, means of determining the costs and benefits that accrue to a large number of alternative staging strategies and selecting the one which is best. This thesis will present a computer program which will perform this task.

The thesis presents a computer program for aiding in the selection of optimal investment strategies for roads in developing nations. It discusses the factors that led to the development of the model, the structure of the model itself, and the interaction of the model's major components. Finally, it presents a report of the actual use of this model in planning for a low volume road through the
Bolivian Andes.
Chapter Two

Review of Literature

This chapter will present a review of the literature on staged construction techniques for highways. A variety of approaches, methods, and decision criteria have been formulated to evaluate staging strategies. The strategies range from simple pavement upgradings to those that involve successive alignment, drainage, embankment, and surface improvements. Decision criteria generally used in these studies include net present worth, benefit/cost ratio, and internal rate of return.

1. Staging Techniques

Richard Bauman's report (1) concerns itself primarily with the forecasting of stage construction levels for emerging countries. He has presented two basic prescriptions for the staged construction of a low volume road.

For the first method, the initial stage would have natural grades, however steep, with sharp horizontal curves on an earth road. In the succeeding stages, the gradient or vertical alignment and the degree of curvature are progressively decreased and the road surface improved with a higher quality surface such as gravel or some type of asphaltic concrete.

This method has one outstanding advantage; that is,
it permits the construction of a low volume road at a very low cost. However, it has serious disadvantages. First, the expense of the succeeding alignment changes will be quite high. (This expense would, of course, be in addition to the regular cost of pavement upgradings.) These changes will become prohibitively costly in rolling or mountainous terrain. Also, because this method leaves steep grades, sharp curves, and rough surfaces on initial roadways, the road user costs at this stage will be quite high. This could be extremely critical to development if traffic growth is curtailed by high operating costs.

The second method of staged construction that Bauman describes would entail initially constructing the road to the same alignment and surface characteristics as the first method prescribes for stage one. For the next stage, however, the roadway alignment would be constructed to its final alignment standards, including small gradients and large horizontal curves, but still having a low or medium type surface. Successive stages then would consist of pavement upgradings only.

The distinct advantage of this method of staging is that only one alignment change is required. By reducing the number of alignment changes, there is no wasting of the old roadway surface; the old surface can be utilized as an improved sub-base to the newer surface.
Bauman concludes that the second method is the one which is predominantly used in countries utilizing stage construction techniques principally because the total costs of this strategy, discounted over its service life, are less than those incurred with method one.

Bauman mentions one more possible staging method. This method is to construct stage one to the ultimate alignment standards but with a low type surfacing. All subsequent stages would be concerned with pavement and possibly drainage adjustments. The idea here is to eliminate or at least reduce alignment changes. By constructing the base, subbase, and surface to the final grade and alignment once instead of changing them many times, sizable savings are realized. By delaying construction of the final surface course, savings are realized since construction and maintenance costs of the surface courses amount to 30 or 40 percent of the total costs of the road (Bauman (1)).

2. Staged Construction: Specific Highway Techniques

This section reviews some staging techniques that have been suggested by Robley Winfrey (19) for use in conjunction with the Interstate Highway System. Winfrey has investigated whether it is most economical to build the full four lanes of a four-lane divided highway or to construct only two lanes at first, which are to be followed some years later by the remaining two lanes.
Winfrey focuses his investigation on a specific project (an Interstate Highway in Virginia), using net present worth as his measure of effectiveness. He seeks to determine which parts of the road should be constructed along with the initial two lanes, and which parts should be constructed during the subsequent expansion to a full four-lane highway. In the case that he is investigating, Winfrey decides that at the time of the initial two-lane construction all the rights-of-way which would eventually be used for the four-lane road should be purchased, the roadway should be graded for the full four-lane width, and all drainage facilities and the major structures such as bridges and interchanges should be built. He makes this decision after concluding that, in this particular application, these measures would represent significant economies of scale. The right-of-way would increase in value over a period of time, so delay in purchase would mean increased expenditures; the major structures, drainage facilities, and gradings would incur large setup charges if constructed separately from the initial two-lane road. Also, providing these items at a later date would probably cause delays to road users and create hazardous driving conditions during construction.

What is the optimal interval between the initial construction and the subsequent upgrading? Winfrey's approach
to this problem is to determine the year in which the net present worth of all road-related costs would be greater for the four-lane road than for the two-lane road (fig. 1), as savings will accrue if the remaining construction can be delayed beyond that time. However, factors such as congestion may make it impossible to wait this long, and if this is the case he quite sensibly recommends going ahead and building the four-lane road immediately.

3. Staged Construction as Practiced in Developing Nations

This section will discuss some examples of the use of staged construction of highways in developing nations. Examples of decision rules and measures of effectiveness for road construction in stages will be given as they have been used in several nations.

As a specific example of staged construction in a developing country, Bauman (1) presents some standards for staging used in Nigeria. The data for his analysis is from Transportation Coordination by C.B. Thompson (2). Apparently, it is common practice in Nigeria, on a low volume road, to start out with an unpaved road and to improve the road surface as traffic volume increases. For low traffic roads, between 100 and 300 VPD, the first stage improvement from an earth road is to a 12 foot wide bituminous surface treatment placed on a 20 foot base course. As further increases in traffic volume occur the width of
Costs of Staged vs. Unstaged Construction

Figure 1
the surface treatment is increased to the full 20 foot base course. Finally, when the volume of traffic reaches 2,000 VPD, the road is surfaced with hot mix asphaltic concrete.

Bauman does not indicate how these particular volumes were determined to be the critical volumes. Also, possible alignment changes were not considered as part of the staging strategy. Unlike Winfrey, Bauman does not explicitly discuss the element of expense in his description of his criteria for determining stage construction levels.

Another example of the stage construction technique for highways is offered by Bonney (3) concerning a transportation study in Sabah, Malaysia. Bonney uses net present worth of road costs as his criterion for determining stage construction levels.

Bonney reduces all costs to annual costs per mile of roadway for the sake of comparison. He calculates this annual cost by straight line depreciation of the fixed facility, including interest charges of six percent. A feeder road was considered to have a ten-year life with no salvage value while a trunk road was considered to have a 20 percent salvage value at the end of its twenty-year life.

Equations indicating the maintenance costs of earth and gravel roads in terms of VPD were derived. The maintenance equations in $/mile/year for earth and gravel roads
respectively are:

\[ \text{maintenance costs} = 264 + 16 \text{ VPD} \]
\[ \text{maintenance costs} = 496 + 13 \text{ VPD} \]

Bonney posits that vehicle operating costs for earth, gravel, and bituminous roads are in the proportion 2.0: 1.2: 1.0 respectively. The total cost per road transport mile was calculated as 13 cents for bituminous roads. This works out to 26 cents per mile for earth and 15.6 cents per mile for gravel roads. These costs are an average for all vehicles using the road.

According to Bonney, at 25 VPD the total annual costs on earth and gravel roads of good alignment are:

- **Earth:**
  - $940 (construction & maintenance) +
  - $1790 (vehicle cost) = $2730

- **Gravel:**
  - $1585 (construction & maintenance) +
  - $1070 (vehicle cost) = $2655

Using this line of reasoning, since the costs are nearly the same it becomes worthwhile to provide gravel roads when the traffic reaches about 25 VPD.

Continuing this analysis, Bonney determines that at 80 VPD the total costs of bituminous trunk roads are approximately equal. He therefore suggests that it is worthwhile to upgrade a trunk road from gravel to bituminous surface at a traffic volume of 80 VPD.

There are several difficulties encountered in using this type of break-even analysis. The most important
drawback is Bonney's use of undiscounted costs and the consequent disregard for the time-dependent nature of highway investments. This in turn will often lead to non-optimal investment strategies. However, it may be argued that this drawback is outweighed by the advantages offered by a model so simple that it requires very little computational effort.

The World Bank Study (4) does not present any data concerning stage construction of earth and gravel roads, but data is presented for varying qualities of bituminous pavements. For predicted volumes of 800 VPD, a low-type bituminous pavement, for example a single surface treatment, is recommended. For traffic up to 2,500 VPD an intermediate type pavement such as multiple surface treatment or a cold mix layer is desired. Finally, a high-type pavement like a regular hot mix layer is recommended for volumes greater than 2,000 VPD. Unfortunately, the criteria and calculations used in arriving at these decisions are not presented in full.

A report by the Road Research Laboratory (5) indicates that a six-inch base overlaid by a single surface treatment is adequate for up to 150 commercial VPD. When traffic increases above 150 commercial VPD it is recommended to add a two-inch layer of asphaltic concrete pavement. It is not stated in the report how the particular staging levels were
4. Staged Construction: Pavement Design

Two frequently referenced sources for pavement design information are the Asphalt Institute (6) and the British Road Research Laboratory (5).

The Asphalt Institute method has been used in staged construction of high volume highways in North America. Bauman (1) has observed that when this method is adopted by emerging countries, over-design results because the method seems to be inaccurate at low volumes of traffic.

The method formulated by the British Road Research Laboratory, however, has been used with considerable success in various parts of the world. The method was developed for use in emerging countries and its use results, according to the Laboratory, in a "realistic design."

5. Empirical Models

Thrower and Burt (7) examine the possibilities of stage construction for road pavements. They feel that concrete pavements, since they have such a long initial life, are unlikely to be considered for staged construction, and so they have limited their discussion to flexible pavements.

Thrower and Burt consider the main problem of staged construction to be minimizing the total costs of construction and maintenance of a pavement over a given period of
They present four alternatives for determining when to begin the second stage of construction.

Case 1: Add the second stage when the first stage has just reached to critical value \( (d_c) \) of permanent surface deformation.*

Case 2: Add the second stage when deformation of the first reaches a fraction \( s \) of the normal failure value \( (d_c) \).

Case 3: Add the second stage using criterion given in Case 1, but assume first stage, because of excessive deterioration, plays no further structural role.

Case 4: Add the second stage when the road is in the same state that it is expected to be in at the end of the analysis horizon (i.e. after the last stage is ready for repair).

Thrower and Burt use these four cases of stage construction to compare their costs to those of a single stage construction for the same overall life. The sensitivity of these costs to traffic growth rate and financial discount rate is

---

*The usual criterion of failure for flexible pavements in Britain is the occurrence of 1" permanent vertical deformation in the near side wheel track, measured from the original level.
also investigated.

In their evaluation of the four cases, the authors comment that Case 1 is the most optimistic assumption for flexible construction. Case 2, although less optimistic than the first case, still has less total material costs than for a single stage construction. Case 3 is a more pessimistic model for flexible construction. In contrast to the two preceding cases, total material costs are always higher than for single stage construction. Finally, Case 4 is often more pessimistic than any of the preceding. It always results in an increase of total material costs.

A method has been suggested by Hewit (9) to use a benefit-to-cost ratio, with VPD as the variable to determine at what time it is economically feasible to improve a road surface. The benefit/cost ratio is defined as the difference in road user savings divided by the difference in highway costs, which include the cost of construction and maintenance.

In a sample situation, Hewit attempts to determine at what volume it is necessary to improve a road from gravel to a bituminous surfacing. Construction cost for the new bituminous surface road consists of the following items: preparation of the road bed, leveling course, base course, and the bituminous surfacing. Drainage, alignment, grades, etc., are considered adequate on the gravel road and therefore no
improvements are necessary.

The decision rule used in this instance is to build a bituminous road when the benefit/cost ratio becomes one. The equation used to determine this point in terms of VPD of heavy vehicles such as trucks and buses is

\[
\frac{B}{C} = \frac{AR}{AH} = \frac{RG - RB}{HB - HG}
\]

where \(AR\) is road user savings and \(AH\) is the cost of providing a bituminous road. The other variables are

\[
RG = 365 \times VPD \times \$.34
\]

\[
RB = 365 \times VPD \times \$.28
\]

\[
HG = 408 \times VPD \times \$.22
\]

\[
HB = \$2,783 + \$310 = HB1 + HB2
\]

\[
HB1 = \text{Amortized cost of bituminous road over 20 years}
\]

\[
HB2 = \text{Annual maintenance cost}
\]

Solving this equation with VPD as the variable, it was found that the road user savings are just equal to the annual cost of improvement less savings in maintenance cost when the traffic reaches 116 VPD. This means that it would be economical to improve a gravel road to one with a bituminous surface when the truck and bus traffic exceeds 116 VPD.

The major disadvantage of this method is the use of the benefit/cost ratio as a decision criterion. This method is subject to several flaws, most notably the conceptual
difficulty of comparing the benefit/cost ratio of a set of projects having varying design lives (11), and the difficulty of incorporating budget constraints into one's analysis (37). Also, this method fails to take into account the variation of user costs with deterioration of the pavement.

6. Mathematical Models for Staging

The previous sections have presented a brief discussion of the advantages and disadvantages of staged construction for highways and have presented some examples of its use in actual road building situations. This section will review the literature that has dealt with the question of how to arrive at an optimal staging strategy. The literature is from fields as diverse as the selection of stocks for an investment portfolio to the planning of a telephone system.

7. Facets of the Problem: The Timing Issue

Construction staging has been described (Marglin (12)) as a two-part problem: selecting a timing strategy and selecting a design. A third, closely related, problem is, given a set of projects and a limited budget in any one period, deciding what projects should be selected for construction in that time period (10, 11). Some authors have assumed that such projects are mutually independent (17) for ease in computation, while others have acknowledged the interde-
pendency of projects in their analyses (36).

Marglin (12) offers one of the more complete discussions of the timing problems. He identifies the major issue as the extent to which costs and benefits vary with the date of construction. He gives a decision algorithm for selecting projects for construction if the time flows of cost and benefits are known and there are budget constraints in every construction period. The algorithm, however, is useful only in the case of independent projects.

Several other authors also consider the timing issue with regard to independent projects. Mori (10) and Gulbrandsen (17) 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 this is one of the reasons that a pure timing approach is not satisfactory in this context.

8. The Design Issue

Manne (13) has considered in some depth a related problem concerning the selection of an optimal plant size and location for three industries in India given constant annual increases in demand, substitutability of imported goods at a known shadow price and economies of scale for plant capacity. Using these assumptions he finds that new plant capacity should be added every n'th year, where for any set of initial conditions n does not vary with time and the additional capacity is equal to the initial plant size. As part of this work, Manne and his co-workers developed a computer program to determine the optimal investment strategy and plant location(s) of these three industries. If this concept could be used in highway planning it would be a relatively simple matter to design and implement a computer program or other algorithm for finding staging strategies for road construction. Manne's approach for estimating the cost (both initial and operating) of a facility was of the form $C = a + b^* V^k$ where $a$, $b$, and $k$ are empirically determined constants and $V$ is the annual production capacity of the facility. Unfortunately for road planners, however, it appears that no similar relations exist for estimating the costs of road construction.
9. Budget Constraints

Ochoa-Rosso (16) formulates the multi-period investment model as an integer programming problem. He is concerned with investment strategies for networks and considers the relationship between links but does not indicate how one can optimize a single project. Nashlund (27) expresses the multi-period investment model as a linear programming problem, in his case dealing with the problem of selecting stocks for an investment portfolio under uncertainty. Of particular interest is his discussion of the selection of a measure of effectiveness, which is based upon the values of the dual variables of the linear programming solution.

The paper by Lack et al. (37) also has some bearing on the subject of staged construction; it 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 model seems to be constructed quite well. However, the relatively simple cost estimating routines 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. Because of this it would be relatively difficult to transfer this model intact from area to area.

10. Staging Under Uncertainty

Pecknold (36) presents an excellent analysis of staged construction of transportation networks. He considers both network and project design, staging and the question of uncertainty in the analyst's estimates of the future. He develops the staging problem as a set of sequential decision trees and then, using various decision rules, prunes branches from the decision trees. He then goes on to produce a model of the sequential decision making/investment staging process. The model operates using Bayesian probability techniques to update the tree under uncertainty.

11. Summary

The models for formulations of staged construction which have been reviewed for the most part deal with transportation networks or other large scale systems rather than with the design of a single link and the subsequent increase of capacity or cost of that link. This is particularly true for the models of Gulbrandsen, Mori, and Ochoa-Rosso, and true to a lesser extent for the models presented by Lack, Manne, and Marglin, whereas the primary concern of this thesis is the allocation of resources to a single road project.
One other difficulty is that these studies (except for Pecknold's) are deterministic in outlook. It is felt that due to the large demand road projects place on both the foreign and local capital reserves of a developing country more information should be presented to the decision maker than is offered by deterministic analysis.
Chapter Three

Developing the HCM

This chapter will report on the actual process used in developing the Highway Cost Model, the technique which was structured to give highway planners in developing countries an easily used tool for determining optimal low volume road investment strategies under conditions of uncertainty.

1. The Basis: Cost Estimating Routines

The basis for the model grew out of previous work aimed at developing a cost estimating routine for low volume roads. This study, sponsored by the International Bank for Reconstruction and Development, resulted in nine FORTRAN programs which modeled the processes involved in low volume road construction, maintenance, and user operating cost (36, 38).

