ANALYSIS OF INVESTMENT STRATEGIES IN HIGHWAY CONSTRUCTION FOR LOW VOLUME ROADS

by

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ABSTRACT

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Submitted to the Department of Civil Engineering on (May 12, 1972) in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

The lack of adequate transportation facilities is a common factor associated with the rate of development in emerging countries. At the same time, investments in transportation and communications make up a relatively large percentage of a developing country's scarce allotment of public expenditures. As a consequence, it is extremely important that these countries make the most efficient use of these limited funds. One way this can be done is by employing quantitative comparative evaluation techniques.

By using certain economic terms such as the notion of the production function, this thesis established a framework that can assist the planner in determining the "optimal" combination of inputs; that is, the best road design and maintenance policies for a given set of conditions. In particular, the process used concentrates on finding the best tradeoff among construction, maintenance and vehicle operating costs.

Using a case study from Argentina, a framework and a set of tradeoff procedures are outlined. A computer simulation model (the Highway Cost Model) used in conjunction with the case study illustrates that decisions and policies can successfully be determined based on this plan of successive tradeoff analyses.

As developing countries typically have an abundance of unskilled labor, this thesis also examines the tradeoffs between labor and capital intensive techniques for roadway maintenance. To illustrate how the results of this analysis depend on local conditions, a second case study from Bolivia was used. The analyses show that in both cases, capital intensive techniques are less costly than labor intensive techniques; although the intensity of maintenance to be performed differed.

Thesis Supervisor: Fred Moavenzadeh

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CHAPTER 1

INTRODUCTION

1.1 Transportation and its Role in Development

The shortage of adequate transportation facilities is a common factor associated with the lack of development of emerging countries. Moreover, transportation is generally thought to be one of the most important factors contributing to the growth of developing nations. In most developing nations, the proportion of total public expenditures devoted to transportation and communications generally ranges between 20 and 40 percent (1, 2, 3). Similar expenditures in the developed countries are around 10 to 15 percent of their social investment.

The desire or need to provide transportation facilities is commonly termed a "derived demand". That is, transportation facilities provide a form of infrastructure, a means to other ends, rather than servings themselves as productive resources. In other words, relatively few trips are taken for their own sake, rather trips are usually intermediate goods which are jointly demanded with other economic goods (4). This is exceptionally true in developing countries where adequate transportation facilities provide other needed or desired objectives such as the ability to: market agricultural commodities, provide access to new land development, assist in the development of industry, expand trade, and increase health and educational programs (5). Consequently, transportation can be considered as the foundation from which all other forms of development emanates. In this aspect, the following statement typifies the belief held by many: "The one sure generalization that can be made about the underdeveloped countries is that investments in transport and communications is a vital factor" influencing its subsequent development (6).

As transportation facilities require a relatively large investment, they become very important absorbers of a developing nation's scarce resources. Therefore, any misdirected investments in this sector could have a serious impact on a country's total economy. Furthermore, much of the investment in transport is large, indivisible, and long lasting; hense, it can tie up vast amounts of resources for long periods of time(2). The importance, then, of accurate and thorough economic analyses of future transportation investments should be stressed and underscored.

Possibly a more convincing argument for concentrating on transportation is the frequent claim that, at least in the early stages of development, transportation is the key "take-off" which will directly affect all other forms of development (i.e. agriculture, industry, education, etc.).

At the least, it is felt that inadequate transportation can surely serve to limit or restrain growth (7).

However, there is also a generally held belief that to be completely successful, transport development must be part of a series of changes, both social and political in nature (8, 9). This supposition is especially true when there exists considerable doubt as to the economic worth or value of a new transport facility. In cases like these, it is realized that non-economic concerns such as social and political factors are just as important to development as economic considerations. Consequently if better economic analyses can be performed by employing some of the techniques presented and illustrated in this thesis, it will allow planners an opportunity to make improved, more responsive decisions in terms of these social and political factors.

1.2 Scarcity of Resources

Most underdeveloped countries have factor endowments that differ significantly from those of more highly developed economies, notably with respect to the relative scarcity of capital and skilled labor and the relative abundance of unskilled labor.

As an example of the shortage of capital experienced by underdeveloped countries, the poorest countries of the world comprize roughly two-thirds of its population, but have to manage with one-sixth of its income. While on the other hand, the wealthiest countries have among themselves one-sixth of the population, but control approximately two-thirds of the worlds' income (10). The former countries have little surplus for investment, yet such investment is essential to their economic and social development. More specifically, the prime requirements for economic and social development are an adequate and properly organized flow of foreign and international capital. Therefore, due to the scarcity of their own capital, developing countries place heavy reliance on foreign loans or grants to help provide the capital investment necessary to achieve the desired rate of growth.

Presently, there is an increasing tendency among international lending agencies (eg. The International Bank for Reconstruction and Development, Agency for International Development, The Organization for Economic Co-Operation and Development, Inter-American Development Bank, etc.) to direct their assistance toward nations which are making a maximum effort to help themselves by pursuing carefully researched development programs (11).

Most of the assistance offered by these agencies, a substancial portion of which is allocated to highway programs, is in the form of loans which must be repaid. The interest rate charged on these loans is usually related to the rate the banks have to raise from loans it itself obtains.

Since developing countries have limited funds for development, it is desireable, if not imperative to gather information concerning the performance of alternative investment strategies not only at the policy level but at the project level as well. This information would thus aid decision makers in their efforts to maximize the impact of limited development funds (12). In addition, if it can be made easier, faster, and less costly to evaluate the costs and service behavior of highway transportation projects, a larger set of alternatives can be investigated. Thus, with the advent of these techniques, it would be possible to either: a) construct or improve a larger section of the transportation network system with the same amount of investment funds as before, or b) return the money saved to the general fund which could then be re-allocated for investments in hospitals, schools, industry, etc. In both cases a larger contribution can be made to the economic development of a country.

1.3 Common Labor: An Abundant Resource

In planning construction and future maintenance projects, planners and engineers are faced with a choice of techniques involving different combinations of labor and capital inputs. Depending upon the exact techniques used, there may be wide variations in the labor force employed.

The choice of labor or capital intensive techniques may be affected by certain considerations of economic and social policy. In many underdeveloped countries there exists a chronic labor surplus in the form of large groups of unemployed or under-employed unskilled laborers while at the same time there are scarcities of capital resources due to the well-known structural imbalance in factor endowment of most of these economies (13). For example, the capital involved in the labor intensive methods is very slight and the foreign exchange requirements may be very low. The bulldozer, on the other hand, represents a large concentration of capital and almost certainly this capital will be required in the form of hard foreign currency which will certainly be in short supply and may not be available at all (14).

One can argue that under the circumstances it is proper for these countries to undertake large engineering projects using labor-intensive techniques, which are not necessarily based on considerations of comparative cost, provided of course that they are consistent with <u>technological</u> requirements. This would release scarce foreign exchange to import capital equipment for industries in which no such possibilities of labor substitution exist.

In terms of the relationship between technological requirements and labor, specifically unskilled labor, one recent study concludes (15) that the employment potential for unskilled labor in road construction is considerable compared to that in other industries. In particular, based on an examination of the list of basic activities performed for road designs of high quality, the study determined that it is technically feasible to carry out 80 to 90 percent of the basic construction activities strictly by the use of labor. In addition, if the standards are relaxed to an intermediate quality, labor can be substituted for about 85 to 98 percent of total road construction cost.

The study further states that the vast majority of common labor that could be employed to replace equipment would require little skill to master the use of hand tools involved in basic construction activities. In other words, unskilled labor can be employed with little if any indoctrination or "class room" training in highway projects and that the training that is necessary can be completed very quickly "on the job".