The construction routines are called HWYCT, EARTH, and RFETH. HWYCT computes 1) pavement quantities and costs, using a geometrical approach, 2) the length in meters and distribution of various sizes of culverts, using a model developed by Lago (53), and 3) calls either EARTH or RFETH to estimate earthwork volumes. EARTH is called if a one-point model of the terrain and final road profile is provided by the model user. When this occurs, an estimate of
earthwork is made, assuming a zero side slope. The quantities of cut, fill, and borrow are returned by EARTH to the routine HWYCT. If contour-line crossing data is supplied rather than the one-point terrain descriptor, routine RFETH is called. Using relationships determined in a study for the Department of Transportation performed by Soux (51), it estimates earthwork quantities as a function of average and maximum desired grades on the road and the number of ten-foot contour lines crossed by each kilometer of the road. It is not as accurate as the one-point model but the data necessary to use it can often be gathered at a considerably lower cost and without knowledge of the details of the final alignment. When control returns to HWYCT all costs are summed and miscellaneous and supervisory expenses are added to this quantity. See Appendix D for a further discussion of these routines.

These routines are used both in estimating the costs of initial construction and for reconstruction of the road. In the latter case, if the road cross section remains unaltered, the earthwork routines are not called.

The maintenance costs are estimated by a set of routines designed by John Alexander. A complete description of these programs is included in reference (36). Essentially, these routines estimate deterioration of the road surface and then compute the work necessary to restore
some measure of the lost serviceability. Estimates are then made of the roughness in inches per mile, the coefficient of friction, and the rolling resistance of the road surface. This is done within routines MAINT and DETER. Other aspects of road maintenance are simulated within routines SHLDR, DRMNT, and VEGT, which compute the shoulder maintenance, ditch cleaning, and roadside clearing efforts respectively. MCOST sums the costs of all maintenance activities and returns these values broken down by activity to MAINT which then returns to NETWK.

The road user operating costs are estimated by the subroutines USER and LOOK. The former computes running speeds, labor, fuel and equipment usage, costs, depreciation and fixed charges on the vehicles on the basis of user-supplied information and data collected explicitly for this model. LOOK is used to interpolate within tables of data developed by de Weille (52).

It should be noted that these models are rather extensive and although not tested in a production environment are fairly accurate when compared with engineering feasibility studies, through comparisons made with data supplied by the British Road Research Laboratory (57).

2. Developing the HCM

It became apparent that these routines, although they comprised a useful tool for estimating the costs accruing
to a single road design, were not a completely successful tool for investigating staging strategies, primarily because of the difficulties associated with communicating with the model. In terms of stage construction the model was awkward to work with--i.e. it could only examine one strategy at a time, and a great many cards were required to define a strategy.

In evaluating a model of this nature, it was decided that heavy consideration must be afforded to the model's relationship with its ultimate user. The ultimate user of the Highway Cost Model would be highway planners in developing nations and, to a lesser extent, officials of the U.S. Department of Transportation. It was felt that neither group would be very eager to use the model if it required more than minimal knowledge of computers.

This posed two main problems: first, developing a method for finding optimal investment strategies under uncertainty and second, developing a means of communicating with the model user which was independent of his knowledge of computers.

Thus, the Highway Cost Model was conceived around the idea of building a "black box". The user would be able to throw data into it, receive his answers, and not necessarily be concerned with the internal mechanism of the model. In addition, the technique being developed had to rely upon
the cost estimating routines developed previously. These routines represented a great wealth of research experience on low volume roads.

3. Selecting an Approach: The Alternatives

Four methods were considered for using the cost estimating routines as a means to determine optimal investment strategies for low volume roads.

The first method considered was to use some form of network analysis such as GERT (Pritsker (56)). This approach would have meant simplifying the cost estimating routines so that they would fit into the relatively simple structure that GERT provided, thereby losing much of the hard-earned accuracy that had been attained. For this reason, the network analysis approach was rejected.

The second approach considered was to use dynamic programming (Wagner (60)) and modify the cost estimating routines so that they were compatible with the d.p. algorithm. This approach had one major advantage—within the accuracy permitted by the cost estimating routines, the optimal solution would certainly be found. However, this advantage was counterbalanced by the very large number of iterations that would be necessary to solve this algorithm and the consequent high computer charges associated with devoting large quantities of computer time to a single run. Furthermore, using a d.p. algorithm would cause the model to ex-
amine so many alternatives that only summary cost figures could be presented unless the model user was to be inundated with a flood of computer output. In view of these disadvantages, the dynamic programming approach was also rejected.

The third approach involved altering the cost estimating routines so that they would be compatible with linear or nonlinear programming techniques. The major advantage of these techniques was that they automatically incorporated resource constraints; a considerable literature existed describing the use of these techniques in capital budgeting. The difficulty with using the linear and nonlinear programming techniques is that in order to keep the measure of effectiveness and constraints simple, it would be necessary to limit them to only fiscal factors. In order to increase the number of factors considered beyond the simplest fiscal concerns, it would be necessary to develop an extremely complex set of constraints and a similarly complex measure of effectiveness. Either alternative was unacceptable.

The fourth approach consisted of adding a set of translating and control routines to the cost estimating routines. The function of the translating routines would be to take a set of simple commands from the user and convert those commands into a form that would be used to control the cost estimating routines. Using this approach, the planner could draw upon his experience and knowledge to guide the
model and make up for whatever inaccuracies and biases it contained. The disadvantage of this approach was that a truly optimal staging strategy would probably not be arrived at unless a very large number of strategies were specified and examined. But this disadvantage was reduced in importance when it was noted that the cost estimating routines were not accurate enough to justify the expectation that even an exhaustive analysis would result in a truly optimal situation.

This last approach had several advantages. Only minor modifications would have to be made to the cost estimating routines, and consequently the accuracy of the model would not be reduced. Also, in letting the model user retain control of the strategies that were investigated, this technique encourages the model user to have more confidence in the answers which the model offers. Finally, as the output of the model would be a summary of the consequences of the various strategies, and not a ranking of the strategies, it would permit the user to choose any measure of effectiveness he desired in evaluating the various strategies.

This approach, then, permits the model user to find a near-optimal solution by making several runs with the model; on the first run he would normally examine a wide variety of staging strategies, while on subsequent runs
he would select the most promising alternatives from previous runs, modify certain timing and design parameters, and determine whether the new strategies are superior. The user could stop whenever the improvement in the measure of effectiveness went below a certain level. At this point he could subject the best strategy to conventional analysis. Thus the model user never loses control of what is happening, and he can compensate for resource constraints and/or his own measures of effectiveness. It was concluded that this approach was the most nearly suited to the development of the Highway Cost Model.

The selection of this approach made necessary the design and implementation of a set of translation and control FORTRAN routines that would interact with the previously written cost estimating routines. Some of the factors that influenced the design of these routines were: efficiency—the routines should use as little space as possible for storing of temporary results, yet they should also permit a reasonable number of strategies to be examined during a single run; speed—the routines should save as many results as possible so that they would not need to be frequently calculated; minimization of input and output—in order to reduce running time, the attempt was made to decrease the number of cards required to specify staging strategies and increase the amount of information that was
always written out; and finally, elegance—the model as viewed by the user should be simple to operate yet sophisticated in terms of its capabilities.

Once the translating routines were written, a control routine was designed and implemented. The function of this routine is to use the list provided by the translating routine so as to cause the cost estimating routines to evaluate the staging strategies specified by the user. These routines, combined with the cost estimating routines developed previously, became the Highway Cost Model.
Chapter Four

The Computer Routines

This chapter discusses the computer routines of the Highway Cost Model. The routines are composed of two interacting groups of FORTRAN subroutines. The first group is a set of ten routines for estimating the costs of construction, maintenance, and vehicle operation; the second group is the staging routines, which act as an interface between the model user and the cost estimating routines. These staging routines permit the model user quickly, easily, and inexpensively to examine the costs accruing to up to thirty alternative staging strategies under an infinite variety of traffic conditions, for an analysis horizon of up to twenty-five years. A further function of the staging routines is to display the consequences of the various staging strategies in a straightforward and readily comprehensible fashion. Since the HCM has been designed as a working tool for the highway planner, this is an important consideration; a poor format will discourage the planner from using the model. For this reason a good deal of time was expended in refining and simplifying the structure of the output.

1. The Staging Routines

There are five main subprograms in the staging routines: they are MAIN, NETWRK, CONSTR, STRAT, and SAVDAT. MAIN, despite its title, is a small routine which determines the
level of detail presented in the output. MAIN also calls several subroutines: PMIN, which reads in the problem description; STRAT, which reads and interprets the staging strategies; and NETWRK, which steps through the decision network. A flowchart for MAIN is given in figure 2.

STRAT is a considerably more complex routine than is MAIN, but it performs fewer functions. STRAT reads the number of staging strategies to be examined during the current run, the number of road designs which are being altered, and the number of years in which construction costs or productivities are different from those in year one. This data is read from a single card. If the model user wishes to add to or alter the "typical" templates and pavement cross sections stored in the array DESIGN in the BLOCK DATA subroutine, STRAT will read in the number of changed designs and temporarily store them in the appropriate locations.

STRAT also has the ability to read in the construction costs and productivities that are expected to be in force over the analysis horizon. Thus, increased costs due to inflation and change in productivity can be included in the analysis and in comparing alternative investments.

By far the most important function of the STRAT routine is reading in the various investment alternatives and interpreting this information (which is presented in a manner analogous to a decision tree) into a form which is used
Figure 2
Flowchart for MAIN

MAIN

set card reader and printer numbers

output parameters and traffic switch

list output parameters and traffic switch

call PMIN

A
by NETWRK and CONSTR in stepping through the decision tree. Briefly, this consists of 1) recognizing nodes in the decision tree, 2) counting the branches from each node, and 3) converting the branch data into numbers defining the construction alternatives. A flowchart for this routine is given in figure 3.

NETWRK is the most important routine in this group. It calls the cost estimating routines, performs bookkeeping, and steps through the decision network defined by the user. A flowchart for NETWRK is presented in figure 4.

A further function of this routine, and one that is of considerable importance to planners, is its capability to examine the consequences of uncertainty in traffic projections. This is done through a loop that encompasses the entire routine. When there are two or more estimates of the traffic, the cost accruing to each is weighted by the probability of that estimate's occurring, and used to find the expected costs of the various construction alternatives. The equation used to find the expected cost where

\[ E = \text{expected cost} \]

\[ n = \text{number of traffic sets} \]

\[ P_i = \text{probability of realizing traffic set } i \]

\[ C_i = \text{costs accruing to traffic set } i \]

is:

\[ E = \sum_{i=1}^{n} (P_i \times C_i) \]
Figure 3
Flowchart for STRAT

STRAT

read #recon alternatives, construction sets, and templates

# Recon. >0

Y

n

read strategies

read year, costs, products

read templates, names cross section

A

return
A

determine # of construction activity

create list of construction activity

locate nodes in list of construction activity

print list: construction activity, nodes, strategies

return
Figure 4
Flowchart for NETWRK

1. Set NTPMF = TPMF (number of sets of initial traffic conditions)
2. Zero array STCST
3. Read PNTPMF = P (initial traffic conditions being right)
4. Write PNTPMF
5. Initialize variables
6. Deterministic traf. prediction

A 55
This is a network problem.

**Call SIMCON**: yes -> year=1, number of strategies = 0

**Call SAVDAT (save node prop.)**: yes -> is this year and strategy a node

**Call CONSTR**: yes -> this year, strategy a constr. period

write year discount factor strategy

A

D

D

C

E
D

F

is this null alternative

no

C

call USER

write year, initial traffic conditions

yes

year = 1

no

call MAINT

sum maintenance, operating costs

G

57
compute foreign exchange components of maintenance and operating costs

print these costs

print these costs

year = year + 1

print a summary of all costs incurred during this strategy

year > length of anal. period

yes

no
locate the node corresponding to this construction

increment construction counter

locate the node corresponding to this construction

call SAVDAT (restore node props.)

store costs in array CSTRT

more strategies to be examined

TPMF ≠ 1

weight array CSTRT by PNTPMF, add this quantity to array STCST

NTPMF = NTPMF - 1

print costs of all strategies (CSTRT)

return

E

I
print PNTPMF, costs of all strategies (CSTRT)

\[ \text{yes: } NTPMF \neq 0 \]

\[ \text{no: } \]

print weighted costs of all strategies (array STCST)

return

60
NETWRK steps through the decision tree by using the list of staging strategies produced by STRAT. Two indices are kept by NETWRK: one for the year that is being simulated and another for the staging strategy being examined. Each time the year index is incremented NETWRK checks whether the period in question is a construction period, a node, or the end of the analysis horizon. If construction is required, CONSTR is called. If a node is located, the costs and traffic at that node are saved by SAVDAT. If the end of an analysis horizon has been reached, SAVDAT will print summary costs for the investment, examine the list of construction alternatives for the next strategy, and restore the costs and traffic at that point (the beginning of the new strategy.)

SAVDAT has two functions: 1) to list and 2) to restore the properties at a node when called by NETWRK. The parameters passed to this routine define the node, and establish whether a save or restore operation is to be performed. The information saved is a complete description of the road at the time SAVDAT is called. This includes costs to date (discounted and undiscounted), the road template and cross section, traffic levels and operating costs per kilometer, and the material and currency consumption required by the previous construction activity. A flowchart for the SAVDAT routine is given in figure 5.

CONSTR performs the same type of bookkeeping and
Figure 5
Flowchart for SAVDAT

SAVDAT

+ TYPE

- TYPE

save road conditions

restore road conditions

write type of operation

return

TYPE is set by NETWRK
control functions as are done by NETWRK. Specifically, CONSTR takes from the BLOCK DATA subroutine details of the road template and cross section, selects the costs appropriate to the year in which construction occurs, and then calls HWYCT to compute the costs of construction. When control returns to CONSTR, costs, material quantities, and earthwork volumes are summed and printed. Surface conditions such as roughness and frictional coefficients are initialized by a call to INITL. Subsequently, the foreign exchange components of construction costs are computed on the basis of material, labor, and equipment expenditures.

CONSTR can, if desired, cause PMIN to read in a new set of vertical points of intersection (VPI's) and topographical data. This information is written over the current data sets and used in further analyses. This permits the user to examine the consequences of constructing roads on different alignments.

A flowchart for this routine is given in figure 6.

2. Relationship to Cost Estimating Routines

Although the previous section has given a brief indication of how the network routines are related to the cost estimating routines, this section describes in a more explicit form both the calling sequences and the information passed between the two sets of subroutines.

Figure 7 shows the calling sequences used in the HCM.
Figure 6
Flowchart for CONSTR

CONSTR

write identification construction

IOP = 0

choose NULL alternative, return

JQ = 1 yes
no

IOP = 1 yes

JQ > 7

no

JQ is the design number

A

A
IOP is the type of construction

IOP = 2

JQ > 9

no

establish design parameters

get cost and productivities for this year

SIMCON

call HWYCT

call INITL

initialize array RCOND

B 65
write costs and volumes

compute foreign exchange costs

print foreign exchange costs

return
Figure 7

Calling Sequences

A dotted line indicates a CALL that does not necessarily occur.
To read it, start at MAIN. The order in which the routines are called is given by the clockwise arrow. Thus, routine MAIN calls PMIN which may call FORIN (if foreign exchange requirements are to be read). MAIN will then call STRAT and NETWRK, which in turn will call CONSTR (or SIMCON if a single investment strategy is being examined). When control is returned to NETWRK it calls USER and MAINT to find the costs of vehicle operation and road maintenance. The year index is then incremented by one, and a check is made to see if a node or construction period has been reached. If this has occurred, NETWRK takes the appropriate action—calling CONSTR to simulate road construction, or, in the case of the node’s being reached, calling SAVDAT to save the conditions at the node.

3. The Highway Cost Model Flowchart

Figure 8 presents a macro flowchart for the entire Highway Cost Model. It shows the flow of control in terms of issues, decisions, and operations in a format which is not directly related to the formal (i.e. FORTRAN language subroutines) structure of the HCM. As can be seen in this figure, the major issues considered here are the tradeoffs between different maintenance, construction, and vehicle operating costs, the effects of uncertainty in traffic projections, and the need to communicate with the model user. It is hoped that the simplicity of the input and the
Figure 8

Macro Flowchart

1. read problem description
2. read construction strategies
3. analyze strategies, find nodes and branches
4. strategy = 1
5. year = 1

A 69
get maintenance policy from storage

compute costs and resources consumed in construction

initialize surface conditions

compute road user costs and traffic

make traffic projections on basis of demand curve, growth rate, and per kilometer costs

is this a construction period

C

A

B
B

compute deterioration of road and right of way

compute necessary maintenance effort on basis of maintenance policy and deterioration

year = year + 1

store costs and traffic at this node

is this a node

yes

no

D
D

C

is this last year of this strategy

yes

print a summary of costs

stop

no

is this the last strategy

yes

restore traffic and costs of last node

set year to year of last node

increase strategy counter

C

72
clarity of the output will make this model and the information it provides accessible to even the relatively inexperienced computer user.
Chapter Five

Experiments in Staged Construction:

Techniques and Results

Several experiments were performed using the Highway Cost Model to test the hypothesis presented in Chapter One, namely that staged construction of low volume roads would reduce the discounted costs of construction, maintenance, and vehicle operation under a variety of circumstances. This chapter will discuss the experiments that were performed and present the results of these experiments. The experiments which were run served to develop a set of pruning rules that the model user could draw upon. These pruning rules, which embody the conclusions drawn from these experiments, make the planner's work easier as he can use these rules to decrease the number of designs and staging strategies which he must examine during the first iteration.