As a consequence of using labor intensive techniques, the number of highly skilled workers normally needed to operate capital-equipment intensive techniques is reduced. Therefore the problem of training sufficient mechanics to service equipment will be eased by the change to labor intensive methods.

Since labor intensive techniques in roadway construction and maintenance are feasible from a technical point of view, they may be justified or designed as outright "make work" measures for unemployment relief. Naturally, if there is no such chronic labor surplus a sudden massive increase in the demand for labor in large scale engineering projects of a few years' duration would result in a major disturbance of the labor market (13).

It is generally favored that when excess labor exists, developing countries should use labor intensive methods for construction and maintenance of transportation systems whenever possible. Under-employment or disguised unemployment of labor in emerging countries is often held to be a major hindrance to advancement. With a transportation investment program designed to maximize the use of labor intensive methods, some of the surplus labor could be diverted into local road construction and maintenance projects. Labor intensive techniques for maintaining roads have proven to be effective over a long history and should not be dismissed as ineffective when compared to modern machine methods (16).

In addition to providing jobs for great numbers of formally totally unproductive workers, there are other benefits accruing from labor intensive methods. For example, in an underdeveloped country, for a given volume of employment, labor intensive techniques and combinations of labor and capital intensive techniques will give a larger volume of producers and consumers goods in comparison to capital intensive techniques. Thus, through what is called "income distribution", this pool of rural labor can be taken from a "barter" into a cash economy, thereby establishing a more suitable domestic market for the developing industrial sector. The point to be made is that, in general the larger the number of persons employed, the broader will be the resulting distribution of income. Conversely, the higher the degree of capital intensiveness of a production process, the narrower will tend to be the distribution of income, at least in a "capitalist economy" (17).

Another basis for using labor intensive techniques, is that human capital can be developed and improved through its employment, so that as the need for skilled labor increases, gradual shifts to less labor intensive construction and maintenance of the rural road network could release "skilled" or "experienced" workers for the urban industry. This analogy is only partially true for machinery.

The objective therefore, of any unemployment relief scheme should be to try to create more jobs for unskilled laborers without significantly increasing costs. Even if extra overall costs are unavoidable, the reduction in the foreign exchange component might justify some additional expenditures on overall economic grounds (18).*

In either case, the process should be flexible so that the overall program can be progressively converted in stages to a more capital intensive process (assuming that it is in fact more desireable or cheaper). As development proceeds and capital is accumulated it will be possible and desireable to provide each worker with more capital equipment thus raising his productivity and total output of the developmental unit.

The research study mentioned above by Harrell (15), suggests that the only way to obtain reliable information sufficiently detailed to permit study of the substitution problem (i.e. labor for equipment) is through direct field observation of on-going construction and maintenance projects. Therefore the only conclusion that can be ventured is that specific physical, economic, and social environmental factors are so important that a case by case analysis is required to determine the optimal mix.

1.4 Thesis Objectives

This thesis will concentrate specifically on the analysis, at the project level, of single highway links

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*The labor-capital tradeoffs presented in Chapter 4 will illustrate how a planner can evaluate this exact issue.

within the larger transportation network in developing countries. It is thus assumed that the particular link under study is a desireable part of the entire network. Furthermore, it is assumed that the investment in the transportation project is preferred to investments in hospitals, schools, housing, or other similar areas.

Analysis at the project level is concerned with selecting the particular physical design features, operating, maintenance, and renewal policies for a road in response to the estimation of various factors such as climate, terrain, demand, prices, productivities; and in general, subject to the availability or constraints of resources. The previous sections have established that emerging countries are confronted with the following "constraints": 1) scarce capital resources, 2) low foreign exchange reserves, and 3) an abundance of unskilled labor. Consequently, any course of action which examines the problems at the project level should explicitly take these issues or constraints into consideration.

One way to do this, which in recent years has gained considerably in acceptance, is to develop detailed quantitative techniques for the economic evaluation of alternative investment strategies. These techniques will enable road engineers to prepare better, more economically efficient programs for road construction and maintenance (19). The result of improved economic analyses are also necessary so that better decisions will evolve based on non-economic factors.

Present manual methods of evaluating alternative investment strategies (eg. the "technical feasibility study") are time consuming, so that one cannot hope to complete more than a handful of projects each year. Therefore, in the past is has not been feasible from a point of view of both time and cost to undertake evaluation of large numbers of projects. Thus, the chance that the "best" projects are being considered are very much diminished.

Based on the issues discussed above, the objective of the research reported in this thesis will be to establish a framework which will:

1) Assist planners at the project level in the initial design and decision phases of transportation planning, especially in terms of future maintenance policies,
2) Lower planning costs by evaluating both quickly and cheaply tradeoffs between various policies and costs, and
3) Asess the consequences in terms of costs both local and foreign of using various labor or capital intensive techniques for roadway maintenance.

1.5 Method of Approach

The framework for evaluating alternative policies will be tested using a computer simulation model which estimates construction, maintenance, and vehicle operating costs based on various input information about the roadway. Chapter 2 describes the essential aspects of the model (The Highway Cost Model) which was developed to aid the highway planner in the comparitive evaluation of policies and projects (20).

In the selection of alternative projects many criteria and measures of effectiveness are usually considered. Typically, transport planners in different areas may have different goals and different constraints. For example, if the economy of an area is to be developed, planners might not hesitate to spend large quantities of money for construction and maintenance to keep operating costs as low as possible. If, on the other hand, road transport is to be discouraged in a certain corridor, in the interest of a balanced transportation system, planners might decide not to spend the required sums of money for highway maintenance. In addition, if the resources available for maintenance are very limited, a maintenance organization might decide to upkeep only the most important highways under its jurisdiction and let the others wait until later years for maintenance or reconstruction. Basically, therefore, the analyst decides whether total costs (the sum of construction, maintenance, and vehicle operating cost) are to be minimized or whether maintenance or user cost are to be kept below a certain amount.

Although in certain instances it may be desireable to minimize one component of total cost, the measure of effectiveness used in the following analyses will be to minimize the total discounted sum of construction, maintenance, and vehicle operating cost.

Bauman and Winch (21, 22) have shown* that the best tradeoff between the choice of minimizing highway cost or minimizing user costs is to minimize total transport costs. Highway costs are the sum of construction and future maintenance cost.

This theory of "optimization" is depicted in Figure 1-1. As the road is improved, the total annual highway costs increase while the total annual user costs decrease. The total annual transport cost curve is obtained by adding the annual user and highway cost curves. As Figure 1-1 illustrates, it is possible to select a certain road improvement schedule which will minimize total annual transport cost (21).

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*The analysis assumes a single road with constant traffic volume and an absense of any single cost constraint.