Chapter Six will discuss the implications of these experiments for planners of low volume roads in general and users of the Highway Cost Model in particular.

1. The Experiments

One of the great advantages of using a computer simulation of a real-world situation is the ease with which experiments can be performed and hypotheses tested. The HCM is an excellent example of this statement; it can inexpen-
sively and accurately investigate the effects of various parameters, decisions, and other factors on the costs associated with low volume roads.

Previous work with the cost estimating routines (38) indicated that the most significant parameters affecting low volume road costs were traffic conditions and terrain. Considerations of lesser importance were the discount rate, the length of the analysis horizon, and factor prices and other site-dependent conditions such as the productivity of the construction work force and the vehicle mix.

In order to learn as much as possible about the effectiveness of various construction staging strategies, the following procedures were used. First, a set of feasible construction strategies were defined for a situation in which 1) reconstruction could occur only at five-year intervals and 2) the roads to be considered were earth and gravel one- and two-lane roads and surface treated and asphalt paved two-lane roads. This set of twenty-five strategies represented a fairly full range of choices available to the planners of the stage construction under these conditions. Figure 9 shows these staging strategies, presented here in the form of a tree where every path from year zero to twenty is a distinct staging strategy, with reconstruction or upgradings of a road occurring at the nodes of the tree. (For the experiments that were run, the one-lane roads were
The Staging Strategies

Figure 9
removed from consideration as at all but extremely low levels of traffic they resulted in excessive unit costs of vehicle operation. Therefore, under the generally higher traffic levels normally used in the experiments, examining these alternatives would have been a waste of time.)

A five year-interval between reconstruction periods was chosen because 1) the total discounted costs of construction, maintenance, and vehicle operation did not vary more than a few percentage points when reconstruction was delayed or speeded up two or three years, and 2) five-year intervals were well suited to the format used for input of construction strategies to the HCM. It should be noted that this interval is not limited to multiples of five years; the HCM can consider intervals of any integral number of years.

2. The Scenarios

In order to examine the effectiveness of the various staging strategies they were tested under a wide range of conditions. The procedure used was to take two "base" scenarios and vary the design and cost parameters. The base scenarios were taken from two engineering feasibility studies. The first, performed by Louis Berger, Inc., investigated National Route 14 in Argentina. The second, done by Baker-Wibberly, reported on the Sapecho-Puerto Salinas road in Bolivia. (62,63)
The two roads differed in many respects, including traffic volume, terrain, and suggested design. The Argentine road was asphaltic concrete, designed to carry fairly high levels of traffic on a straight, flat embankment on a floodplain north of Buenos Aires. The Sapecho-Puerto Salinas Road, on the other hand, was expected to carry relatively little traffic through the Andes, fifty miles northeast of La Paz. Appendix C contains the data which was used to represent the base scenarios of both roads.

Even though these roads seemed to encompass the extremes that would be encountered by planners, it was felt that firmer conclusions could be drawn and pruning rules formulated if the staging alternatives had been examined under a wider variety of conditions.

3. Expanding the Parameters

To obtain an expanded number of parameters for this experiment, the following manipulations were made to the base scenarios: the traffic volume was varied, the terrain data was switched (that is, taking the terrain data from the Bolivian site and combining it with the cost factors, designs, and traffic volume and types of the Argentine site, and vice versa), and several discount rates and analysis horizons were used. Specifically, the three parameters which define expected traffic—initial level, elasticity
of demand, and annual growth rate—were varied from the values given by the engineering feasibility studies; then the costs of each staging strategy was determined. Tables 1 and 2 show the traffic, growth rates, and price elasticities used for the Argentine and Bolivian roads.

4. Elasticity of Demand

To test the effects of increasing elasticity of demand, a series of experiments were performed with input data identical to the base run in all respects but one—the elasticity of demand for all vehicles was increased to five percent. The total discounted costs of the twenty-five strategies for both the high and normal elasticities of demand is given in figure 10. As this figure shows, increasing the elasticity of demand caused significant reductions in total costs for the better strategies even though in some cases it increased the costs of the lower quality strategies. The changes in costs were almost completely limited to operating costs; the elasticity of demand is a factor in determining the traffic volume of the road so only slight change in maintenance occurred. In general, increased elasticity tended to make improved roads better choices, since the increased elasticity of demand generated more traffic and increased the consumer surplus on the higher quality roads. However, the increased traffic caused increases in the total costs of vehicle
<table>
<thead>
<tr>
<th>Vehicles/Day</th>
<th>Base Cost $/KM</th>
<th>Elasticity</th>
<th>Growth Rate</th>
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<tr>
<td>15</td>
<td>1.342</td>
<td>0.012</td>
<td>0.090</td>
</tr>
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<td>15</td>
<td>2.405</td>
<td>0.003</td>
<td>0.090</td>
</tr>
<tr>
<td>30</td>
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<td>0.090</td>
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<td>0.012</td>
<td>0.090</td>
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<td>0.090</td>
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<td>0.090</td>
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<td>0.003</td>
<td>0.090</td>
</tr>
<tr>
<td>6</td>
<td>5.370</td>
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<td>0.090</td>
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Other Growth Rates

<table>
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<tr>
<td>0.045</td>
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Other Growth Rates

<table>
<thead>
<tr>
<th>Other Elasticities</th>
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<tbody>
<tr>
<td>0.050 and 0.0</td>
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Traffic Conditions for Bolivia Data

Table 1
<table>
<thead>
<tr>
<th>Vehicles/Day</th>
<th>Base Cost $/KM</th>
<th>Elasticity</th>
<th>Growth Rate</th>
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</thead>
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<td>35.</td>
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<td>0.066</td>
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<tr>
<td>15.</td>
<td>0.357</td>
<td>0.003</td>
<td>0.042</td>
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<td>16.</td>
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<td>0.042</td>
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<td>9.</td>
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<td>0.003</td>
<td>0.042</td>
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<tr>
<td>5.</td>
<td>2.366</td>
<td>0.009</td>
<td>0.037</td>
</tr>
<tr>
<td>170.</td>
<td>0.255</td>
<td>0.012</td>
<td>0.066</td>
</tr>
<tr>
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<td>0.003</td>
<td>0.042</td>
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<td>0.042</td>
</tr>
<tr>
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<td>44.</td>
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<td>0.009</td>
<td>0.037</td>
</tr>
</tbody>
</table>

Other Growth Rates

| .122 | .033 |
| .084 | .021 |
| .084 | .021 |
| .074 | .018 |

Other Elasticities

| 0.050 and 0.0 |

Traffic Conditions for Argentina Data

Table 2
Elastic Traffic + Normal Traffic

Argentina: Costs due to Normal and Highly Elastic Traffic

Figure 10
operation and thus caused the incongruous situation of gravel roads having lower total user costs than surface treated roads over the analysis horizon. (It should be noted that this situation arose only in cases of very elastic demand. Fortunately for planners, it seems that traffic in developing nations is only slightly elastic and so this situation is not likely to occur (Soberman (58), Haefele (48)).

5. Growth Rate

Next, the annual traffic growth rate of the base scenarios was varied. In the HCM the user generally specifies this parameter as an annual percentage increase; the traffic in year \( n + 1 \) is given by the expression:

\[
T_{n+1} = \left( \prod_{i=1}^{7} \left( t_{in} \times (1 + g_i/100) \right) \right)
\]

where \( t_{in} \) is the traffic in class \( i \) in year \( n \) and \( g_i \) is the growth rate of traffic in class \( i \).

Due to the multiplicative nature of this parameter, small changes in it lead to considerable variations in traffic over the life of the road. For this reason, and also because of the difficulty in estimating the growth rate of traffic, three growth rates—low, medium and high—were associated with each class of vehicle, and the effects were noted.

The experiments showed that high growth rates were
associated with reduced costs for high type roads, and low growth rates favored poorer quality surfaces (Figure 11). This was even more apparent when the discount rate was increased from its normal value of seven or eight percent to ten or twelve percent. Figure 11 shows the costs of the Argentine base scenario for growth rates of seven and twelve percent.

6. Maintenance Policies

The Highway Cost Model permits the model user to specify a wide range of both labor and capital intensive maintenance policies (Table 3). Six such policies—poor, normal, and excellent capital and labor intensive maintenance—were defined, and their effects on the utility of the various staging strategies were noted over several sets of initial traffic conditions.

The tradeoff that occurs is that increases in maintenance reduce the unit cost of vehicle operation, while reductions in maintenance increase the unit cost of vehicle operation and may lead to the need for more frequent reconstruction of badly deteriorated surfaces. Because a relatively small percentage of total costs are due to maintenance activities, earth and gravel roads in both flat and rolling terrain had lower total costs when excellent maintenance policies were used than they had when poorer maintenance was given. The reduced total costs
Low Growth Rate

High Growth Rate

Strategy

Increasing Strategy Quality
<table>
<thead>
<tr>
<th>Maintenance Policy</th>
<th>Blading Frequency</th>
<th>Rut Fraction Filled</th>
<th>Maximum Rut Depth cm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor Capital Intensive</td>
<td>10,000</td>
<td>.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Normal Capital Intensive</td>
<td>5,000</td>
<td>.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Excellent Capital Intensive</td>
<td>2,500</td>
<td>.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Poor Labor Intensive*</td>
<td>10,000</td>
<td>.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Normal Labor Intensive</td>
<td>5,000</td>
<td>.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Excellent Labor Intensive</td>
<td>2,500</td>
<td>.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

* Labor intensive maintenance is not as effective as Capital Intensive Maintenance for Gravel and Earth Road Blading
were due to the higher velocities made possible by the increased smoothness of the highly maintained roads, and the consequent reduction in time dependent expenditures. This is shown by figure 12 which gives total vehicle operating costs over the analysis horizon for earth and gravel roads on the Argentine alignment for poor, normal and excellent capital intensive maintenance. Figure 13 shows the velocity of each vehicle class on route 14 in year five for poor, normal and excellent capital intensive maintenance.

The situation is slightly different for surface-treated and asphalt roads. On both these surfaces, relatively little maintenance is required in the first years after construction, but in succeeding years more maintenance is required each year until reconstruction (Figure 14). Also, due to the way in which these roads are maintained, labor and capital intensive maintenance techniques are essentially identical, differing only in such tangential aspects as ditch cleaning and vegetation control (Vance (61), Alexander (36)).

For this reason both surface treated and asphalt roads exhibit similar maintenance and vehicle operating costs over the first seven to ten years of the analysis horizon, after which costs increase more rapidly on the surface treated roads. Therefore, an often economical
Per kilometer operating costs vs. Maintenance Policy

Figure 12
Maintenance Policy vs. Velocity

Figure 13
Asphalt + Surface Treated Reconstruction in year 18

Maintenance Cost (1000's of Dollars)

Strategies

Maintenance Cost of Asphalt and Surface Treated Roads

Figure 14
staging policy is to build a surface treated road and, when the serviceability index reaches the range 1.5 to 2.0, (Alexander (36)) to build the final layer of asphalt. Experiments made with the HCM have shown that this procedure often reduces total discounted costs over a wide range of initial traffic conditions and a range of discount rates from seven to twelve percent per year (Figure 15).

7. Discount Rates

In recent years, interest rates on development loans have been increasing rapidly; where rates of two or three percent were once common, some projects in recent years have been evaluated at discount rates as high as fifteen percent. In part, these increased rates reflect the demand for risk capital; they are also partly due to the high rate of inflation occurring in many parts of the world. Several experiments were run using the HCM to test the desirability of the various strategies in view of this important factor. The experiments showed that higher discount rates made the use of staged construction even more advantageous, because the compounding of the discount rate causes future expenditures to weigh less heavily than present expenditures. Figure 16 shows the total discounted costs accruing to the twenty-five strategies on the Argentine route for interest rates of seven and twelve percent. Asterisks (*) indicate those strategies where
Advantages of Staged Construction

Figure 15
Effect of interest Rates on Total Discounted Costs

Figure 16
staged construction did not occur.

8. Foreign Exchange

Foreign exchange consumption can often be an important factor in deciding what type of road to build. The limited foreign exchange resources of most developing countries make necessary the careful consideration of the uses to which this resource is put. Some roads will require more foreign capital than others, either because they are more expensive or because their design requires greater quantities of imported materials or equipment to build.

Foreign exchange requirements are calculated in the HCM by asking the user to state the percentage of vehicle, fuel, tire, construction and maintenance equipment, construction labor, and construction material costs that must be purchased using foreign exchange. Table 4 shows the percentages used for both data sets. These percentages were used to estimate foreign exchange consumption by use of expressions of the form

\[
\text{Foreign exchange needed} = \sum_{i=1}^{7} \left[(\text{unit cost}_i \times \text{consumption}_i \times \text{percent offshore costs}_i \times \text{exchange rate})\right]
\]

where the subscripts refer to the seven categories described in Table 4.

The way in which offshore costs varied with staging
<table>
<thead>
<tr>
<th>Item</th>
<th>Percent Offshore Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>80.</td>
</tr>
<tr>
<td>Labor</td>
<td>43.</td>
</tr>
<tr>
<td>Construction Material</td>
<td>0.</td>
</tr>
<tr>
<td>Fuel</td>
<td>70.</td>
</tr>
<tr>
<td>Tires</td>
<td>80.</td>
</tr>
<tr>
<td>Construction Equipment</td>
<td>100.</td>
</tr>
<tr>
<td>Maintenance Equipment</td>
<td>100.</td>
</tr>
</tbody>
</table>

Foreign Exchange Component of Costs

Table 4
strategies for medium levels of traffic in Argentina is closely related to the way in which total costs varied, with the single exception that earth roads were considerably less expensive in terms of foreign exchange than the total costs would indicate. Examination of the offshore costs accruing to different levels of traffic showed similar effects. Figures 17, 18, and 19 show foreign exchange costs for the twenty-five strategies for the three traffic levels previously described. By reference to figure 9 one can see that strategies 1 through 10 were initially earth roads, 11 through 17 were initially gravel and the remainder were surface treated or asphalt. Thus, in those cases where foreign exchange consumption is an important consideration, high type roads may be preferred to poorer quality surfaces even though higher initial construction costs will be incurred.

9. Length of the Analysis Horizon

Because any fixed-length analysis period represents a length of time which is shorter than the total life of the road involved, any analysis of the road which considers only that period will be somewhat misleading. For example, if two or more staging strategies are compared, the length of the analysis period will affect the ranking of the alternatives. Consider the impacts of the following strategies in the case of Argentine Route 14. Strategy 1 consists of
Foreign Exchange Requirements
Argentine Route 14 Low Traffic

Figure 17
Foreign Exchange Requirements
Argentine Route 14 Normal Traffic

Figure 18
Foreign Exchange Requirements
Argentina Route 14 High Traffic

Figure 19
building an asphalt road and giving it normal maintenance. Strategy 2 consists of initially building a surface treated road and upgrading it to asphalt in year fifteen, giving it normal maintenance throughout the analysis horizon. Given an analysis period of twenty years, it is unlikely that Strategy 1 will have lower discounted total costs. But if the analysis period is lengthened to twenty-five years, the situation may be reversed—the asphalt road will have required reconstruction and in the interim the user costs will have increased to more than compensate for the costs of upgrading the surface treated road. The costs over time of both roads would be given as in Figure 20. This implies that longer analysis periods favor roads that are reconstructed in the last half of the analysis period, while shorter analysis periods are more favorable to construction strategies having only a single construction activity.

10. Results of the Experiments: The Pruning Rules

The experiments just described examined the costs accruing to twenty-five different construction strategies under a very large number of conditions. As has been noted, one of the objectives of running these experiments was to develop a set of pruning rules which planners could use to reduce the time and effort required to arrive at an optimal investment strategy whether or not they used the Highway Cost Model.
Bolivia: Costs to Date of Roads both Using and not Using Staging

Figure 20
The remainder of this chapter will discuss a set of pruning rules which have been developed using as a measure of effectiveness the total discounted costs of each staging strategy.

11. Rules for Flat Terrain

For all but the lowest i.e., less than twenty-five vehicles per day over the analysis horizon, levels of traffic, growth rates, and price elasticities of demand, the lowest net present costs occur when a surface treated road is initially chosen. As traffic warrants, it may be desirable to upgrade to an asphalt road at year ten or fifteen (assuming a twenty year analysis horizon). Discount rates greater than ten percent favor resurfacing and minimum construction expenditures in any one year.

Heavy vehicle loadings (in terms of the number of vehicles using the road and their weight) increase the desirability of an asphalt road, except at exceptionally high (greater than ten percent) discount rates. In most cases, surface treatments and resealing would seem to be adequate.

12. Mountainous Terrain

For low and medium levels of traffic, gravel roads appear to be best in terms of total discounted costs. Earth roads are acceptable in mountainous regions if traffic
is initially very low (under twenty-five vehicles per day) and increasing slowly, on the condition that good or excellent maintenance can be obtained.

As velocity on mountainous roads is limited by the grade, asphalt or surface treated roads generally result in only small savings for road users. Unless the expected traffic is exceptionally heavy, the savings will be less than the cost of the asphalt layer.

High traffic growth rates suggest a need for better roads, but the opportunity loss due to unrealized traffic growth and a more expensive surface may well be greater than the additional user costs due to running on a gravel surface. Unless high traffic levels are very probable, a gravel road would be preferred.