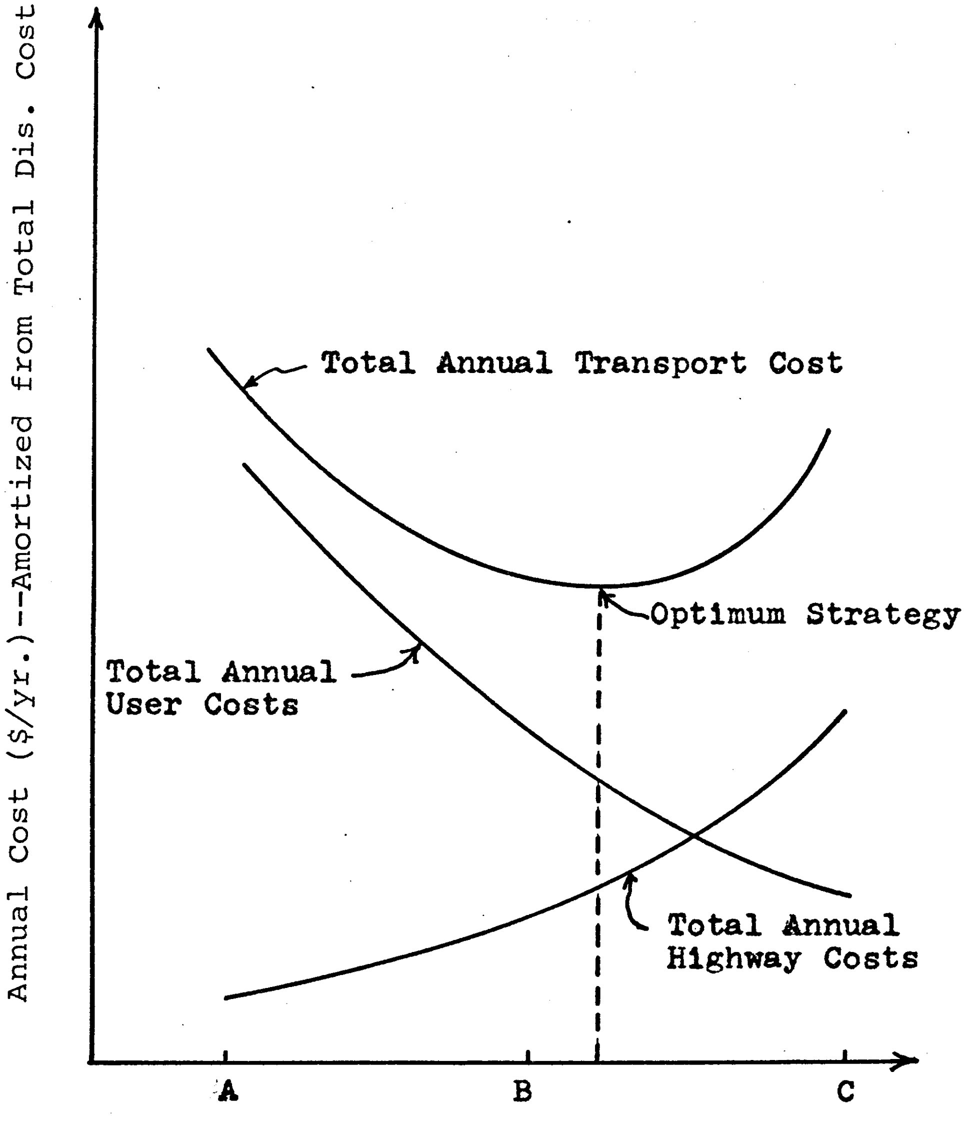

Figure 1-1: Relationship of Total Cost to Road Improvement, assuming Constant Traffic Volume (Ref. 28)

Although the curves shown are for a very generalized and oversimplified situation, they do underline the basic theory behind total cost as a measure of effectiveness.

In summary, the advantages of using total discounted cost as the measure of effectiveness is that it will result in the optimal, long-run allocation of funding among construction, maintenance, and vehicle operating cost. However, other measures of effectiveness may in fact be more desireable than minimizing least total cost. For example, as mentioned above, it may be better to spend more money than is normally necessary in construction and maintenance so that vehicle operating costs will be as low as possible. Also, there may be constraints in the amount of funds available for construction which would not allow a road to be built to the initial quality necessary to keep operating costs low. In general, if there are constraints on the maximum amount of resources which can be expended on any one of the individual cost components, it may not then be possible to construct or maintain the road to the level anticipated using total discounted cost as a criterion.

The point has been made above that since developing countries have limited funds for development, decision makers should exert a strong effort to maximize the impact of these constrained funds. One way to accomplish this, at the project level, is to test or simulate various design decisions and maintenance policies until one set which appears optimal is found. Unless a framework of orderly procedures is followed, this trial and error approach would be quite time consuming and costly.

Chapter 3 therefore outlines and illustrates a procedure whereby through the use of tradeoff analyses, various policy and design decisions can be simulated in an attempt to find that set of "optimal" or "desireable" policies.

It was further established that most developing countries have an abundance of cheap and unemployed labor but seriously lack foreign exchange reserves. It follows therefore that labor intensive techniques might be preferred either economically or otherwise over the use of capital intensive techniques. That is, one would surely use labor intensive techniques if they were cheaper and might be willing to use them anyway if they were not overly expensive. In either case, in examining the substitution problem, it was previously determined that a case by case analysis should be performed.

Chapter 4 illustrates how the Highway Cost Model can be used to examine the economic consequences (i.e. in terms of both total cost <u>and</u> foreign exchange) of various labor or capital intensive techniques for roadway maintenance.

To insure a more realistic comparison of various road investment strategies, a prototypical, but actual case study was used in the analyses presented in Chapters 3 and 4. An actual case study has been chosen rather than a hypothetical case in order to provide an opportunity to explicitly compare actual costs to the costs predicted by the model.

The two case studies used were from data gathered in Argentina and Bolivia. Both of these case studies are discussed in more detail in Appendix A.

CHAPTER 2

THE HIGHWAY COST MODEL: AN OVERVIEW

2.1 Introduction

This chapter, which provides an overview of the Highway Cost Model (HCM), is divided into three sections. The first section discusses the general framework of the entire cost model. Specifically, the logic of the model is discussed in terms of a production process which uses construction, maintenance, and vehicle operating activities as inputs. For a given set of inputs, the model determines the output or the total cost of transportation services. An overview of the total cost model is also presented describing the iterative time simulation of construction, maintenance, and vehicle operating activities.

The next two sections of this chapter each deal with a specific function of the entire HCM. In particular, the second section describes the three major cost estimating submodels: The construction submodel, the maintenance submodel, and the vehicle operating submodel. These estimating submodels are concerned with the estimation of costs and resource consumption.

Finally, the last section of this chapter briefly discusses the stage construction capabilities of the model. For a complete and comprehensive discussion of all the detailed aspects of the model, the reader is referred to references 20 and 23.

2.2 Framework of the Total Cost Model

2.2.1 Logic For Development

Road transportation can be viewed as a production process in which a time stream of inputs are transformed into a time stream of outputs. The inputs are referred to as construction, maintenance, and vehicle operating resources while the outputs are mainly road transportation services. As in most production processes, the inputs can be combined in many ways to obtain a desired transportation goal. Thus, the problem a highway designer must resolve and which the HCM was developed to assist in, consists of obtaining that combination of inputs which over time results in the most efficient production process. In terms of transportation for developing countries, this may imply capital expansion over time, usually through some form of staging, that is, the upgrading or rebuilding of roads as traffic volume or the demand for road use increases. Viewed in this context, rational transportation planning can be seen as a problem of selecting the optimum amount, mix, and timing of capital inputs to attain an optimal output of transportation services (24).

The model described in this chapter addresses itself to solving the production process discussed above. More formally, it is intended that the model be used by the highway planner who seeks to identify the optimal combination of inputs for providing low volume rural roads in developing countries throughout the world. Chapter 3 illustrates through a case study approach how the HCM can be used in locating a "optimal" set of design and maintenance policies.

2.2.2 Model Overview

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

Since it was anticipated that the model would be used at several stages during the preliminary analysis of a project, the model was designed to be responsive to different levels of information. For example, during the very initial preliminary analysis of a road project, the terrain can be described by the rise and fall of the ground along the path of the road. But, later when a specific alignment is chosen, the model can accept more detailed digitial terrain information in the form of stations and elevations for a series of verticle points of intersection (VPI). In a similar manner, the model is capable of analyzing roadway construction costs for either "typical" roadway cross sections supplied by the model, or for specific cross sections and templates supplied by the analyst.

The model is designed as a fairly straightforward iterative time simulation of construction, maintenance, and vehicle operating activities. The flow chart shown in Figure 2-1 illustrates this aspect of the model. Since this iterative simulation approach is quite flexible in representing physical and economical relations (i.e. resources consumed and their costs) it led to the development of a highly modular model. As a consequence, the modularity of the model makes it relatively simple to incorporate new information as it becomes available.* Likewise, it allows for easily made changes in the model relationships for purposes of sensitivity and tradeoff analyses.