Longer, flatter routing of mountain roads (that is, going around the mountain rather than going over the mountain) may reduce both construction and vehicle operating costs if the following expression is true

$$\# \text{ km} \times \text{uc/km} \geq (\# \text{ km} + \Delta \text{km}) \times (\text{uc/km} - \Delta \text{uc/km})$$

where

- $\# \text{ km}$ is the original length of the road
- $\Delta \text{km}$ is the additional mileage constructed on the flatter routing
- $\text{uc/km}$ is the per vehicle operating cost on the original routing and
$\Delta u c/km$ is the reduction in per kilometer operating costs as a result of flatter grades. If it is, the increased costs due to extra mileage will be less than the savings caused by less earthwork and lower grades. Of course, this is very dependent on the original and alternate alignments, but as the HCM permits the use of contour line crossing data this alternative could—and should—be inexpensively explored.

13. Maintenance

The experiments performed during this research suggested that capital intensive maintenance is least costly for many earth and gravel roads. However, as this course of action can lead to foreign exchange consumption, it may be desirable to use labor intensive maintenance at the expense of an increase in total costs. For the factor prices and productivities used in these experiments, it costs more do to a given amount of work using labor intensive techniques than to do the same work using capital intensive procedures. However, different factor prices and a high shadow price for foreign exchange may make labor intensive techniques preferred. The interesting tradeoff here is the ease of establishing a labor intensive work force against the increased cost of maintenance. One must recognize that, in an economy having high levels of
unemployment, the shadow price of labor is less than the wages paid. For example, by employing unemployed workers, one may be eliminating the expense of providing them with relief funds. For this reason, the creation of a labor intensive maintenance force may be less costly than is indicated by the HCM.

14. Pruning Rules: Other Issues

Staged construction can be counter-productive unless the commitment to staging is kept. A road built with the expectation of being upgraded in ten years can be a definite hindrance to development after that date if it is not improved.

Maintenance is a far more important issue than it is usually considered to be. Poor maintenance procedures and policies should not be used for more than five years at the very most, or most of the original investment may be lost due to the encroachment of vegetation, loss of surface materials due to traffic, erosion, and other factors. For this reason, effective maintenance agencies should be formed during the construction of the road, and not left until maintenance is badly needed.

Finally, unless there are very strong reasons for only using one analysis horizon, the planner should examine the alternative staging strategies for their effectiveness at periods five years longer and shorter
than the length of the nominal analysis horizon.

15. The Use of the Pruning Rules

What can the planner do with these pruning rules and why are they important to him? The answer to these questions is that the pruning rules will make it easier for the planner to determine an optimal investment strategy. This is because he can use these rules to discard a large number of undesirable strategies at the beginning of his investigation --for example, earth roads and all staging strategies deriving from earth roads--and replace them in his input to the HCM during the first iteration with a wider range of gravel and surface-treated designs, staging strategies, and maintenance policies. Essentially, the use of the pruning rules enables him to combine the work of the first and second iterations, thereby reducing by as much as a third the time and effort required to obtain an optimal strategy.
Chapter Six

Use of the HCM

This chapter describes the use of the HCM in an experimental situation, namely, searching for an optimal design for the road between Sapecho and Puerto Salinas in Bolivia (see figure 21). The entire scope of activities associated with using the model--from data collection to design and engineering decisions--will be considered. Topics covered are data collection, i.e. what type of information is required, possible sources, and the required accuracy of this information; and the development of staging alternatives through the use of pruning rules and engineering judgment. Also discussed is the iterative search of the decision space with regard to the timing of investment and road design; maintenance policies ranging from poor labor intensive to excellent capital intensive maintenance; and the issue of uncertainty in traffic projections.

1. Data Collection

The matter of data collection is perhaps the single most important area of interest in this section, as whatever results are obtained by the model are only as precise and useful as the data which has been used as input.

The area where the most attention to accuracy should be given is the construction cost and the productivity
Map of Sapecho-Puerto Salinas Route

Figure 21
data. This is because 1) on most low volume roads, construction costs are the major component of total road transportation costs, and 2) in the productivity data, errors frequently have the same bias—for example, consistently underestimating productivity—to a greater extent and significance than occurs with costs related to maintenance and user operating costs. The reason for this bias is that the required data will often come from one or two closely related sources and any error made in either source will thus be propagated. (In the remaining areas of data collection, however, there will almost always be a wide variety of sources, so that the possibility of offsetting errors is increased.)

2. Construction-Related Data

There are three groups of construction-related data that are required by the HCM. They are: 1) site-dependent factors such as alignment, haul distances, and topographical information; 2) materials, labor, and equipment prices, which can often be considered fairly constant over a large area; and 3) design variables such as pavement cross sections, templates, and maximum and average grades.

In the first stages of the design process, I feel that the greatest effort should be expended in determining the values of the second data set, as both the first and third groups are much more easily manipulated by the model user.
It is a simple matter, for instance, to change a road cross section, but it is quite difficult to alter the productivity of labor or the unit costs of pavement construction.

The prime source for construction-related data would be engineering feasibility studies of roads in the same area, progress reports from construction projects in that region showing cost and resources consumed in performing a given amount of work, and summary figures for previous construction activity. Of course, the planner should be careful to establish that the figures used are not taken from a different type of construction organization from that which is expected to construct the road under question. For example, domestic and foreign constructors often operate at significantly different levels of performance and cost. Thus using the wrong data set would probably cause errors of considerable magnitude.

The other construction-related data, especially the site-dependent factors such as alignment, horizontal curvature, haul distances, and terrain descriptions, can be roughly estimated at the early stages of work and given in greater detail as more data becomes available. For instance, terrain properties can first be described by using contour line crossing densities and later be replaced by a one-point descriptor of the roadway center-line when details of the alignment are better known. The tradeoff between costs of
data collection and accuracy of the answer cannot be explicitly stated; however, it is suggested that the best available maps be used during the design stages and that if the model is used during the final design stages, less than total reliance should be placed on earthwork volumes and costs since the one-point model, although inexpensive to use, is inaccurate when used on terrain having a non-zero side slope.

Design variables can be specified in either of two ways: first, by letting the model specify the designs, or second, by explicitly specifying designs to replace those stored in the model. Unless there are extraordinary design requirements, i.e. very thick or thin pavement layers or narrow or wide lanes, it is often most convenient to let the model specify the designs for short cut analysis.

3. Maintenance-Related Data

This class of data is often the easiest to collect, due to the small number of items that comprise it--maintenance policy, equipment rental rates, and material costs. The policy data can be supplied by the model or the user, and the per hour costs of equipment and men and the unit prices for materials can frequently be determined by reference to readily available sources within the maintenance division. In any case, since maintenance costs are usually only a small percentage of total costs, the total cost is
fairly insensitive to errors in these figures. Also, since costs are computed on the basis of resource consumption, errors in estimating the cost of maintenance will not affect the way in which the maintenance is performed. Thus it can be seen that the user should not devote extensive resources in determining these numbers during the preliminary design stages.

4. Data Related to User Operating Costs

User operating cost is a fairly sensitive area, as indicated by the research presented in the DOT report (57). The points of greatest concern are the initial costs of the vehicles and the per hour costs for the vehicle and its driver. Data derived from run #150, which was the base run for this analysis, showed that on a gravel road with a roughness of 512 inches per mile for commercial vehicles driver costs were between 11 and 23 percent of total market costs while vehicle expenses due to the initial cost of the equipment and tires was between 44 and 62 percent of total market costs. It must be recognized that these percentages vary with the road characteristics and, perhaps more importantly, with the user's definition of costs. The cost figures that were used as input to the HCM were admittedly uncertain and it is unlikely that these would be the exact figures derived if completely accurate data was used. How-
ever, the use of other, more accurate, data (derived from
the Argentine National Route 14 study) yielded similar re-
sults.

Sources of information on user operating costs are
likely to be readily available, but confusion may arise as
to the distinction between market and economic costs as
they are used by the model. "Market cost" refers to costs
that are borne directly by the user, such as taxes, import
duties, registration fees, purchase price, and similar items
which will be paid for out of the user's pocket, while
"economic cost" refers only to the cost to the economy, i.e.
the price of the resources lost to the economy by the pur-
chase and use of the vehicle and/or its accessories.

The most important user operating costs are the initial
prices of the vehicles and the gross weights of the vehicles
(since these have significant effects on the deterioration
of the road surface.)

Figure 22 is a reproduction of the input data as
echoed and annotated by the Highway Cost Model. By examining
this illustration one may learn: the characteristics of the
road alignment; the costs and productivities of construc-
tion; the normal maintenance policy; the topography along
the road centerline; the California Bearing Ratio (CBR) of
the subsoil; the percentage of the roadway that has heavy,
normal, and light groundcover; some of the hydrological
Bolivian Base Scenario Data

Figure 22
<table>
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<th>Drainage Related Data-Chain</th>
<th>Water-Related</th>
<th>Haul Distance</th>
<th>Water-Related</th>
<th>Distance</th>
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</thead>
<tbody>
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<td>Flow</td>
<td>Available</td>
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consideration the model needs to know; the haul distances for construction materials; maintenance unit costs; and vehicle descriptions and prices (among other factors). It should also be noted that a road design is described under the headings ROADWAY CROSS SECTION and ROADWAY DESIGN DATA. This information is what the model must know before it can determine the costs of a road.

5. Development and Selection of Staging Alternatives

This section discusses the problems involved in selecting a set of strategies for investigation and how they can be "winned" from the large number of alternative designs and staging strategies that do exist. In order to reduce the number of designs which require examination, the problem is to distinguish within the continuum of all possible designs and staging strategies in such a way that 1) a representative number of alternatives is considered and 2) the number of alternatives examined is small enough so that undue amounts of time are not spent in computing their associated costs.

The first parameter that can be used to narrow down the investigation is that of pavement design. There are four types of surfaces generally used for low volume roads—earth, gravel, surface treated, and bituminous or asphalt concrete. It is difficult to make meaningful distinctions between closely related road designs for the earth and
gravel roads while using the HCM, with the exception that regraveling will be required with less frequency on thicker gravel roads. However, regraveling has only a very slight effect on total road transport costs and can be disregarded during this discussion. Also, a surface treated road is a fairly well-defined design, with variations permitted only in the design of the base and sub-base. In contrast to the limited variations found in these designs, however, asphalt road designs can be found in far greater proliferation. There do exist design techniques that can be used (AASHO, RRL, Asphalt Institute, and local experience) to determine a starting point for the initial investigation.

6. Timing

Timing of reconstruction is obviously one of the most important issues; the crucial question is: how sensitive are the total costs to small changes in the timing of reconstruction—for example, changing the reconstruction interval from every five to every six years. The HCM has demonstrated that for discount rates of twelve percent per year and less, if reconstruction is performed anywhere within a four- or five-year interval only small changes in total discounted construction, maintenance, and vehicle operating costs occur. For this reason a five-year interval for reconstruction is considered appropriate during the initial investigation of costs accruing to various strategies. It should be noted
that because of the iterative approach used in finding the optimal construction strategy, errors due to this somewhat arbitrary interval choice will be minimized.

7. Upgradings

This section will further delimit the alternate investigation space by defining feasible strategies for reconstruction. These strategies are based on the premise that the model user will wish to improve the quality of a road in time, or to leave it alone (subject to considerations of deterioration and maintenance.) Thus there are only a limited number of upgrading policies which can be implemented. For example, a gravel road can be upgraded to a surface treated or paved surface, but a paved road can only receive an overlay. Figure 9 shows the twenty-five feasible strategies that can be derived using this philosophy. An "S" as the last letter indicated new construction and is used in any but year one, or after the NULL option indicates an alignment change.

The alignment change option should be explained in more detail. The model offers the option of changing the alignment of the road during the design life. Thus a road constructed with steep grades and sharp curvatures could be flattened out some years after the initial construction. Because of the great variety of situations in which this
type of reconstruction might be performed, it is difficult to generalize about a good choice for this option. However, as the pruning rules in the previous chapter indicate, reconstruction on a new alignment may be appropriate if some of the following conditions hold: the original road is on a very steep alignment; there is a narrow right-of-way with little room for expansion; traffic has grown at a high (ten percent or more) per year rate and delays due to slow, heavy vehicles in the traffic stream are great; a suitable alternative alignment exists that does not unduly increase point-to-point distances. It is recognized that these conditions are not objectively defined and offer little practical guidance to the model user. Further research and use of the HOM in the field may yield sufficient experience to formalize these rules, which could then be incorporated into this work. However, since the model is inexpensive enough in actual use, such alternatives could be readily examined by the model's users.

8. Maintenance

Previous studies (Alexander and Moavenzadeh (36, 38)) have indicated the importance of maintenance in the operation of low volume roads. The role of maintenance is essentially to preserve the running surface and thereby reduce operating and reconstruction costs. The model offers the user the choice of six maintenance policies plus whatever he may
devise for himself.

The results of several experiments with the HCM have indicated that under conditions of high labor prices the best policy in terms of total maintenance and user costs is normal capital intensive, while if the shadow price of foreign exchange is high, normal labor intensive appears to be the best policy. If it is desired that road users pay a greater proportion of road transport costs, then, of course, poor maintenance policies could be used; if it is desired that they pay a smaller proportion, excellent maintenance would be most appropriate. It should be noted, however, that indications are that savings to the government due to poor maintenance policies are considerably less than the extra costs incurred by road users. This may not be true in contexts other than the Bolivia and Argentina scenarios, though, and the model user is urged to test this hypothesis by defining a staging strategy and examining the costs accruing to it when each of the six maintenance policies is used in conjunction with the staging strategy. In many cases he should find that total costs are lowest when normal or excellent maintenance is employed and that the savings due to poorer maintenance are overshadowed by increased user operating costs and the need (in some cases) for earlier reconstruction.

Assuming for the moment that there is no alternate
alignment suitable for examination, we are left with twenty-five alternate strategies suitable for investigation. This number can be further reduced by reference to the pruning rules of the previous chapter. For example, assuming that initial traffic conditions are those presented in Table 5, the pruning rules indicate that earth roads, and any road that has an earth surface and is later upgraded, are undesirable. Thus, the number of alternatives to be investigated has been reduced by a factor of two, with corresponding reductions in direct computer costs. The utility of using the pruning rules and the consequent cost reductions must be traded off against the knowledge that these pruning rules have been based solely on two sets of factor prices and terrain data, and may very well be inaccurate under different conditions. Again, it is recommended that the user gain familiarity with the model and modify those areas of the documentation that do not agree with his experience.

9. Search for the Optimal Road

This section will discuss in some detail the procedure to be followed in using the Highway Cost Model to select an optimal road design within the limit of precision provided by the HCM. The reader should recognize that "optimal" is used in the context of a local optima, that is, within the decision space examined rather than a global optima which
<table>
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<td>.003</td>
<td>9</td>
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</table>

Traffic Data Used in Bolivian Base Scenario

Table 5
would be the best of all possible roads. No techniques are known to exist that could find the latter. For the purposes of this examination, we shall continue to use the Bolivian data, along with the traffic projections and construction staging strategies already examined. It is expected that sufficient information will be presented to permit the reader to use the HCM effectively and accurately.

The examination of the twenty-five alternate staging strategies makes up the first iteration of the model. Figure 23 shows the total discounted costs accruing to each of these strategies and their relative rank.

The timing of reconstruction can cause significant changes in cost. In order to investigate these effects, a second run was made. The strategies chosen for this run (see figure 24) were similar to the best strategies of the previous run (numbers 11, 14, 18, 19, 22) except that the timing of reconstruction for the staged alternatives was altered by +2 and -3 years respectively. The costs accruing to these strategies are given in figure 25. Examination of these costs shows that the altered alternatives are more expensive than the original policies and should not be chosen for implementation.

Since a change in timing has been shown to be ineffective in this case, the next issue to consider is the maintenance policy. The third iteration answers the question
Figure 23
Costs of the first iteration
Staging Strategies for the Second Iteration

Figure 24
Figure 25

Costs of the Second Iteration

Total Discounted Cost ($10,000)

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<td>5</td>
<td>230</td>
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"will excellent or poor maintenance policy decrease the costs accruing to these strategies?" This can be investigated by means of the input shown in figure 26. The numbers following the design indicate the various maintenance policies, ranging from capital intensive to labor intensive and from poor to excellent. The figure shows the costs due to each of these maintenance strategies and indicates that an excellent capital intensive maintenance policy is the one to select if the measure of effectiveness is lowest net present worth.

10. Continuing the Iteration

At this point the user should ask whether to continue the search process or to halt it. There are two criteria that can be used to make this decision. The first is "are the expected costs of performing another run greater than the expected reductions in costs due to finding a better staging strategy?" The second is "do you feel that this strategy can be successfully implemented?" If the answer to either of these questions is "no", then the search pattern should be extended, another iteration performed, and the questions repeated.

11. Length of the Analysis Period

The model user can choose this parameter on the basis of several factors—for example, institutional requirements
Strategy Definition

1 Poor Capital Intensive
2 Normal Capital Intensive
3 Excellent Capital Intensive
4 Poor labor intensive
5 Normal Labor Intensive
6 Excellent Labor Intensive

Figure 26

Costs of the Third Iteration
such as those of A.I.D. or the World Bank.

The experience with the HCM indicates that the effect of varying the length of the analysis period is very much dependent on the context in which it is done. For example, extending the analysis horizon while examining gravel and asphalt roads will have different effects on the relative desirability of each road depending upon the growth rates of each vehicle class, the interest rate, the alignment (particularly the average grade), and the traffic level. Because of the multitude of factors involved in determining the effects of changes in the analysis horizon, no recommendations as to the sensitivity to this parameter can be made. However, it is suggested that the model user, upon finding an optimal strategy, repeat the last iteration while varying the analysis period plus and minus five years to see the effect these changes have on the determination of the optimal strategy.

12. Effects of Uncertainty in Traffic Projections

This section will discuss the effects of uncertain knowledge of future traffic levels on total costs, the distribution of costs among users, the road agency, and the optimal strategy for investment.

Uncertainty in traffic projections as used in this report refers to the three factors used to describe traffic:
1) the number of vehicles in year one, 2) the elasticity of demand, and 3) the annual growth rate, either in terms of vehicles per year or percent per year. For low volume roads, and especially for penetration roads, most of these factors will not be definitely known.

As variations from the estimates of these factors often occur in practice, and frequently cause the effectiveness of a road to be significantly diminished—a paved road, for example, being used by only thirty vehicles a day, or an earth road carrying one hundred seventy vehicles a day—it is desirable to decrease as far as possible the effects of uncertainty in the parameters.

13. Effects on Total Costs

As expected, the factor which had the greatest effect on total costs was the growth rate. The reason for this is quite clearly the compound growth caused by constant percentage increases in traffic. For example, if the estimated yearly growth rate for one vehicle class is eight percent while in reality it turns out to be only six percent, then (assuming inelastic demand) after twenty years the total traffic will be overestimated by approximately twenty-five percent, while the number of vehicles using the road in year twenty will be seventy percent of the original estimate. Table 6 shows the costs and numbers of vehicles using the Bolivian road under these conditions. It should be noted
<table>
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<th>Vehicle Class</th>
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<th>Vehicles in Year 20 G=8%</th>
<th>Ratio</th>
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<td>140</td>
<td>0.7</td>
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</table>

Effect of Inaccurate Growth Rates

Table 6
that although the total discounted road user costs have not shown a twenty-five percent change and while total costs are even less sensitive, there is a significant change in both categories.

The second factor that is significant here is the elasticity of demand. Elasticity of demand is a measure of how sensitive the number of vehicles using the road is to changes in road user cost (for example, the cost reductions due to running on a paved rather than a gravel surface). In a situation with very elastic demand, total traffic would be considerably greater on a paved road after twenty years than it would be on an earth or gravel road. (The relative increase is, of course, a function of the growth rate.) Table 7 shows the effects of different elasticities of demand on one class of vehicles for earth, gravel, and paved roads.

In order to compare alternative strategies when the traffic demand function is elastic, the concept of willingness to pay was introduced. Appendix B presents a brief description of this concept and its use in strategy evaluation. Willingness to pay, as Appendix B shows, makes it possible to compare roads carrying different traffic volumes, since willingness to pay calculations involve determining a "base per kilometer cost" for each type of vehicle against which all operating costs are measured. If for a given road and vehicle type the per kilometer operating costs are lower
### Number of Vehicles in Year 20 for Two Demand Elasticities

**Table 7**

<table>
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<th>Road Type</th>
<th>E=5%</th>
<th>E=1.2%</th>
<th>Ratio</th>
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<td>Gravel</td>
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<td>Paved</td>
<td>30</td>
<td>22</td>
<td>.73</td>
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than the base cost, the HCM subtracts the incremental willingness to pay from the total user costs. Similarly, if the per kilometer operating costs are higher the incremental willingness to pay is added to the user costs. The planner should recognize the necessity of using the same base strategy (and thus the same base costs) in all of his runs, or else he will introduce a bias into the succeeding iterations.

14. Initial Traffic Levels

This variable is perhaps as difficult to estimate as any of the parameters discussed in this section, but fortunately its effects can be readily discerned.

The relationship between total road user costs and the initial number of vehicles is

\[ UC = \sum_{i=1}^{K} a_i N_i \]

where \( a \) and \( N \) refer to a given class of vehicles operating on a certain road type and maintained to a given standard. Thus, if the initial estimate of traffic is doubled, user costs will also be doubled relative to the estimate. It should be noted that this is only true for similar construction strategies, and that there will be a slight variation due to faster deterioration of the road when it is used by heavier traffic and to the increased maintenance costs on that road.

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15. Effects on the Optimal Strategy

As the previous discussion has indicated, uncertainty in the planner's knowledge of future traffic conditions can cause the estimated costs to differ significantly from the costs which occur in actual practice. Obviously such changes will affect the choice of optimal investment strategy under many conditions, assuming that road user costs are included in the measure of effectiveness used in evaluating competing costs.

It is for this reason that the HCM offers the user the option of specifying, during a single run, one or more sets of initial traffic conditions so that he may 1) estimate the probability of the realization of each set, 2) define the properties of each set: elasticity, growth rate, and initial traffic, and 3) see the costs accruing to each set and the expected value of the costs computed by the formula

\[ E(C) = \sum_{i=1}^{n} P_i C_i \]

where \( P_i \) is the probability of realizing traffic set \( i \), \( C_i \) is the costs accruing to set \( i \), and \( n \) is the number of sets of traffic.

Through this process the model user is given the opportunity to see how the optimal strategy varies with initial traffic properties. Once this information has been obtained, several procedures can be followed. The simplest
procedure is to build the optimal road as defined using the expected costs determined from the equations presented above. Another approach would be to use that strategy which is optimal under the most likely (that is, having the highest probability of occurring) traffic set. A third procedure would be to select the strategy which has been ranked first more frequently than any other alternative. (If there is a tie for the greatest number of "firsts" then the one of these which also has the greatest number of "seconds" would be chosen, and so on.) In addition to these three selection procedures there are of course many other techniques; but it is recommended that the first approach be used for the following reasons: 1) In specifying the initial traffic sets and their probability of occurring, the user is attempting to describe a continuous distribution of traffic using a small number of points. In so doing it is very unlikely that an accurate description has been made because of human error and the incomplete data that must be used in preparing estimates. 2) Over the long run, the use of the "expected cost" best strategy will have the highest benefits (this was established by Pratt at al. in Statistical Decision Theory (54)). 3) The choice of a strategy on the basis of other than the expected costs implies that the user has not accurately assessed his estimates of the probability of occurrence of the traffic sets;
by choosing a different strategy from the one found using expected costs he signifies that he does not believe his original assessment of the probabilities. 4) Assuming that the range of traffic conditions is not too great, a similar strategy will probably be optimal for many of the initial sets of traffic.

Using this approach, the model user can expect that the optimal strategy will be closely approximated by the road he has chosen for construction, even though it may not be identical to the optimal strategy under traffic conditions that do prevail.

If the traffic that does materialize is considerably different from that which was expected, it may be worthwhile to use the model to estimate the costs which are incurred due to this new traffic and see how much the effectiveness of the link is reduced by the non-optimal design. If the reduction in effectiveness is considerable, it may be desirable to alter the design, either to the optimal design for the observed traffic level or to a design close to the optimal.

16. Road User Benefits

During the previous discussion of the use of the HCM the concept of benefits has only been discussed in conjunction with incremental willingness to pay. It should not be assumed, however, that it is being suggested that
roads be constructed solely on the basis of perceived costs. It is recognized that benefits will accrue to the economy as a result of road construction—benefits which are important factors in the decision to build a road. This subject is not explicitly considered because of the difficulty in defining, measuring, and evaluating the benefits accruing to a road; the realization that these benefits are very much a function of the use of the road, the location, the products it carries, cannot be expressed as a formal model.

To a limited extent, the incremental willingness to pay is a surrogate for these unmeasured benefits, and it is suggested that planners use the HCM in the early design process to seek out three or four construction strategies for further evaluation. The techniques presented here are designed for use at this stage of the design process; it cannot be emphasized too heavily that they should not be the basis of a final build-or-no-build decision. The HCM is a model with several well-defined areas requiring more research, and others requiring more sophistication. For this reason, its estimates should be utilized only in a clearcut role as estimates.
Chapter Seven

Conclusion

The Highway Cost Model can be a highly effective tool, providing fairly sophisticated planning for even the relatively inexperienced computer user. In the tradition of the "little black box", the model is able to perform this feat by internalizing its complexities.

An example of the model's internalized complexity can be seen in the communications section of the program. This subroutine can take as input a list of the model user's staging strategies, which are written in a form close to conventional English; for example, the user would specify a two-lane earth road by writing "EARTH2S". This list would then be converted by the subroutine into a two-dimensional array which would then be utilized by the network routine to decide what actions NETWRK should take. As figure 27 demonstrates, the communications subroutine can take a list of staging strategies such as the one shown in the top half of the figure and convert it into the array shown in the bottom half of the figure. The translation is accomplished by several hundred FORTRAN statements, which search a dictionary for the meaning of the user's commands and simultaneously keep track of the position of each of these commands in both time and space. STRAT can also, if necessary, redefine the dictionary; if local conditions (for
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### Action of the Communication Subroutine

**Figure 27**
example, very strong subsoils) exist, the model user can
tell the model to remove certain road designs from the
dictionary, and replace them with designs he feels are more
appropriate.

In addition to being simple, the model also makes al-
lowances for the inexperienced user by being self-checking;
if the model user specifies staging strategies incorrectly
the model will bring a message to this effect, and will not
execute the program at this time. For example, if the user
types a card saying, "15GRAVEL2 10EARTH2S," the model will
respond by saying, "STRATEGY 1 IS SPECIFIED INCORRECTLY."

But the model does not seek to eliminate the user; on
the contrary, it asks for his skill, knowledge, and exper-
ience as it searches for the best use to which the planner
can allocate his funds and energies. For example, the
model user is asked to define the staging strategies which
he feels are appropriate to the road under consideration,
and to evaluate each of these strategies. After evaluating
this first iteration, he is then asked to alter the best
strategies in a way that he feels will make them more ef-
fective; the model is thus at all times benefiting from the
user's practical experience and his knowledge of the area,
rather than merely seeking on its own some purely theoreti-
cal solution.

The HCM is a modest program; it does not overreach its
own limitations or inflate its estimates into hard-and-fast predictions. This can be especially valuable in an uncertain situation. It is hoped that further implementation of the model (see Appendix A) will make it possible for the model to increase its precision without sacrificing its flexibility.

In view of these advantages, it is suggested with some confidence that the HCM is an effective technique, which will be of service to planners in helping them to allocate scarce resources to road projects, thus aiding in the optimal economic development of emerging nations.
REFERENCES
REFERENCES


APPENDICES

A. Recommendations for Further Work
B. Willingness to Pay
C. Argentina And Bolivia Data
D. The Earthwork Models
E. Listing of the Highway Cost Model
Appendix A

Recommendations for Further Work

Although the Highway Cost Model has been used extensively in analyses of Argentine and Bolivian road projects, it has not yet been used during the actual planning of a low-volume road in a developing nation. It is suggested that the HCM be used in the preliminary design stages of an appropriate road. Because it will be desirable to compare the effectiveness of the HCM with standard practices, perhaps the best approach would be to perform parallel analyses using both approaches. If, after the analysis is complete, significant variations are found to exist between the solutions, it is recommended that the user reconsider carefully the assumptions which were made by the model and the engineering analyst who is using standard practice, and the planner should then attempt to reconcile the differences by modifying these assumptions where necessary.

Additionally, the HCM could be modified to operate in an interactive model on a time sharing system. This comparatively simple modification would make the planner an even more active force in seeking an optimal investment strategy and would probably decrease both the time and cost necessary to find the best strategy.

If field testing demonstrates that the HCM is useful in this context, it is recommended that further work be
performed to determine the accuracy of some of the more important relationships derived during the sensitivity analysis (DOT(57)), most particularly the relationship between velocity and road roughness. Also of importance is the problem of determining the culvert and drainage requirements and the relationship between frequency of blading unsurfaced roads and the observed roughness in inches per mile.
Appendix B

Willingness to Pay*

A short discussion of the supply and demand relationships of traffic will be used to explain the concept of willingness to pay and its use in strategy evaluation.

The idealized demand curve shown in figure 28 as CD indicates the number of vehicles that will travel between two points as a function of the user's perceived price of travel.

The supply curves for two strategies are labeled 1 and 2. These represent the perceived cost the user must pay (perceived user cost) as a function of traffic volume for each strategy. For strategy 1, the supply and demand curves intersect at point E. Thus $V_1$ vehicles use the road and each will have to pay the price $P_1$ in user costs. This results in a total cost to users of $(P_1)(V_1)$. This is represented by the area GEHO in figure 28. However, by definition, the demand curve is a representation of willingness to pay. Most of the users in volume $V_1$ would have been willing to pay more than the actual price $P_1$. The last user to make up the volume $V_1$ is represented in the demand curve at point E. He paid exactly what the trip was worth to him.

*This material is appended courtesy of its author, John Alexander.
Definition of Willingness to Pay

Figure 28
All the other users paid less than the trips were worth to them. The price they would have been willing to pay is represented by the portion of the demand curve between E and C. Presumably, the vehicle that wanted to use the road the most would have been willing to pay up to price $P_0$. The difference between the total that users would have been willing to pay, $CEHO$, and what they actually paid, $GEHO$, is called consumer surplus, area $CEG$. Since this is a savings to the users of the system, it is usually considered a user benefit in economic analysis.

If the same procedure is followed through for strategy 2, the user cost paid is represented by area $FJOI$, willingness to pay is area $CFJO$, and the consumer surplus is area $CFI$.

When comparing alternative strategies, the analyst is interested in the differences in costs and benefits. In the example, strategy 2 can be considered to have a net user benefit relative to strategy 1 equal to the change in consumer surplus. This is shown as the shaded area $EFIG$ in figure 28. The change in consumer surplus is used as the measure of net road user benefit for this study.

Change in consumer surplus, $EFIG$, is the difference between areas $GEFJO$ and $FJOI$. $FJOI$ represents the total road user cost paid for strategy 1 plus $EFJH$. Areas $CEHO$ and $CFJO$ have been shown to represent the total amounts.
that users are willing to pay at prices $P_1$ and $P_2$ respectively. EFJH is thus called the change in total willingness to pay, when going from strategy 1 to strategy 2. Therefore change in consumer surplus between two alternative strategies is

$$\Delta CS_{ij} = UC_1 + WTP_{1j} - UC_j$$

or

$$\Delta CS_{ij} = UC_1 - (UC_j - WTP_{1j})$$

where

$$\Delta CS_{ij} = \text{change in consumer surplus when changing from strategy } i \text{ to strategy } j$$

$$UC_i = \text{total user cost for strategy } i$$

$$UC_j = \text{total user cost for strategy } j$$

$$\Delta WTP_{1j} = \text{change in willingness to pay when changing from strategy } i \text{ to strategy } j.$$

As the previous section has suggested, the incremental willingness to pay increases in absolute value with increases in the elasticity of demand. As it can be considered a cost, it will affect the total costs of the road in question and make comparisons between alternate strategies slightly more complex and meaningful than they might otherwise be.

For the Bolivian traffic data previously presented (see page ) Table 7 shows the costs as calculated by the HCM. By comparing the column labelled "Ratio" in both tables it can be seen that for both demand curves costs are proportional to the number of vehicles using the road for
any single road type. However, slight differences do exist and these are caused by the incremental willingness to pay being different for the two demand curves. (Alexander(36))
Appendix C

Argentina and Bolivia Data

The following illustrations present a reproduction of the input data to the Highway Cost Model as echoed and annotated by the HCM of the base scenario for Argentina and Bolivia respectively.
### ARGENTINE DATA

**ALIGNMENT DATA-ALGN**

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**PROFILE DATA - PROF**

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**ROADWAY SECTION (VERTICAL)-PARK**

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**ROADWAY DESIGN DATA (VERTICAL)-PAV**

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**FOREIGN RATE OF EXCHANGE (PESOS) OR DOLLARS**

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**PERCENT OF LAYER COST**

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### TOPOGRAPHY - TOPOG

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**SOIL EROSION Converter**

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**DRAINAGE RELATED TO SUBWAY**

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**HAUL DISTANCES CONSTRUCTION**

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### Argentine Base Scenario Data

**Figure 29**

159
EARTHWORK
BORROW TRANSPORT PROD LCGST FQCGST
1.76 0.06 256.00 95.94 417.34

PAVEMENT
PROD SOURCE TRANSPORT LCGST FQCGST
400.00 1.86 0.00 67.52 147.20
163.00 22.30 0.01 96.23 207.77
387.00 65.70 0.00 151.61 441.16
163.00 22.30 0.00 96.23 207.77

DRAINAGE
NO. OF CULVERTS = 1.00
SCOST WEIGHT TROST
67.10 55.00 0.00
107.41 110.00 0.00
168.37 160.00 0.00

OTHER COMPONENTS
XTCOST SLABOR
0.00 0.00 0.00

MAINTENANCE COSTS AND PRODUCTIVITIES-MUC
MACH TRANSPORT TRAVEL MACHINERY ROLLER TRACTOR WATER
15.00 6.40 29.00 23.60 0.00 0.00 0.00
CLABOR FSTEER FOREMAN TANDER LIGHTING PADDLE COWHALL
2.45 5.40 6.70 6.90 0.00 0.00 0.00
DIESELFUEL GROCST GASGAST WATER
0.00 0.00 0.00 0.00

USER COSTS, ECON. AND MARKET-ECON. MARKET
LABORC DRIVER GASGAST OILSFL
1.50 1.99 0.14 0.14
3.00 3.99 0.37 0.37

INITIAL COST PEPH COST VEHICLE COST LABOR COST
FECNOM MARKET ECONOM MARKET ECONOM MARKET
1000.00 1600.00 97.00 130.00 2.70 3.10 0.0 0.0
2400.00 3000.00 47.00 80.00 1.90 1.50 0.0 0.0
3600.00 4000.00 300.00 470.00 2.30 2.30 0.0 0.0
4000.00 4000.00 490.00 600.00 2.70 4.10 0.0 0.0
3000.00 4000.00 500.00 700.00 2.20 4.10 0.0 0.0

VEHICLE DATA-VFF
OFFICE MEVENT WORKERS HARSERING INSPECTION CHRYSTAL FEUGHT VEHUNT AIRCFA. FUELTYPE
0.10E 01 0.10E 01 0.30E 05 0.24E 02 0.0 0.0 0.0 0.0 0.0 0.0
0.30E 01 0.30E 04 0.15E 04 0.15E 05 0.0 0.0 0.0 0.0 0.0 0.0
0.30E 01 0.30E 04 0.15E 04 0.15E 05 0.0 0.0 0.0 0.0 0.0 0.0
0.42E 01 0.24E 04 0.11E 05 0.12E 05 0.30E 02 0.0 0.0 0.0 0.0 0.0 0.0
0.40E 01 0.50E 06 0.30E 14 0.10E 33 0.74E 02 0.0 0.0 0.0 0.0 0.0 0.0
Bolivian Base Scenario Data

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Appendix D

The Earthwork Models

Earthwork costs are often the largest single construction cost component in low volume roads and they are often the hardest to estimate.