One more important aspect of the iterative approach is the ability of one submodel to rely on information from other submodels in the simulation of physical relationships between construction, maintenance, and the number of vehicles.

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*For example, as better information is developed on the relationship between roadway surface roughness and vehicle velocity, especially for unpaved surfaces, it can be incorporated into the model without altering any other part of the model. This example is very typical of all the relationships used in the model.

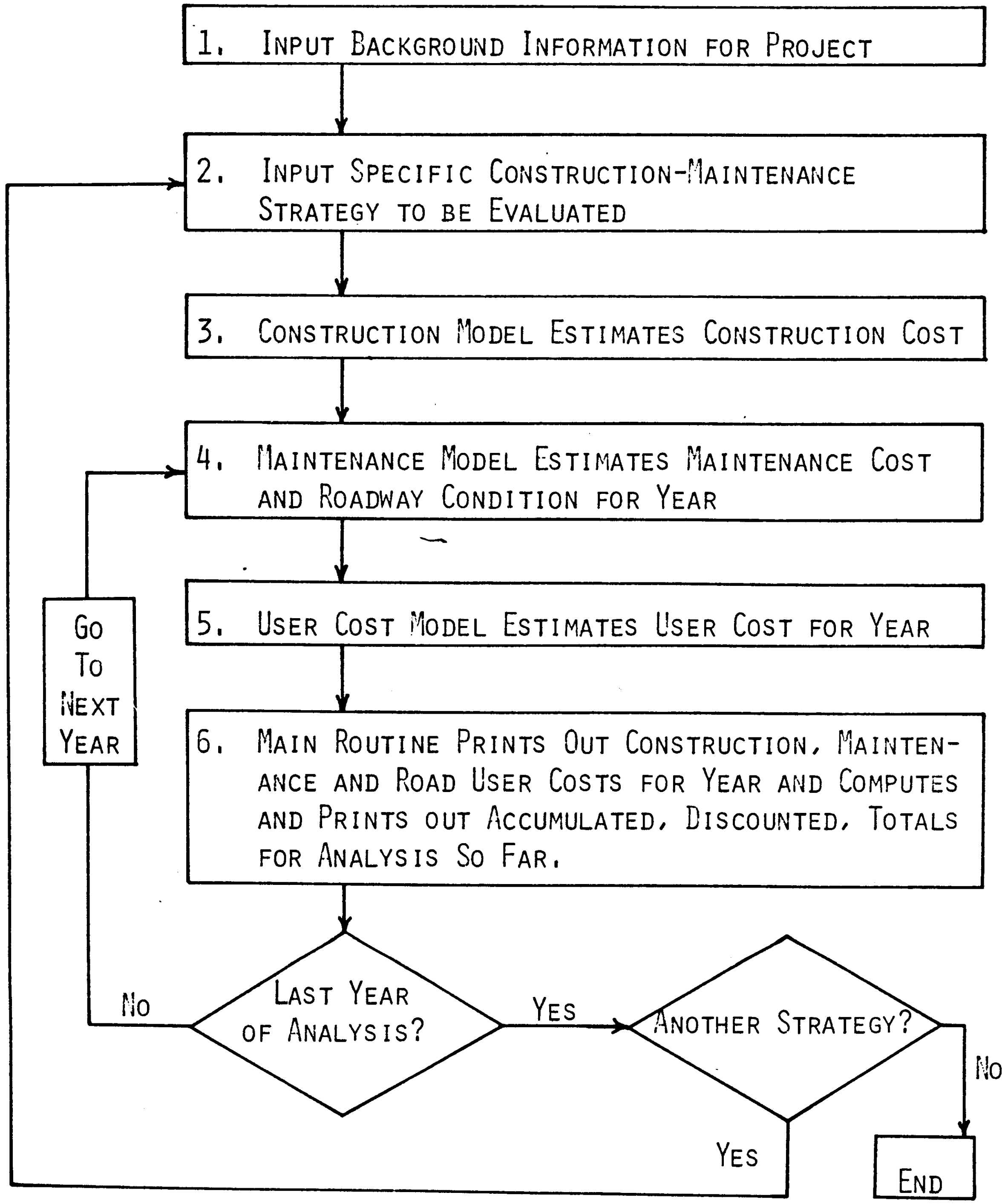

FIGURE 2.1: OPERATION OF THE TOTAL COST MODEL

In particular, by making predictions of resource consumption, costs, deterioration, and number of vehicles year by year during the analysis period the submodels are able to base their future predictions partly on information generated by the other submodels.

Using this method, some of the feedback characteristics of the physical system can be simulated. As an example, the prediction of maintenance cost and the deterioration of the road surface for each year is influenced by the subsequent volume and type of traffic predicted for that year by the user cost submodel as well as by the initial description of the roadway from the construction submodel. The user cost submodel in turn estimates individual vehicle costs for each year as a function of the new deteriorated roadway condition predicted by the maintenance model and the physical description of the road. This interaction between the various submodels can best be illustrated by Figure 2-2.

Being circular in nature, this interaction continues one step further. That is, roadway condition, curvature, and average grade of the roadway are the input variables used by the user cost model to determine the perceived cost of operating each vehicle type. This perceived cost of operation is then used with the specified traffic demand function to predict the traffic volume for the year. Thus, both user costs and traffic volumes are influenced by the

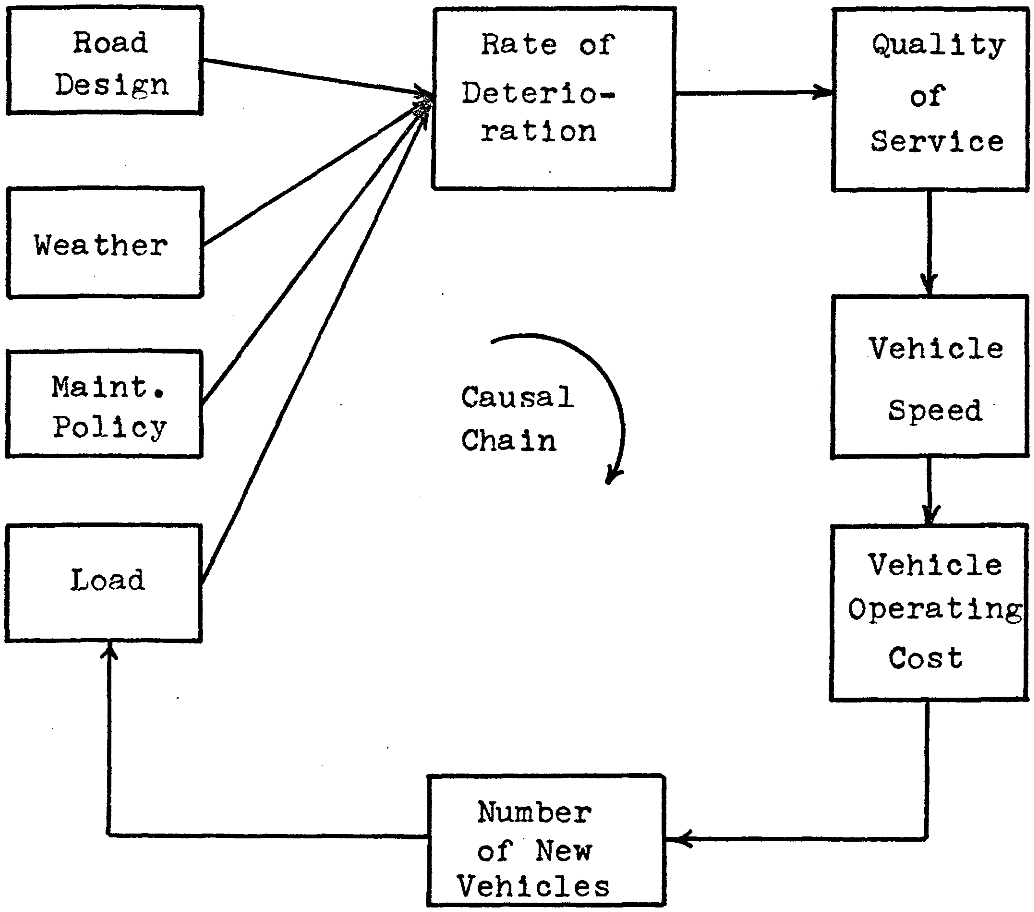

Figure 2-2: Causal Chain between Vehicle Operating Cost and Factors Affecting Roadway Surface Condition

predictions of the maintenance model.