A wide variety of earthwork estimating techniques exist and considerable development has gone into computer aided roadway design systems. These systems are of high accuracy but require large amounts of input data. This is in contrast to the requirements of the HCM which can accept less accuracy so long as the input requirements are also reduced.

The earthwork models used in the HCM require as input the template and cross section of the pavement and either a series of stations taken along the center-line of the roadway or contour line densities which represent the rise and fall of the roadway.

The one point model uses as input the series of stations of both the roadway and terrain alignment taken along the center-line of the road. It computes earthwork quantities taking into account pavement design and the horizontal template of the roadway using the average end area approach. In this case the end areas at a
terrain station are determined by summing the trapezoidal sections across the roadway. Suitable consideration is given to problems caused by transitions from cut to fill and the need to maintain grades.

The contour line crossing density model was derived from work performed by Augusto Soux (52). This model estimates the earthwork volume required to bring a roadway alignment to grade as a function of the maximum allowable grade, road width, side slope, and the density of ten foot contours per mile.

The data base was generated using a simple one point terrain model and utilized 84 separate roadway designs through a wide spectrum of terrain types. Road profiles were fitted to these terrain profiles and adjusted by trial and error to yield a minimum earthwork design, while at the same time retain a balance between cut and fill.

The earthwork volumes were then plotted against contour density and curves were fitted to these data points with one for each maximum grade. The subroutine RFETH uses one set of the data developed and while it is properly sensitive to variations in design and topography the current version should be used with care as limitations in the data base and the orientation of Soux's study to high design standard roads may cause some
problems in transferring the results to low standard roads.

(The material in this appendix appeared in a different form in Working Paper 96 of the International Bank for Reconstruction and Development Economics Department. It was prepared by Messrs. Moavenzadeh, Stafford, Suhrbier, and Alexander of CLM Systems, Inc. (Consultants, Cambridge, Mass.) (64).)
Appendix E

Listing of the Highway Cost Model

The remainder of this appendix contains a listing of the routines MAIN, NETWRK, STRAT, SAVDAT, and CONSTR. These five routines make the cost estimating routines of the HCM a more effective and readily used tool for planners than it was initially.
MAIN PROGRAM OF THE HIGHWAY COST MODEL

THIS SET OF COMPUTER PROGRAMS WAS DESIGNED AND PROGRAMMED AT MIT

UNDER DCT CONTRACT OS-00996

INTEGER OU,OYRMOD,OTRACE,TPMF,OSWTH(3)
DIMENSION SUM(12),SUMD(12),OUTPT(12),TOTAL(12),
1 OUTPD(12),GROW(7),OUTFR(28),DOLAR(2),FOREX(7),FMONY(3)

COMMON/INOUT/IN,OU,IRCON,OYRMOD,OTRACE,TPMF,DISC,PNTPMF,IOIND
1,IODVD

COMMON/POLICY/ POL(30,20),COST(5,20),SAVE(20,170),RSTRT(30,4),
1 NODE(30,3),NRECON,NNODE,NSTRT,DLSIGN(27,12),CONCOS(30,4),
2 STRMPL(20,6)

COMMON/RMBR/ BCCS(7),ECOS(7),TGROWS,GROW,SUM,SUMD,TOTAL,TASK(12)
1,GTTL,GTTLD,STCST,CSTRT,OUTPT,OUTPD

COMMON STOR(963)

EQUIVALENCE (OSWTH(1),STOR(961))
IN=5
OU=6

READ(IN,12)OSWTH,OYRMOD,OTRACE,TGROWS,TPMF,MORE,IODVD

IF (TPMF.EQ.0)TPMF=1
IF(OYRMOD.EQ.0)OYRMOD=1
WRITE(OU,13)OSWTH,OYRMOD,OTRACE,TGROWS,TPMF

CALL PMIN
CALL STRAT
CALL ERASE(CONCOS,120)
CALL NETWRK
IF(MORE.NE.0)GO TO 1
CALL EXIT

12 FORMAT(512,8I5)
13 FORMAT('1 OUTPUT SWITCHES FOR THIS RUN ARE CONSTRUCTION',I3,'
MAINTENANCE',I3,' USER',I3/' OUTPUT IS PRINTED FOR YEARS THAT HCM 320
ARE A MULTIPLE OF',I3,' UNLESS THIS NUMBER',I3,' IS POSITIVE'/ HCM 330
THE TRAFFIC GROWTH SWITCH IS',I4,' AND THERE ARE',I3,' SETS OF HCM 340
INITIAL TRAFFIC CONDITIONS ASSOCIATED WITH THIS PROJECT ')
HCM 350
FORMAT('0 ***** ALL COSTS ARE FOR THE TOTAL LENGTH OF THE ROHCM 360
SECTION IN QUESTION ***** '/' ********PLEASE DISREGARD " PERHCM 370
KILOMETER " IN OUTPUT HEADINGS ')
HCM 380
END
HCM 390
SUBROUTINE NETWRK

THIS PROGRAM CAUSES THE DECISION NETWORK TO BE STEPPED THROUGH AS

INTEGER OU, OYRMOD, OTRACE, TGROWS, ONVEH, OSWTH(3), RBLD(11), TPMF,
1 RECON(25), STRT, YR, YRF, CCNST, YRICNT
REAL INT, MAPR(20), HDIST(10), MARK(32)
DIMENSION ALIGN(3), PROFI(104), TEMPL(15), PAVE(12), ROUGH(13),
1 DEMAN(7,3), TRAF(7), ECON(4), TOPOG(305), GOLGY(3), GRDCV(4),
2 DRAIN(8), PROD(54), ECONO(32), VEH(7,12), OUT(150), WORK(40),
3 UXYZ(25)
DIMENSION TRAFF(7,3), IOSWT(3), SAVMPL(20)
COMM /INOUT/IN, OU, IRCN, CYRMOD, OTRACE, RPMF, DISC, PNPMPF, IOIND
1, IODVD
COMMON/POLICY/ POL(30, 20), COST(5, 20), SAVE(20, 170), RSTRT(30, 4),
1 NODE(30, 3), NRECON, NNODE, NSTRT, DESIGN(27, 12), CONCOS(30, 4),
2 STPMPL(20, 6)
COMMON/RATEX/ FOREX(7), FMCNY(3), XRATE, OUTER(28), OUTFRS(28)
COMMON/RMBR/ BCOS(7), ECOS(7), TGRWS, GROW(7), SUM(12), SUMD(12),
1 TOTAL(12), TASK(12), GTRL, GTTLD, STCST(30, 8), CSTRT(30, 8), OUTPT(12),
2 OUTPD(12)
COMMON/RMBR2/ TRAFF2(7, 3)
COMMON ALIGN, PROF, TEMPL, PAVE, ROUGH, DEMAN, TRAF, NPER, ECON, MAPOL,
1 RBLD, TOPOG, GOLGY, CBP, GRDCV, DRAIN, HDIST, PROD, UXYZ, ECONO, MARK, NUVEH,
2 VEH, OUT, WORK, OSWTH
EQUIVALENCE(TRAFF(1, 1), DEMAN(1, 1)), (YRF, NPER), (INT, ECON(1)),
1 (OU, IPRNT)
DATA ICHBODD/5/

AT FIRST ENTRANCE INTO NETWRK STORE USER SPECIFIED MAINTENANCE

POLICIES IN SAVMPL

DO 71 IK = 1, 20
71 SAVMPL(IK) = MAPOL(IK)
WRITE(OU, 2018)
IF (TPMF.EQ.1) GO TO 2001
C NTPMF IS THE NTH SET OF INITIAL TRAFFIC CONDITIONS HAVING AN
C ASSOCIATED PROBABILITY OF OCCURRENCE PNTPMF
C TPMF= TPMF
C CALL ERASE( STCST,240)
C STATEMENT 2012 IS THE STARTING POINT OF THE LOOP ASSOCIATED WITH
C UNCERTAINTY IN PREDICTIONS OF INITIAL TRAFFIC
2012 READ(IN,2013) PNTPMF
WRITE(OU,2014) PNTPMF
C 2001 CONTINUE
C YR1CNT IS USED TO PERMIT THE USE OF TO SUPPLY DEMAND CURVES ONCE
C YR1CNT=-1
C NNODE IS THE # OF NODES IN THE DECISION NETWORK
C NRECON IS THE # OF RECONSTRUCTIONS
C NSTRT IS THE # OF STAGING STRATEGIES
C STRT IS THE STRATEGY BEING EXAMINED
C
C START INITIALIZATION OF VARIABLES
CS=0.
STRT=1
YR=1
C CONST IS A POINTER TO THE CONSTRUCTION ACTIVITY BEING PERFORMED
C THE ARRAY POINTED AT IS RSTRT
C
C INITIALIZE THE ARRAY POINTED AT RSTRT
CONST =0
IOSWT(2)= OSWTH(2)
IOSWT(3)= OSWTH(3)
WORK(33) =0.
WORK(35)=0.
WORK(37)=0.
C INITIALIZE OF ARRAYS
C
C INITIALIZE OF ARRAYS
C CALL ERASE ( TRAF,7,SUM,12,SUMD,12,OUTPT,12,OUTPD,12, TOTAL,12,
1 RECON,25)
C END VARIABLE INITIALIZATION
DISC = 1./((1.+INT)**YR)
IF(OTRACE.GT.0) GO TO 931
WRITE ( IPRNT,105 ) YR,DISC ,STRT
931 CONTINUE
IOIND=1
C CHECK IF THIS RUN IS NOT SPECIFIED USING THE TREE STRUCTURE
IF((NSTRT.EQ.0).AND.(YR.EQ.1)) GO TO 901
GO TO 1
S01 IOP=0
C ENTER ROUTINE CONSTR AT ENTRY SIMCON FOR SIMPLE CONSTRUCTION
CALL SIMCON(IOP)
GO TO 9C11
C CONTINUE
1 I IS THIS A NODE
DO 12 I= 1,NNODE
IF((NODE(I,1).EQ.YR).AND.(NODE(I,2).EQ.STRT)) GO TO 13
CONTINUE
12 I IS THE NODE
IJ=I
TYPE= 1
C SAVE ROAD AND TRAFFIC PROPERTIES
CALL SAVDAT (STRT,YR,IJ,TYPE)
14 CONTINUE
C IS THIS (STRATEGY,YEAR) A RECONSTRUCTION PERIOD
DO 9 I =1,NRECON
IRS1= RSTRT(I,1)+.01
IRS4= RSTRT(I,4)+.01
IF (((IRS1.EQ.YR).AND.(IRS4.EQ.STRT)) GO TO 10
CONTINUE
GO TO 112
C I IS THE # OF THE RECONSTRUCTION
C
10 CONST= CONST +1
C CALL CONSTRUCTION COSTING ROUTINES
C
44 CALL CONSTR(STRT,YR,IJ,CCNST,ICHIND)
C
C SELECTION OF MAINTENANCE POLICY
C
C TRANSFER USER SUPPLIED MNTPOL
K=I
70 IF( RSTRT(K,3) .GE. 0.1 ) GO TO 73
DO 72 IK=1,20
72 MAPOL(IK)= SAVMPL(IK)
GO TO 74
C TRANSFER PROGRAM SUPPLIED MNTPOL
73 JKK= RSTRT(K,3) +.01
DO 75 IK=1,20
75 MAPOL(IK)= STRMPL(IK,JKK)
74 IF(YR .EQ. 1) GO TO 112
C INDICATE TO MAINT THAT CONSTRUCTION HAS OCCURRED
RECCN(YR-1)= 1
C CHECK IF PREVIOUS CONSTRUCTION WAS THE NULL ALTERNATIVE
IF((CONST .EQ. 1) .OR. (RSTRT(CONST-1,2).GT.1.)) GO TO 112
DO 11 IZ=1,NUVEH
DO 11 IT=1,3
11 TRAFF(IZ,IT)= TRAFF2(IZ,IT)
112 CONTINUE
C CHECK IF THE NULL ALTERNATIVE IS BEING EXAMINED
IF(RSTRT(CONST,2).LE.1.1 ) GO TO 141
C USE THIS SECTION IF LINEAR STRATEGY SPECIFIED
9011 CONTINUE
C CALCULATIONS OF USER COSTS
CALL USER (YR,YRICNT)
C IF(YR.EQ.1) WRITE(OU,1029) YR,((TRAFF(IZ,IT),IT=1,3),GROW(IZ),
1 IZ=1,NUVEH )
C CALCULATIONS OF MAINTENANCE COSTS
CALL MAINT(YR,RECON)
C C SUM MAINTENANCE AND OPERATING COSTS
C CHECK ON FORM OF OUTPUT
DIVIS=ALIGN(1)
IF(IODVD.NE.0) DIVIS=1.
DO 1341 I=5,8
1341 OUTPT(I)= OUT(I+71)/DIVIS
1344 OUTPT(9)= OUT(103)
OUTPT(10)=OUT(102)
OUTPT(11)=OUT(104)
OUTPT(12)=OUT(101)
C CHECK ON FORM OF OUTPUT
IF ( IODVD.EQ.0) GO TO 1345
DO 1346 I=9,12
1346 OUTPT(I)= OUTPT(I)* ALIGN(1)
1345 DO 1342 I=5,12
OUTPD(I)=OUTPT(I)*DISC
SUM(I)=SUM(I)+ OUTPT(I)
1342 SUMD(I)= SUMD(I)+ OUTPD(I)
C TOTAL(5)= OUTPT(5)+ OUTPT(6)+ OUTPT(7)
TOTAL(6)= OUTPD(5)+ OUTPD(6)+ OUTPD(7)
TOTAL(7)= SUM(5)+ SUM(6)+ SUM(7)
TOTAL(8)= SUMD(5)+ SUMD(6)+ SUMD(7)
TOTAL(11)=SUM(9)+SUM(10)+SUM(11)+SUM(12)
TOTAL(12)=SUMD(9)+SUMD(10)+SUMD(11)+SUMD(12)
TOTAL(9)=OUTPT(9)+OUTPT(10)+OUTPT(11)+OUTPT(12)
TOTAL(10)=OUTPD(9)+OUTPD(10)+OUTPD(11)+OUTPD(12)
GTTL= TOTAL(3) + TOTAL(7) + TOTAL(11)
GTTLD= TOTAL(4) + TOTAL(8) + TOTAL(12)
IF ((YR.EQ.YRF).AND.(OTRACE.GT.0)) GO TO 504
IF(OTRACE.GT.0) GO TO 932
IF(IOIND.LT.0.5) GO TO 932
C
IF(OSWTH(2).LT.1) GO TO 1026
IF(IODVD.EQ.0) GO TO 1027
C
COMPUTE EFFORT REQUIRED FOR ENTIRE ROADWAY
DO 2019 IK=1,12
2019 TASK(IK)= TASK(IK)*ALIGN(1)
1026 CONTINUE
C
IF(OSWTH(3).LT.1) GO TO 504
C
PRINT DETAILED USER OPERATING COST DATA
505 WRITE(IPRNT,5002) (OUT(I),I=105,146),(TRAF(I),I=1,7)
C
504 CONTINUE
WRITE(IPRNT,304) (OUTPT(I),OUTPD(I),SUM(I),SUMD(I),OUTPT(I+4),OUTPNET 2000
1D(I+4),SUM(I+4),SUMD(I+4),I=5,7) ,OUTPT(12),OUTPD(12),SUM(12),SUMDNET 2010
1(12) , (TOTAL(LL),LL=5,12 )
5033 CONTINUE
932 CONTINUE
C
FOREIGN COST FOR MAINTENANCE EQUIPMENT
IF(ECON(2).GT.0.) GO TO 621
OUTFR(17) =OUTPT(6)*FOREX(7)
OUTFR(18)=OUTPD(6)*FOREX(7)
OUTFR(19)=SUM(6)*FOREX(7)
OUTFR(20) =SUMD(6)*FOREX(7)
C
FOREIGN CAPITAL USED IN OPERATING MODEL
WORK(33)=WORK(32) +WORK(33)
WORK(35)=WORK(34) +WORK(35)
WORK(37)=WORK(36) +WORK(37)
OUTFR(21)=WORK(32)*FOREX(1)+WORK(34)*FOREX(2)+WORK(36)*FOREX(3)
OUTFR(22)=OUTFR(21)*DISC
OUTFR(23) = WORK(33) * FOREX(1) + WORK(35) * FOREX(2) + WORK(37) * FOREX(3)
OUTFR(24) = OUTFR(23) * DISC
C TOTAL FOREIGN CAPITAL COSTS
OUTFR(25) = OUTFR(17) + OUTFR(21)
OUTFR(26) = OUTFR(18) + OUTFR(22)
OUTFR(27) = OUTFR(15) + OUTFR(19) + OUTFR(23)
OUTFR(28) = OUTFR(16) + OUTFR(20) + OUTFR(24)
IF(YR.EQ.1) GO TO 333
GO TO 334
333 OUTFR(25) = OUTFR(25) + OUTFR(15)
OUTFR(26) = OUTFR(26) + OUTFR(16)
334 CONTINUE
C COMPUTE COSTS IN DOLLARS
DO 5034 I=17,28
5034 OUTFRS(I) = OUTFR(I) * XRATE
IF((YR.EQ.YRF) .AND. (OTRACE.GT.0)) GO TO 5032
IF((OTRACE.GT.0).OR.(IOIND.LT.0.5)) GO TO 933
C PRINT OUT FOREIGN COSTS
5032 WRITE(IPRNT,600C) YR,FMONY,(OUTFR(I),I=17,28)
621 IF((OTRACE.GT.0).OR.(IOIND.LT.0.5)) GO TO 933
C WRITE(IPRNT,310) GTTL, GTTLD
933 CONTINUE
C STEP TO NEXT TIME PERIOD
141 CONTINUE
C CHECK FOR END OF ANALYSIS
YR= YR+1
C THIS SECTION LIMITS OUTPUT TO YEARS ZERO MODULO INTM
MODK = MOD(YR,YR%INTM)
IF(MODK.EQ.0) GO TO 704
OSWTH(2)= 0
OSWTH(3) = 0
IOIND = C
GO TO 706

704 OSWTH(2) = IOSWT(2)
OSWTH(3) = IOSWT(3)
IOIND = 1
IF (OTRACE .LE. 0) WRITE (OU, 2018)

706 CONTINUE
IF ((OTRACE .GT. 0) .OR. (IOIND .LT. 0.5)) GO TO 934
WRITE (IPRNT, 105) YR, DISC, STRT

934 CONTINUE
C
IF (NSTRT .EQ. 0) GO TO 9011
GO TO 1
C
C THIS STRATEGY HAS BEEN EXAMINED
C STORE THE COSTS DUE TO THIS STRATEGY IN ARRAY CSTRT
C
714 CONTINUE
C INDICATE TO USER AND CONSTR THAT THE FIRST DEMAND CURVES HAVE
C BEEN READ AND THAT USER SHOULD NOT READ ANOTHER SET
YRCNT = YRCNT + 2
C
YR = YR - 1
WRITE (OU, 1029) YR, (TRAFF(IZ, 1), OUT(IZ + 125), TRAFF(IZ, 3), GROW(IZ),
IZ = 1, NUVEH )
CSTPT (STRT, 1) = TOTAL(3)
CSTRT (STRT, 2) = TOTAL(7)
CSTRT (STRT, 3) = TOTAL(11)
CSTRT (STRT, 4) = GTTL
CSTRT (STRT, 5) = TOTAL(4)
CSTRT (STRT, 6) = TOTAL(8)
CSTRT (STRT, 7) = TOTAL(12)
CSTRT (STRT, 8) = GTTLD
C
C ZERO THE RECONSTRUCTION ARRAY
CALL ERASE (RECON, 25)
IOIND=1
C ARE ANY NODES ON THIS STRATEGY UNEXAMINED
CONST= CONST+1
IF(CONST.GT.NRECON) GO TO 40
IF(NRECON.EQ.0) GO TO 40
YR= RSTRT(CCNST,1)
S1= RSTRT(CONST,4)
IS1= S1+.01
DISC = 1./((1.+INT)**YR)
WRITE(OU,1051) IS1,YR,DISC
C LOCATE THE NODE TO BE RESTORED
C
421 DO 42 K=1,NNODE
42 IF(NODE(K,2).EQ.IS1) GO TO 41
423 IS1=IS1+1
41 CONTINUE
K1=K
411 IF(NODE(K1,1).EQ.YR) GO TO 441
412 K1= K1+1
IF( K1.GT.NNODE) GO TO 423
GO TO 411
C CONTINUE
C THE NODE # IS SET EQUAL TO K1
C
441 CONTINUE
C TYPE=-1
C COMPUTE EXPECTED COSTS DUE TO UNCERTAINTY
C
CALL SAVDAT(IS1,YR,K1,TYPE)
STRT= S1+.01
GO TO 44
443 WRITE(OU,201) YR,S1
RETURN
40 CONTINUE
IF( TPMF.GT.1) WRITE(OU,2015) PNTPMF
WRITE(OU,100) ( K,(CSTRT(K,J),J=1,8),K=1,NSTRT )
WRITE(OU,1771) ( K1,(POL(K1,K2),K2=1,16),CSTRT(K1,8),K1=1,NSTRT) NET 3250
C
IF( TPMF.EQ.1) RETURN
C
COMPUTE EXPECTED COSTS DUE TO UNCERTAINTY IN TRAFFIC PROJECTIONS
DO 2016 K1= 1,NSTRT
DO 2016 K2= 1,8
STCST(K1,K2) = STCST(K1,K2)+ PNTPMF*CSTRT(K1,K2)
NTPMF= NTPMF-1
IF( NTPMF.GE.1) GO TO 2012
WRITE(OU,2017)
WRITE(OU,100) ( K,(STCST(K,J), J=1,8),K=1,NSTRT)
WRITE(OU,1771) ( K1,(POL(K1,K2),K2=1,16),STCST(K1,8),K1=1,NSTRT) NET 3370
RETURN

FORMAT STATEMENTS
100 FORMAT('0 COSTS FOR THIS RUN ARE ''//
1 T30, ' UNDISCOUNTED ', T75,' DISCOUNTED ' /
A ' STRATEGY', ' CONSTRUCTION MAINTENANCE OPERATING TOTAL',NET 3430
1 5X, ' CONSTRUCTION MAINTENANCE OPERATING TOTAL' NET 3440
B // ( I5, 8F14.0 )
NET 3450
105 FORMAT('0 YEAR',I3,' DISCOUNT FACTOR',F7.3,' STRATEGY', I3) NET 3460
201 FORMAT('0 ERROR IN RECONSTRUCTION LIST, CANNOT FIND RECONSTRUCTIONNET 3470
1 AT YEAR',I5,' STRATEGY',F10.0) NET 3480
304 FORMAT(1HO,T30,' MAINTENANCE COSTS ($/KM)',T80,' OPERATING COSTS ($/NET 3490
1KM)' //T22,2('TNET 3500
2THIS PERIOD',14X,' SUM TO DATE',8X)/T16,4('ACTUAL DISCOUNTED ' NET 3510
3)/
4 ' LABOR',T12,8F12.0/' EQUIPMENT',T12,8F12.0/' MATERIAL',T12,8F12.0NET 3530
5 ' INCREMENTAL WILLINGNESS TO PAY',T60,4F12.0' TOTAL',T12,8F12.0) NET 3540
310 FORMAT( '0 SUM OF ALL COSTS TO DATE($/KM) ACTUAL DISCNET 3550
1OUNTED '/T33,2F15.0 ) NET 3560
**OPER KILOMETER MAINTENANCE COSTS BY TASK**

<table>
<thead>
<tr>
<th>1</th>
<th>REGRAVEL ROADSIDE MOW DRAINAGE BLD WET</th>
<th>PATCH CLDMIX HANET</th>
</tr>
</thead>
<tbody>
<tr>
<td>2UL CLDMIX SEAL CRK</td>
<td>/9F12.0</td>
<td>Haul Aggrgt Pitch Rut Haul RNet</td>
</tr>
<tr>
<td>3UTPTCH SHOULDER</td>
<td>/7F12.0</td>
<td></td>
</tr>
</tbody>
</table>

**TRAFFIC IN YEAR**

- VEHICLES /DAY BASE COST$/KM ELASTICITY GROWTH RATE

**START OF ANALYSIS FOR STRATEGY**

- IT IS YEAR, IT IS YEAR

**STRATEGIES AND COSTS**

<table>
<thead>
<tr>
<th>STRATEGY DESCRIPTION</th>
<th>TOTAL DISCOUNTED COST</th>
</tr>
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<tbody>
<tr>
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</tbody>
</table>

**THE ANALYST SPECIFIED PROBABILITY ASSOCIATED WITH THE INITIAL TRAFFIC CONDITIONS IS**

**THE USER SPECIFIED PROBABILITY ASSOCIATED WITH THESE COSTS IS**

**THE EXPECTED COSTS OF ALL STRATEGIES ARE AS FOLLOWS**

### Detailed Output for User Cost Model

- **Labor Hours**: 19X, 7F10.3
- **Velocity, KPH**: 17X, 7F10.3
- **Fuel Consumption, Liters**: 6X, 7F10.3
- **Market Cost, Dollars**: 7F10.3
- **Parts Cost Factor per 1000 KM**: 1X, 7F10.3
- **Inc. Will Net**: 300

- **Number of Vehicles**: T30, 7F10.1

**Foreign Exchange Costs for Year**: 12

- **Are**: T31, **This Period**: T60, **Sum To Date**: T26, **Actual**: T41

**Grand Total**: T21, 4F15.1

**END**
SUBROUTINE STRAT

This routine reads the reconstruction staging data

INTEGER OU, OYRMO, OTRACE, TGROWS, DNVEH, OSMTH(3), RBLD(11), TPMF

DIMENSION ALPHA(11,2)
DIMENSION RSTRT(30,4), NODE(30,3), POL(30,20), COST(5,20),
1 SAVE(20,170), DESIGN(27,12)

COMMON/INOUT/ IN, CU, IRCON, OYRMO, OTRACE, TPMF, DISC, PNTPMF, IOIND
COMMON/POLICY/ POL, COST, SAVE, RSTRT, NODE, NRECON, NNODE, NSTRT, DESIGN
1 , CONCCS(30,4)
COMMON/YRCOST/YRCS(5)

C

EQUIVALENCE( IPRNT, OU)
EQUIVALENCE( NSTRAT, NSTRT)

C

NNODE = # OF NODES
NRECON IS THE # OF CONSTRUCTION PERIODS
NSTRT IS THE NUMBER OF STAGING STRATEGIES

DATA ALPHA /'NULL','EART','EART','EART','GRAV','GRAV','GRAV','SURF','SURF','ASPH',
1 'EART','GRAV','SURF','ASPH', ', ', 'H1S','H2S','EL1S','EL2S',
2 'ACES','ALTS','K2 ', 'EL2 ', 'ACE ', 'ALT ' /

C

NALPH IS # OF ROAD DESIGNS IN STORAGE
DATA NALPH/12/

YRCS(1)= -1
READ(IN,15) NSTRAT, NEXDS, IDESSW

15 FORMAT(8I10)
WRITE(OU,351) NSTRAT, NEXDS
351 FORMAT('1 THE NUMBER OF RECONSTRUCTION STRATEGIES IS ',5I5,' AND TH',5I5)

C

NSTRT IS THE NUMBER OF STAGING STRATEGIES
NRECON = 0
IF (NSTRAT.EQ.0) GO TO 199

C

INITIALIZE ARRAYS
CALL ERASE( RSTRT, 120, POL, 600, NODE, 90 )
C CHECK IF NEW DESIGN IS DESIRED
   IF ( IDESSW .EQ. 0 ) GO TO 84
   DO 82 IZ = 1, IDESSW
      READ (IN, 15) ID
      WRITE (OU, 83) ID
      READ (IN, 80) ALPHA (ID, 1), ALPHA (ID, 2)
      WRITE (OU, 81) ALPHA (ID, 1), ALPHA (ID, 2)
      READ (IN, 831) (DESIGN(I, ID), I = 1, 11)
      READ (IN, 831) (DESIGN(I, ID), I = 16, 27)
      WRITE (OU, 802)
      WRITE (OU, 830) (DESIGN(I, ID), I = 1, 11)
      WRITE (OU, 803)
  82 CONTINUE
C WRITE (OU, 174 )
   DO 175 I = 1, NSTRAT
      READ (IN, 176) (POL(I, J), J = 1, 16)
      WRITE (OU, 177) (POL(I, J), J = 1, 16)
  175 CONTINUE
   N = 0
   IF ( NEXDS .LE. 0 ) GO TO 180
   N = N + 1
   READ (IN, 179) YRCS(N)
   WRITE (OU, 1792) YRCS(N)
   READ (IN, 179) (COST(N, J), J = 1, 20)
   NEXDS = NEXDS - 1
   GO TO 178
  180 CONTINUE
C THE REMAINING SUBROUTINES
   NRECON = 0
   N = NRECON
C INITIALIZE COUNTERS
J=0

150 J=J+1
J4=-3
IF(J.GT.NSTRT) GO TO 190

151 J4=J4+4
IF(J4.GT.17) GO TO 150
C TEST FOR DESIRED RECONSTRUCTION
IF( POL(J,J4).EQ.0) GO TO 151
C FIND PROPERTIES OF THIS RECONSTRUCTION
C INCREMENT RECONSTRUCTION COUNTER
NRECON= NRECON+1
N= NRECON
C YEAR
RSTRT(N,1) = POL(J,J4)
C RECONSTRUCTION TYPE
I=0

155 IF( I.GE.NALPH) GO TO 152
I=I+1
IF( POL(J,J4+2).NE.ALPHA(I,2)) GO TO 155
RSTRT(N,2) =I
C MAINTENANCE POLICY
RSTRT(N,3)= POL(J,J4+3)
C STRATEGY
RSTRT(N,4)= J
GO TO 151
C
C ERROR IN INPUT DATA
1521 WRITE(OU,153) J1
CALL EXIT
C
152 WRITE(OU, 153) J
CALL EXIT
C
C WRITE ARRAY RSTRT ON PRINTER
190 WRITE(OU,191)
WRITE(OU,192) ( I,(RSTRT(I,J),J=1,4),I=1,NRECON)
C THIS SECTION LOCATES NODES IN THE DECISION NETWORK
C NODES ARE POINTS WHERE TWO OR MORE ALTERNATIVES EXIST
C I IS THE NODE NUMBER
C THE SUBSCRIPT J REFERS TO STRATEGIES
IF ( NSTRAT.EQ.0) GO TO 199
NODYR1=-1
I=0
J=1
197 J4=-3
J=J+1
IF ( J.GT.NSTRAT ) GO TO 194
C LOCATE BRANCHES
195 J4=J4+4
IF ( POL(J,J4).EQ.0) GO TO 195
C LABEL NODES
I=I+1
NODE (I,1)= POL(J,J4)
IF ( NODE(I,1).EQ.1) GO TO 207
C LOCATE MAIN BRANCH
J1=J
196 J1=J1-1
IF ( J1.EQ.0) GO TO 1521
J14=J4
198 J14= J14-4
199 IF ( J14.LT.1) GO TO 196
IF ( POL(J1,J14).EQ.0) GO TO 1981
NODE (I,2)=J1
NODE(I,3)= NODE(I,3)+1
C CHECK IF THIS NODE HAS BEEN PREVIOUSLY IDENTIFIED
203 JI= I-1
IF ( JI.EQ.0) GO TO 197
IF ( NODE(I,1).EQ.NODE(I1,1) ) GO TO 205
GO TO 197
205 IF ( NODE(I,2).EQ.NODE(I1,2) ) GO TO 204
GO TO 197
C UPDATE NUMBER OF BRANCHES FROM NODES I, I-1
204 NODE(I,3) = NODE(I,3) - 1
205 NODE(I+1,3) = NODE(I+1,3) + 1
C RESET NODE COUNTER
206 I = I-1
207 GO TO 197
C THIS SECTION IS USED WHEN A STRATEGY IS SPECIFIED IN YEAR 1
208 CONTINUE
209 IF (NODYR1.LT.0) GO TO 209
C A BRANCH FROM YEAR 1 HAS BEEN FOUND PREVIOUSLY
210 NODE(KNOYR1,3) = NODE(KNOYR1,3) + 1
C DECREASE NODE COUNTER
211 I = I-1
212 GO TO 197
C THIS IS FOR FIRST BRANCH FROM YEAR 1
213 IF (POL(KI,1).EQ.0) GO TO 213
214 NODE(I,2) = KI
215 NODE(I,3) = NODE(I,3) + 1
216 KNOYR1 = I
217 NODYR1 = 1
218 GO TO 197
C WRITE OUTPUT DATA
C
C NNODE IS THE NUMBER OF NODES IN THE DECISION NETWORK
194 NNODE = I
195 WRITE(OU,200) I, ((NODE(J,K), K=1,3), J=1, I)
202 RETURN
199 WRITE(CU,193)
RETURN
C FORMAT STATEMENTS
8C FORMAT(2A4)
THE USER SPECIFIED DESIGN IS '2A4 / ' IT HAS THE FOLLOWING CHARACTERISTICS