In using this sequential simulation procedure, the overall model framework can simulate the major interaction between construction, maintenance and use of the road. To do so otherwise, would require independent estimates of the construction, maintenance, and user costs for the entire analysis period. This would be highly duplicative because as was indicated above, the relationships between the three costs are highly dependent on each other.

2.2.3 Model Input

Solving the production process for a given design or in particular for the "optimal design", which usually involves the minimization of total roadway cost, requires a knowledge of what inputs are necessary. Generally, it may be thought that any data which is needed to describe a road can be classified into two main types: 1) that data information which the designer has no control over and, 2) that data which is alterable or variable in some manner so as to make it possible to improve on a solution.

The inputs to the model which are generally considered fixed are:

a. Unit prices of resources (labor, equipment, and material cost)

b. The physical environment (terrain, climate, geology, and available construction material)

c. The demand for transportation by vehicle type (initial vehicles per day, elasticity or market cost)

d. The social opportunity cost of capital (discount rate)

The inputs to the model which can be classified as variable are:

a. Engineering decisions (alignment, profile, pavement specifications, cross sections, templates, staging alternatives, analysis horizon)

b. Maintenance policy decisions (blading, patching, sealing, resurfacing, regravelling, and the labor-capital intensity)

Once given a complete set of inputs, the model will simulate construction, maintenance, and vehicle operation activities to determine total cost. The designer can improve on this design by only changing those inputs which are variable. It should be noted however, that the fixed inputs can change from one location to another. Generally they are only fixed over a given link in a network.

2.2.4 Model Output

Output from the HCM is available in several forms to the user. The output can be quite detailed with costs and quantities for construction, maintenance, and vehicle operation given. Costs can be printed in discounted and undiscounted form for each year in the analysis horizon. It is also possible to examine a breakdown of the costs by labor, material, transport, equipment, and the foreign exchange requirements attributed to each. Finally, some very detailed output on the physical quantities consumed is available.

2.3 The Cost Estimating Submodels

The HCM includes three sets of submodels for estimating costs and resource consumption. Specifically, the submodels estimate construction, maintenance, and vehicle operating cost and quantities for a given roadway over a specified time horizon. Each submodel is comprized of two or more subroutines. The design of these subroutines is such that as new information becomes available that requires the alteration in one or more specific area of the model, it can be made without interference to any other part of the model. This modularity of design can therefore provide for easily made updates of the model.

2.3.1 Construction Submodel

The basic operation of the construction submodel is the estimation and simulation of all the costs and physical quantities associated with normal roadway construction.* In particular, the construction submodel can estimate and in certain instances calculate the quantities of material, equipment, labor and transport resources needed for each of the primary construction operations. The operations are taken as: site preparation, earthwork, pavement or surfacing, drainage, overhead and supervision, and miscellaneous (for example, bridges).

Once the model estimates the resources consumed for each activity, productivity rates which are supplied to the model by the analyst are used to determine the time required for each operation or activity. Unit cost data is then used to compute the cost of each operation which are then sumed and printed.

2.3.2 Maintenance Submodel

The basic operation of the maintenance submodel is the estimation of costs and quantities for road surface and drainage maintenance. In addition the maintenance submodel predicts the condition of the roadway surface, usually referred to as its serviceability by estimating how much the road has deteriorated from the condition of the previous

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*The only immediate exception is the cost of major drainage structures like bridges. However, this item can be supplied by the analyst as a lump-sum input to the model.

year. Both of these tasks are performed each year of the analysis horizon.

Maintenance costs are determined by first computing the quantities of labor, equipment, and materials which are expended for the various maintenance operations. The operations can be divided into four activities: surface maintenance, shoulder maintenance, drainage maintenance and vegetation control.

Surface maintenance and shoulder maintenance includes all activities associated with both paved and unpaved surfaces such as patching and sealing of paved surfaces, blading unpaved surfaces, and regravelling of gravel roads. Drainage activities include the clearing of side ditches and the cleaning and repair of culverts. Vegetation control is the maintenance allocated for mowing (25).

For paved roads, the quantity of patching and sealing required is estimated as a function of the Present Serviceability Index (PSI)* of the road. The actual percentage of this amount which will be patched and sealed is determined as an input by the model user. Productivity rates for this operation, which unlike the construction rates are stored in the model, are applied to determine the time and thus cost

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*Present Serviceability Index as defined by AASHO (26) is a measure of the roadways surface and riding condition.

required to perform the maintenance.

These productivity rates are based on whether labor or capital intensive techniques are to be employed as specified by the model user. For each technique, three levels of effort, corresponding to a low, medium, or high maintenance policy can be specified (20). A low maintenance effort, either labor or capital intensive, implies little yearly maintenance which generally results in faster deterioration of the roadway and consequently more frequent or sooner reconstructions. Conversely, a high maintenance policy implies a considerable amount of yearly maintenance accounting for a slower deterioration of the roadway surface and less frequent or possibly no reconstructions.

The model is currently programmed to simulate what are thought to be typical maintenance operations being done by common crew-equipment mixes of reasonable efficiencies. However, if the model user has information on the details of local practice, he may take full advantage of this information by making changes to the DATA statements of the model.

2.3.3 Vehicle Operating Cost Submodel

The main function of the vehicle operating cost (VOC) submodel is the estimation of resources consumed in the operation of vehicle fleets from which operating costs can be determined. In addition, this submodel estimates the number of new or generated vehicles which will use the road over and above those already anticipated.

The basic element in the VOC submodel which allows it to estimate the resources consumed in operating a specific vehicle fleet over a homogenous roadway is its production routine. This routine is used iteratively as the main element in the vehicle cost submodel to determine the quantity of resources consumed in operating different vehicle types over different pavement surfaces and in different seasons.

Like the previous submodels, the calculation of operating costs and quantities by the model may be divided into various categories. They are: 1) the costs and quantities associated with the journey which includes items such as driver wages, and vehicle cost, 2) fuel and tire cost and quantities and 3) cost and quantities of vehicle wear which includes maintenance and depreciation.

The roadway characteristics which influence these vehicle operating costs are vertical profile, horizontal alignment, and surface condition. Vertical profile and horizontal alignment are determined from the construction submodel while surface condition, as explained in the previous section, is determined from the maintenance submodel. No effects of traffic on operating cost, that is, congestion effects are considered because the model is assumed to be used for the evaluation of roadways with traffic volumes low enough to preclude any significant amount of vehicle interaction.

The steps which are followed in the basic production routine are the estimation of the time required to traverse the segment, the fuel requirement, tire wear, vehicle maintenance, and vehicle depreciation. The key element needed for evaluating these steps is the velocity of the various vehicles.

Once the model determines the controlling velocity for each vehicle type, the quantity of resources consumed for fuel, labor, tires, vehicle maintenance, and the time value of capital invested in cargo is determined. From these estimates and the unit prices supplied by the analyst, a total VOC can be calculated. This cost is then summed with the construction and maintenance cost to determine total road cost.

At this point in the operation of the HCM, foreign exchange requirements are calculated from the percentage of: 1) construction labor, 2) construction material, 3) construction equipment, 4) maintenance equipment, 5) vehicle, 6) fuel, and 7) tire costs that must be purchased offshore using foreign exchange. These seven percentages are used to estimate the total foreign exchange needed by use of the equation:

$$\text{Foreign Exchange} = \sum_{i=1}^{7} \left[(UC_i \times C_i \times P_i) \times \text{exchange rate} \right]$$

Where: Subscript i = 7 Categories of foreign exchange

UC = Unit Cost (eg. $/hour)

C = Consumption (eg. # of hours)

P = Percent needed from offshore sources

The exchange rate is the current conversion rate. In Argentina, for example, the rate would be expressed as 0.003 Pesos/U.S. Dollar.

2.4 Stage Construction

2.4.1 Model Capability

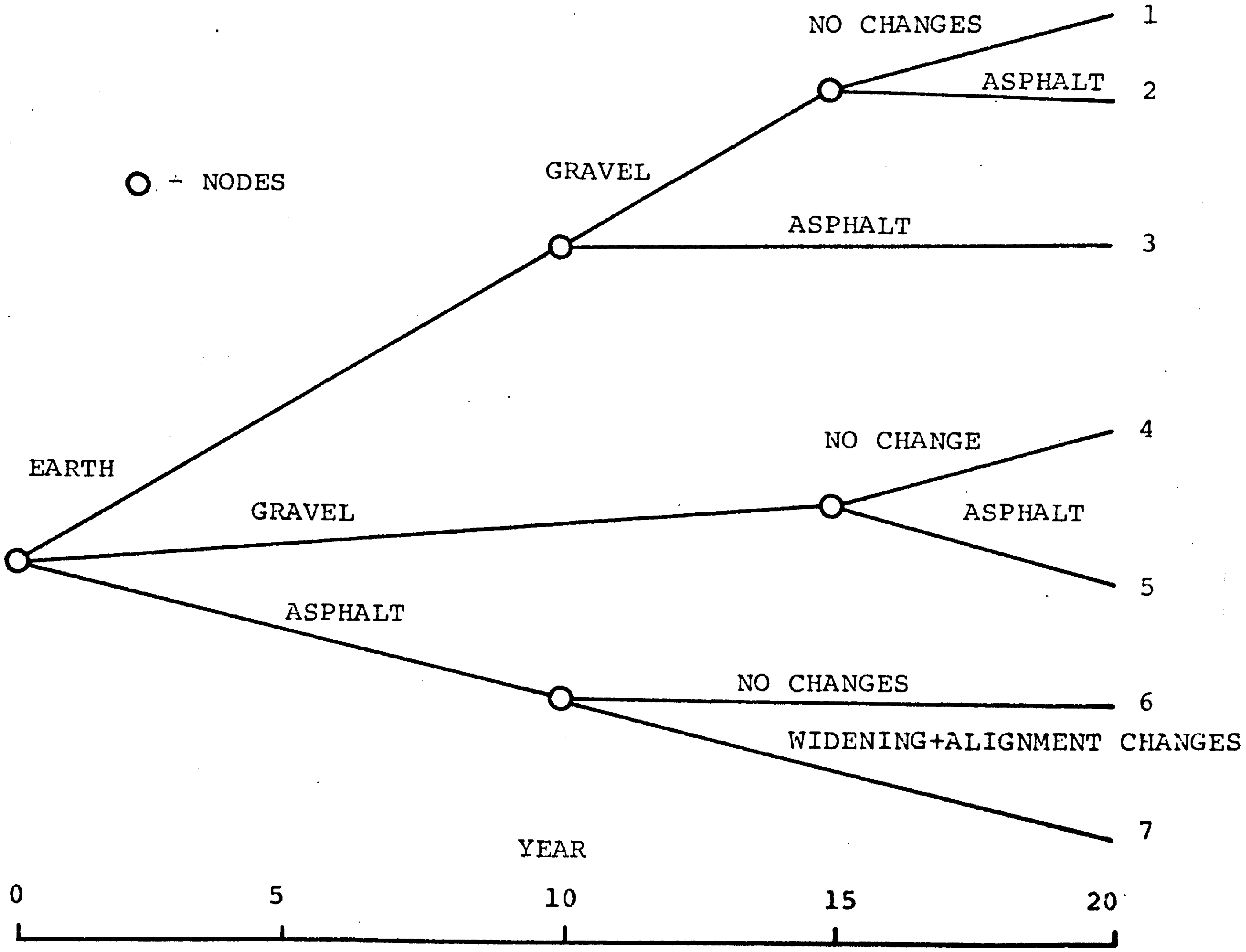
Stage construction of a low volume road is a procedure whereby a road is initially built to a level sufficient to meet the immediate requirements of traffic and at a later date is reconstructed or upgraded to meet the increased demands of traffic. In order to accomodate the increased traffic, staging strategies may include improvements in surface type (for example a road is initially constructed with an earth surface but later is upgraded to gravel and finally a paved surface), improvements in vertical and horizontal alignment, changes in roadway template, or a combination of these strategies.

Previously, in the initial version of the HCM, it was only possible to evaluate one construction strategy at a time, that is, the input information needed by the model to describe a road could not be changed during the analysis period. For example, it was only possible to evaluate the cost of a gravel road for 15 or 20 years; the analysis horizon being the only variable. Therefore, in order to examine one simple staging strategy, say a gravel road for 15 years after which time an asphalt surface is constructed, a series of simulations were needed along with some hand calculations. In addition, each time a new strategy was to be evaluated over a given alignment, all the input data necessary for describing the roadway had to be reread into the model.

To overcome some of the repetitiousness inherent in this procedure, and more importantly to make it possible to evaluate construction staging strategies, a set of "network routines" were incorporated into the model. Specifically, these routines permit the planner to easily investigate various stage construction strategies by specifying the strategies in the form of decision trees (networks). Also, with the network routines, only one data set is needed to specify up to the 30 strategies possible (27).

Figure 2-3 is an example of a decision tree that examines the cost due to constructing a road with different surfaces initially and after a specified time goes through various reconstructions. For this example, only minor

FIGURE 2.3


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

modifications in the basic data deck are needed. The HCM will then determine the total discounted cost of each of the seven strategies over the 20 year service life of the road.

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

CHAPTER 3

AN ITERATIVE APPROACH TO OPTIMALITY THROUGH TRADEOFF ANALYSES

Chapter 2 introduced the notion of how the HCM can be considered a production process which simulates various inputs about construction, maintenance, and vehicle operating activities. If it is assumed that given certain constraints about the roadways future conditions, for example by setting a minimum limit on the present serviceability index of the roadway, then it can be stated that the analysts' objective is to minimize a production function (Z) which can be represented by:

$$Z = \sum_{i=1}^{n} \sum_{j=1}^{m} (\text{Construction}_i + \text{Maintenance}_j + \text{Vehicle Operating Cost})$$

Where: i and j are various strategies, policies, and design decisions.

And, Z = Total discounted cost of the resulting sum of construction, maintenance, and vehicle operating cost.

Then the HCM can be used as a tool by the planning agency to evaluate the tradeoffs among the three sets of costs to obtain the optimum point on the production function.

3.1 Procedure for Selection

To demonstrate the effects various conditions of inputs have on total cost, a series of tradeoffs were undertaken where one at a time, an input to the production function was analyzed. Briefly, the process to be used might be called an iterative approach to optimization through an analysis of tradeoffs. The procedure is described as follows. First, from the large set of inputs, select a number of variables or parameters that are considered important inputs to the production process, that is, inputs which will result in suspected or known tradeoffs.