DATA FOR USER SPECIFIED DESIGN #', I5)

RECONSTRUCTION STRATEGY ', I4,' IS IMPROPERLY SPECIFIED'

ORFCONSTRUCTION STRATEGIES'

1 MAINT. POLICY STRATEGY '

1 NO RECONSTRUCTION THIS RUN '

NUMBER OF NODES IS ', I3 /( ' YEAR STRATEGY BRANCHES')/

YEAR, TYPE

MAINT. POLICY STRATEGY '

NUMBER OF NODES IS ', I3 /( ' YEAR STRATEGY BRANCHES')/

YEAR, TYPE

WIDTH SLOPE SHLD-WD SHLD-SL DTH-WD DTHSTRA1950

1-SL DTH-WD DTH-SL CUT-SL FILL-SL PAVE-WD SIDE-CL'

PAVE-CD LAYERS MAT-TPE THICKNESS MAT-TPE THICK1

THICK SHLD-TPE THICK2 THICK3'

THICK1 THICK2 THICK3'

12F10.2)

8F10.2)

F10.0)

THESE COSTS ARE FOR YEAR', F10.0)

END
SUBROUTINE SAVDAT (STRT, YR, IJ, TYPE)

C THIS PROGRAM STORES AND RESTORES ROAD AND TRAFFIC CONDITIONS AT NOD

INTEGER STRT, YR, OUT

DIMENSION RSTR (30, 4), NODE (30, 3), POL (30, 20), COST (5, 20),

SAVE (20, 170), DESIGN (27, 12)

COMMON /POLICY/ POL, COST, SAVE, RSTR, NODE, NRECON, NNODE, NSTRT, DESIGN

COMMON /CONCOS/ (30, 4)

COMMON STOR (963)

COMMON /PMBR/ STOR2 (58)

COMMON /INOUT/ IN, OUT

C IF TYPE IS NEGATIVE THIS IS A RESTORE
C IF TYPE IS POSITIVE THIS IS A SAVE

IF (TYPE) 1, 2, 3

C RESTORE ROAD CONDITIONS
C PAVEMENT TEMPLATE AND TRAFFIC LEVELS

DO 11 I = 1, 67

STOR (107 + I) =SAVE (IJ, I)

PRODUCTIVITY

DO 10 I = 68, 107

STOR (920 + I - 67) = SAVE (IJ, I)

C TRAFFIC DEMAND AND ELASTICITY

DO 9 I = 108, 165

STOR2 (I - 107) = SAVE (IJ, I)

WRITE (OUT, 12) STRT, YR, IJ

RETURN

C SAVE ROAD CONDITIONS

DO 111 I = 1, 67

SAVE (IJ, I) = STOR (107 + I)

DO 101 I = 68, 107

SAVE (IJ, I) = STOR (920 + I - 67)

DO 92 I = 108, 165

SAVE (IJ, I) = STOR2 (I - 107)

WRITE (OUT, 31) STRT, YR, IJ

RETURN
FORMAT STATEMENTS

12 FORMAT('ROAD AND TRAFFIC CONDITIONS HAVE BEEN RESTORED',
   ' STRATEGY ', I3, '
   ' YEAR ', I3, '
   ' NODE NUMBER ', I3 )

31 FORMAT('ROAD AND TRAFFIC CONDITIONS HAVE BEEN SAVED ',
   ' STRATEGY ', I3, '
   ' YEAR ', I3, '
   ' NODE NUMBER ', I3 )

END
SUBROUTINE CONSTR(STRT, YR, IJ, CONST, YRCNT)

THIS ROUTINE CAUSES THE CONSTRUCTION AND RECONSTRUCTION (WHEN
DESIRED) OF A ROAD. IT THEN COMPUTES THE ACCRUED COSTS
PRINTS THESE COSTS AND THEN RETURNS CONTROL TO ROUTINE NETWRK OR
ROUTINE CONSTRU. THE ENTRY POINT SIMCON IS USED FOR 'SIMPLE'
CONSTRUCTION. IT IS THIS POINT THAT IS CALLED BY DETE WHEN
RESURFACING OF AN ASPHALT OR SURFACE TREATED ROAD IS REQUIRED
INTEGRAL DU, DYMOD, DTRACE, TGROWS, DONVEH, OSWSH(3), RBLD(11), TPMF,
RECON(25), STRT, YR, YRF, CONST, YRCNT
REAL INT, MAPOL(20), HDIST(101), MARK(32)
DIMENSION ALIGN(3), PROF(104), TEMPL(15), PAVE(12), ROUGH(13),
Deman(7,3), TRAF(7), ECON(4), TOPOG(305), GOLGY(3), GRDCV(4),
DRAIN(8), PROD(54), ECONO(32), VEH(7,12), OUT(150), WORK(40),
UXYZ(25)
COMBOM/INU1/IN, OU, IRCON, DYMOD, DTRACE, TPMF, DISC, PNTPMF, IOIND
1, IOVDO
COMBOM/POLICY/ POL(30,20), CCST(5,20), SAVE(20,170), RSTRT(30,4),
NODE(30,3), NRECON, NNODE, NSTRT, DESIGN(27,12), CONCOS(30,4),
STPMPL(20,6)
COMBOM/RATEX/ FOREX(7), FMONY(3), XRATE, OUTFR(28), OUTFRS(28)
COMBOM/FMBP/ BCOS(7), ECOS(7), TGROWS, GROW(7), SUM(12), SUMD(12),
TOTAL(12), TASK(12), GTTL, GTTLD, STCST(30,8), CSTRT(30,8), OUTPT(12)
OUTPD(12)
COMBOM/YRCOST/YRCS(5)
COMBOM ALIGN, PROF, TEMPL, PAVE, ROUGH, DEMAN, TRAF, NPER, ECCN, MAPOL,
RBLD, TOPOG, GOLGY, CBR, GRDCV, DRAIN, HDIST, PROD, UXYZ, ECONO, MARK, NUVEH
VEH, OUT, WORK, OSWSH
EQUIVALENCE ( OU, IPRNT )
DATA INSUB/12/
DATA ICPO, IOP1 / 7, 7 /
K=CONST
IJ=K
WRITE(OU,1) K, (RSTRT(K,J),J=1,4 )
FORMAT ( '0 CONSTRUCTION # YEAR TYPE MAINTPOL CON 390
1 STRATEGY / T20, I5, 2( 2F10.0, F10.0 )
C
JQ = RSTRT(IJ, 2)
IOP = 0
IF( JQ.GT.IOPO ) IOP = 1
IF( JQ.GT.IOP1 ) IOP = 2
C
CHECK IF THIS IS NEW OR PAVEMENT CONSTRUCTION
IF((IOP.EQ.0).OR.(IOP.EQ.1)) GO TO 17
C
CHECK IF THE ROAD WIDTH IS UNCHANGED. IF IT IS THIS IS A
TYPE 1 (PAVEMENT ONLY) RECONSTRUCTION
IF( TEMPL(1). EQ. TEMPL(1,JQ)) IOP = 1
C
ESTABLISH DESIGN PARAMETERS
DO 10 I = 1, 15
10 TEMPL(I) = DESIGN(I, JQ)
TEMPL(12) = TEMPL(1)*2.
TEMPL(13) = TEMPL(11)
DO 1011 I = 1, 12
1011 PAVE(I) = DESIGN(I + 15, JQ)
C
CONVERT LAYER THICKNESSES TO METERS
DO 1012 KL = 4, 12, 2
1012 PAVE(KL) = PAVE(KL)/100.,
PAVE(11) = PAVE(11)/100.
C IF( OTRACE.GT.0) GO TO 939
WRITE(OU, 78)
78 FORMAT( 'THE PAVEMENT DESIGN FOR THIS CONSTRUCTION IS' )
WRITE(OU, 802)
802 FORMAT( 'WIDTH SLOPE SHLD-WD SHLD-SL DTH-WD DTH-WC CON 700
1-SL DTH-WD DTH-SL CUT-SL FILL-SL PAVE-WD SIDE-CL')
WRITE(OU, 830) (TEMPL(I), I = 1, 10), TEMPL(12), TEMPL(13)
830 FORMAT(12F10.2)
WRITE(OU, 803)
C CHECK FOR NEW ALIGNMENT
IF (( IOP.NE.0). OR. ( YR.EQ.1)) GO TO 19
C READ NEW TERRAIN AND TOPOGRAPHICAL DATA
ISTORE=IN
WRITE(OU,192)
192 FORMAT('0 NEW ALIGNMENT DATA ')
CALL PMIN1 (INSUB)
CALL PMIN2 (INSUB)
IN= ISTORE
19 CONTINUE
IF( YRCS(1).LT.0) GO TO 92
DO 9 II=1,5
IF (YR.GE.YRCS(II)) GO TO 91
9 CONTINUE
GO TO 92
91 JK=II
DO 11 I=1,20
11 PROD(10+I)= COST(JK,I)
92 CONTINUE
IF ( OTRACE.GT.0 ) GO TO 931
WRITE(OU,818) (PROD(I), I=11,30)
818 FORMAT('O PAVEMENT UNIT COSTS AND PRODUCTIVITIES /
1 ' PROD SOURCE TRANSPORT LCOST EQCOST '/
2( 5F10.2,3X ) )
931 CONTINUE
C
74 CONIND=1.
GO TO 76
C
CALL CONSTRUCTION COSTING Routines
ENTRY SIMCON(IOP)
CONIND=-1.
CALL HWYCT(IOP)
CALL INITL TO INITIALIZE SURFACE PARAMETERS
CALL INITL
SUM COSTS AND PRINT OUTPUT IF DESIRED
IF ( OTRACE.GT.2 ) GO TO 657
IF ( OSWTH(1).LT.1 ) GO TO 657
PRINT DETAILED CONSTRUCTION COST DATA
WRITE(OU,400) ( OUT(I),I=1,14),OUT(36), (OUT(I),I=15,35),OUT(37), CON 1260
OUT(59), (OUT(I),I=33,58), (OUT(I),I=60,72 )
400 FORMAT(1HO,T16,'AREA', T17,'VOLUME', T9,'FILL_VOL', T9,'BDR_COST', T9,'BDR CON 1270
1HAUL TIME LABOR EQUIPMENT TOTAL '/T14,' HECTARES CON 1290
2 CU.M CU.M $ $ HOURS CON 1300
3 $ $ '/ SITE PREP.', T9,F12.0,T69,4F12.0/ CON 1310
4 EARTHWORK', T21,8F12.0 / 'PAVEMENT ', CON 1320
A T17,'AREA VOLUME', T9,'MATERIAL COST', T9,'HAUL CON 1330
1 COST TIME LABOR EQUIP. LAYERCOST TOTAL '/TCON 1340
216,'SQ.M CU.M $ $ HOURS $ CON 1350
3 $ $ '/ T9,F12.0,T107,F12.0 / CON 1360
1 ' LAYER 1',T21,7F12.0/ 'LAYER 2',T21,7F12.0/ 'LAYER 3',T21,CON 1370
17F12.0 / 'SHOULDER',F11.0,T107,F12.0/ 'LAYER 1',T21,7F12.0/ 'LAYER CON 1380
2 2',T21,7F12.0/ 'LAYER 3',T21,7F12.0 / 'DRAINAGE LENGTH CON 1390
3F CULVERT (M)*,T74,'SOURCE COST', T9,'TRANSPORT TOTAL '/T10,8F12.0 /CON 1400
1 1HO,T26,'LABOR ($)', T9,'EQUIPMENT ($)/' OTHER COMPONENTS',2CON 1410
1F14.0/ 'OVERHEAD',SUPERVISION',F14.0,F14.0 , T50,'TOTAL CONSTRUCTION CON 1420
2ON COST FOR THIS PROJECT IS $ ',F12.0)
657 OUTPT(1)=OUT(3)+OUT(11)+OUT(19)+ OUT(26)+ OUT(33)+ OUT(42)+ CON 1450
1 OUT(49)+ OUT(56)+ OUT(68)+ OUT(70) CON 1460
OUTPT(2) = OUT(4) + OUT(12) + OUT(20) + OUT(27) + OUT(34) + OUT(43)  
1 + OUT(50) + OUT(57) + OUT(69) + OUT(71)  
OUTPT(3) = OUT(8) + OUT(16) + OUT(23) + OUT(30) + OUT(39) + OUT(46)  
1 + OUT(53) + OUT(65)  
OUTPT(4) = OUT(9) + OUT(17) + OUT(24) + OUT(31) + OUT(40) +  
1 + OUT(47) + OUT(54) + OUT(66)  

DO 133 I = 1, 4  
IF ( IODV0. NE. 0 ) GO TO 134  
OUTPT(I) = OUTPT(I) / ALIGN(I)  
134 OUTPD(I) = OUTPT(I) * DISC  
SUM(I) = SUM(I) + OUTPT(I)  
133 SUMD(I) = SUMD(I) + OUTPD(I)  
TOTAL(1) = OUTPT(1) + OUTPT(2) + OUTPT(3) + OUTPT(4)  
TOTAL(2) = OUTPD(1) + OUTPD(2) + OUTPD(3) + OUTPD(4)  
TOTAL(3) = SUM(1) + SUM(2) + SUM(3) + SUM(4)  
TOTAL(4) = SUMD(1) + SUMD(2) + SUMD(3) + SUMD(4)  
IF ( OTRACE. GT. 2 ) GO TO 658  
WRITE ( IPRNT, 303 ) ( OUTPT(I), OUTPD(I), SUM(I), SUMD(I), I = 1, 4 ),  
1 ( TOTAL(I), I = 1, 4 )  
303 FORMAT ( 1HO, T40, ' CONSTRUCTION COSTS (PER KILOMETER)' / T30, ' THIS ', T30, ' PERIOD ', T65, ' SUM TO DATE ', T25, ' ACTUAL DISCOUNTED ', T55, ' EXCHANGE RATE', T20, 2(2F15.0, 5X) / ' TRANSPORT ', T20, 2(2F15.0, 5X) / ' TOTAL', T20, 2(2F15.0, 5X) )  
658 CONTINUE  

CON 1470  
CON 1480  
CON 1490  
CON 1500  
CON 1510  
CON 1520  
CON 1530  
CON 1540  
CON 1550  
CON 1560  
CON 1570  
CON 1580  
CON 1590  
CON 1600  
CON 1610  
CON 1620  
CON 1630  
CON 1640  
CON 1650  
CON 1660  
CON 1670  
CON 1680  
CON 1690  
CON 1700  
CON 1710  
CON 1720  
CON 1730  
CON 1740  
CON 1750  
CON 1760  
CON 1770  
CON 1780  
CON 1790  
CON 1800  
CON 1810  
CON 1820
C COMPUTE DISCOUNTED COST FOR THIS PERIOD
DO 315 I=1,3
   II= (I-1)*4 + 2
315 OUTFR(II) = FORFX(I+3)*OUTPD(I)
C ACCUMULATED COST TO DATE
DO 320 I=1,3
   II= (I-1)*4+3
320 OUTFR(II) = FORFX(I+3)*SUM(I)
C COMPUTE ACCUMULATED COSTS DISCOUNTED TO DATE
DO 325 I=1,3
   II= I*4
325 OUTFR(II) = FORFX(I+3)*SUMD(I)
C TOTAL FOREIGN COSTS FOR CONSTRUCTION
   OUTFR(13) =0.
   OUTFR(14) =0.
   OUTFR(15) =0.
   OUTFR(16) =0.
   J=0
DO 327 I=13,16
   J=J+1
327 OUTFR(J) =OUTFR(I) +OUTFR(JJ)
C COMPUTE FOREIGN COSTS IN DOLLARS
DO 330 I=1,16
330 OUTFRS(I) = OUTFR(I)*XRATE
C IF ( OTRACE.GT.0) GO TO 331
WRITE(OU,332)
1 FMNCY, (OUTFR(I),OUTFR(I+1),OUTFR(I+2),OUTFR(I+3),OUTFRS(I)) CON 2110
   1,OUTFRS(I+1),OUTFRS(I+2),OUTFRS(I+3), I=1,13,4 ) CON 2120
332 FORMAT(1H0,T50,'OFFSHORE COSTS FOR CONSTRUCTION'/ T30,'IN ',3A4, CON 2130
   2 T80,'IN DOLLARS'/ T14,2(7X,'THIS PERIOD',15X,'SUM TO DATE',7X ) /CON 2140
   2 T14, 4( 6X,'ACTUAL DISCOUNTED' ) / CON 2150
   2 ' LABOR',T13,8F13.0/' EQUIPMENT',T13,8F13.0/ ' MATERIAL',T13 , CON 2170
   3 8F13.0 /'TOTAL',T13,8F13.0 ) CON 2180
331 RETURN