For example, the tradeoff or relationship between construction and maintenance costs can be characterized by an input variable such as pavement thickness. Thick pavements yield a high construction cost but reduce subsequent maintenance costs, while on the other hand, thinner pavements have lower construction costs and conversely higher maintenance costs.

Once the input variable of interest is selected, it is varied so that a "production function" can be drawn and an optimum strategy determined. Clearly the optimum is "sub optimal" in terms of the whole transportation problem. But all else held constant it does represent the optimum strategy for that <u>one</u> variable. In the pavement thickness example, as will be shown later in this chapter, various thicknesses are simulated until one that results in the least total discounted cost is located, and this is termed the "optimal" strategy.

Second, from the "optimum" values obtained from the tradeoff analysis on each input variable, select that one which appears to be most dominating or controlling. Third, keeping the input variable selected in step two constant at its determined optimal value, repeat the same process followed in the first step; that is, examine the individual tradeoffs by obtaining a production function and select the optimal policy.

Finally, select again a dominant optimum as in step three and repeat the process until all parameters are considered. As a check on the accuracy of the model, the final output or results obtained from the model should approach a more "global optima" than each of the previous optima. The process described can be represented by the flow diagram in Figure 3-1.

The tradeoffs presented in this chapter are meant to be illustrative of how the model can be used in the afformentioned iterative process. Therefore, the presentation concentrates on the procedures and techniques for performing tradeoffs and of analyzing the results and is not intended to be establishing any particular "design policy". In

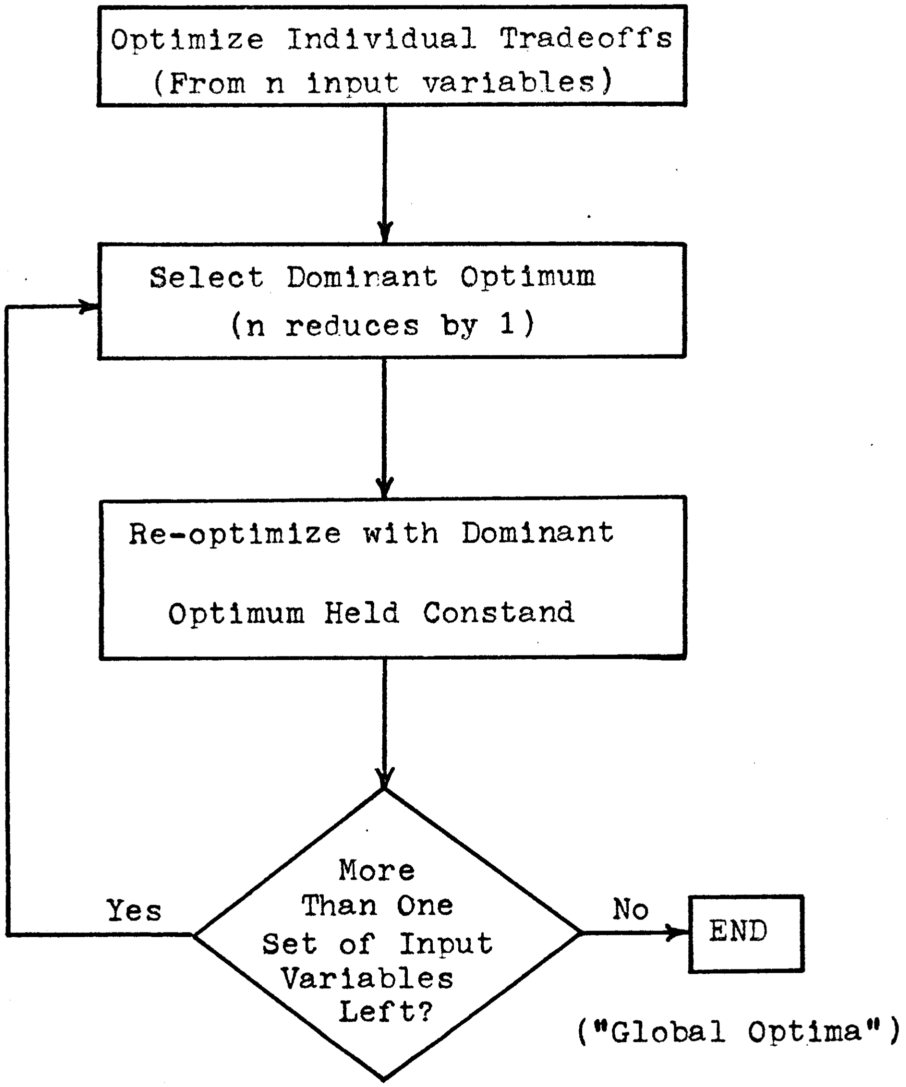


Figure 3-1: The Iterative Process to Optimality

addition, it should be realized that any conclusions drawn are mainly illustrative of the procedures and of the particular analysis or case study in question and will probably not be applicable to a wide range of conditions. All the tradeoffs were run with the Argentina Case Study which is described in more detail in Appendix A.

3.2 Analysis of Input Variables Selected

The tradeoffs which were considered fall primarily into two classes: 1) design (construction) variables and, 2) maintenance policy variables. Design variables include those variables associated with construction which when altered not only affect construction cost but also maintenance and possibly vehicle operating cost. A few examples are: pavement thickness, pavement type, roadway width, reconstruction strategies and overlay thickness. Of course, there exists all the possible combinations of two or more design variables; for example, the implementation of various reconstruction strategies <u>and</u> overlay thickness. Of the possible design variables listed, pavement thickness and reconstruction strategies were selected for more detailed study because of the importance associated with these variables in design and because they are typical and thus illustrative of how tradeoffs with the other variables can be examined.

Similar to design variables, maintenance policy variables include those variables associated with maintenance which when changed not only affect maintenance cost but reconstruction and vehicle operating cost as well. Again some examples include: yearly maintenance procedures which can be separated into the fraction of cracking patched and sealed plus the fraction of rutting filled, and finally allowable mean rut depth. There is also the possibility of combinations.

Other maintenance policy variables such as the question of labor vs. capital intensive techniques for maintenance, which is of prime importance to developing nations, and its relationship to foreign exchange will be considered in more detail in Chapter 4. A list of the exact input tradeoff variables which were selected for simulation are presented in Table 3-1.

3.3 Results of Tradeoff Analyses

3.3.1 Pavement Thickness

The effect of varying pavement thickness can be viewed as a tradeoff between construction and maintenance costs. In short; for thicker, more expensively constructed pavements the amount of subsequent maintenance, keeping the actual "maintenance policy"* constant, will be less than for pave-

TABLE 3-1

Tradeoff Analysis; Design and Maintenance Policy Variables

I. Design Variables

  A. Pavement Thickness

  B. Upgrading of a Paved Road

    1. Reconstruction when PSI = 1.0, 1.5, 2.0, 2.5, and 3.0

    2. Reconstruction at all Possible 5 Year Intervals

II. Maintenance Policy Variables

  A. Combined Maintenance (yearly)

  B. Disaggregated Maintenance (yearly)

    1. Patching of Cracks

    2. Sealing of Cracks

    3. Rut Filling

ments with a standard design thickness. Conversely, the amount of annual maintenance required, plus the costs associated with reconstructions, will be more for thinner or less expensive pavements.

The model normally considers reconstruction as a form of construction staging and therefore includes its cost as a construction expenditure. However, for pavement thickness analyses _only_, a reconstruction cost of the roadway is viewed as a resurfacing cost and thus it is included as a maintenance expenditure.

Figures 3-2 and 3-3 illustrate the typical standard pavement sections which were proposed for the Argentine case study. Using the typical pavement thickness as the "control" or base, the HCM was used to evaluate the tradeoff between construction and maintenance cost for the different thickness strategies listed in Table 3-2. The first six strategies were chosen by varying the individual layer thicknesses, one at a time, by a fixed percentage in each direction. For example; for run number 1, the surface, base and subbase thickness were held constant but the subgrade thickness was changed by a factor of minus 100%. For run number 2, the subgrade layer was increased to twice the original thickness (i.e. plus 100%). For run numbers

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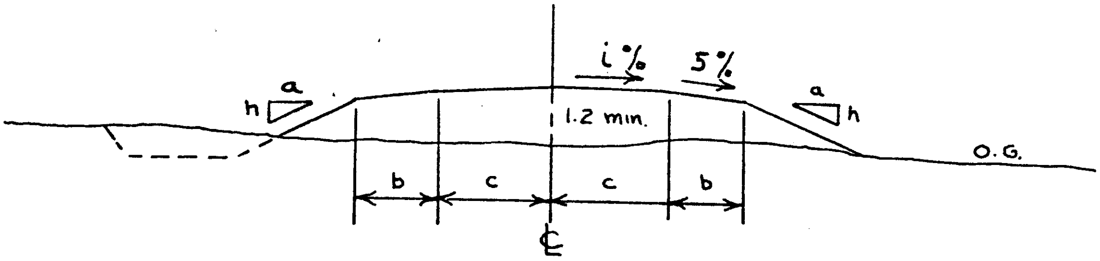
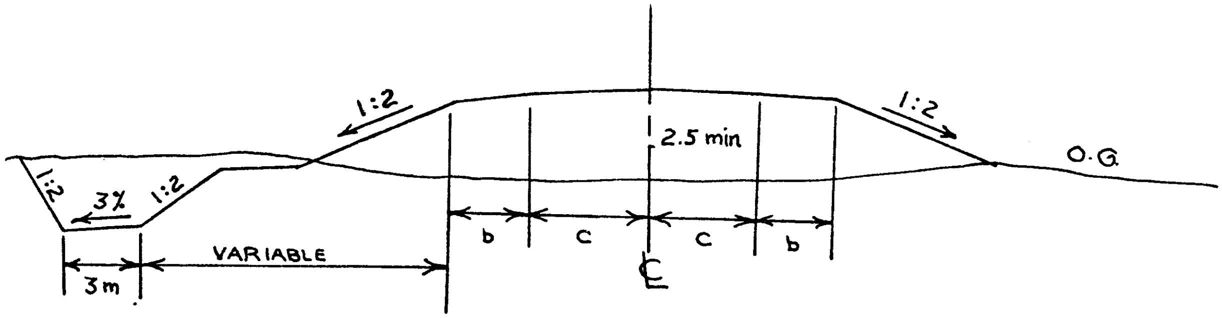
*Maintenance policy is defined as the percent of cracks which will be patched or sealed and the fraction of ruts which will be filled.

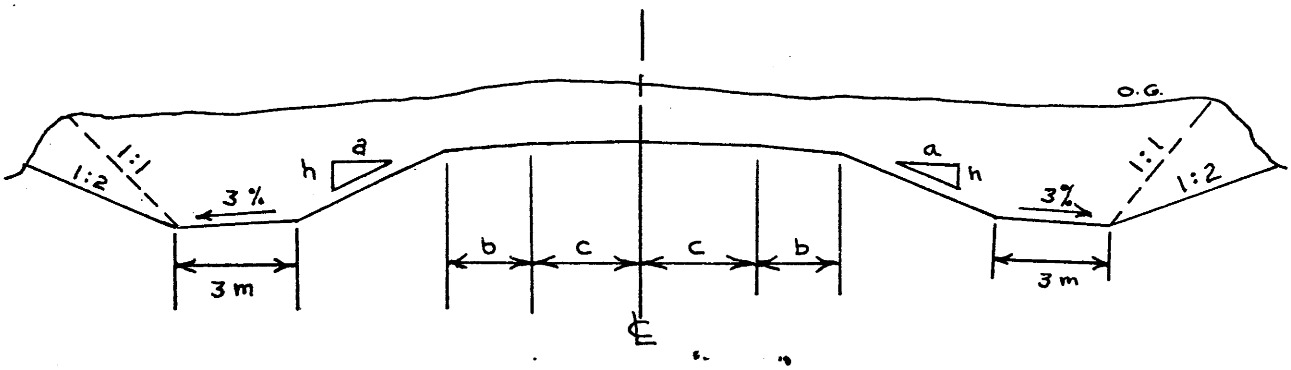
TYPICAL SECTIONS



Shallow Fill



Deep Fill



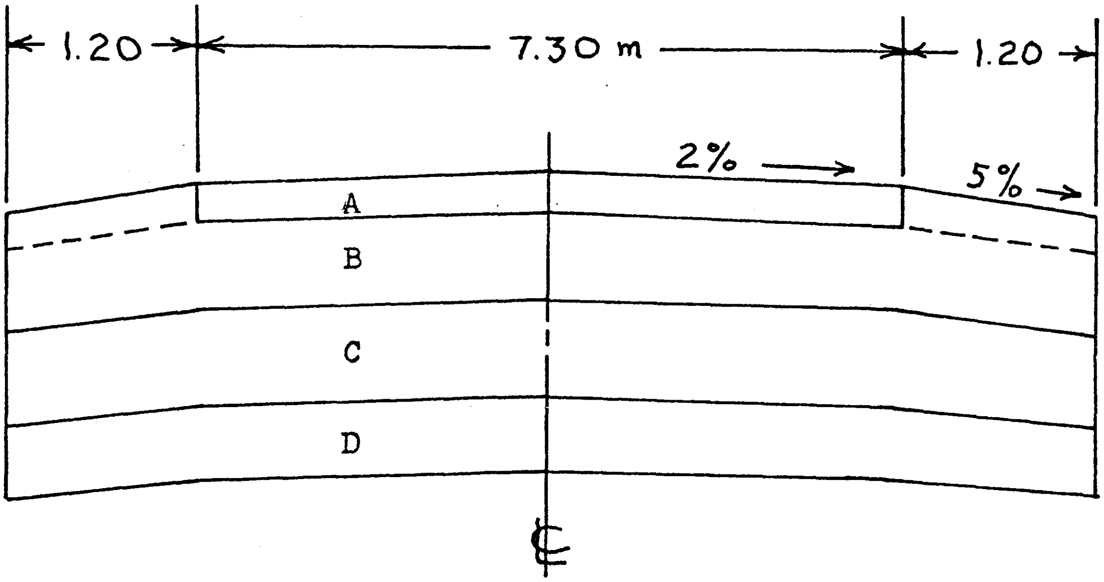
Cut

Tables of Values

Sec.	≤ 3m		≥ 3m		Width		Slope
	h	a	h	a	b	c	i
II	1	4	1	2	3.00	3.65	2.00

Figure 3-2: Typical Sections for Argentina Rte. 14

TYPICAL SECTION



Legend	Thickness	Type
A	7.5 cm	Asphalt
B	24.0 cm	Sand-clay cement base
C	24.0 cm	Sand-clay lime subbase
D	20.0 cm	Lime stabilized subgrade

Figure 3-3: Pavement Typical Section for Argentina Rte. 14
Courtesy Louis Berger, Inc. (28)

Run Number	Surface	Base & Subbase	Subgrade
Base	7.5 cm	48. cm	20. cm
1	7.5	48.	0.
2	7.5	48.	40.
3	10.0	48.	20.
4	5.0	48.	20.
5	7.5	72.	20.
6	7.5	24.	20.
7	7.5	0.	20.
8	7.5	0.	0.
9	5.0	0.	0.
10	2.5	0.	0.

Table 3-2: Pavement Thickness for Tradeoff Strategies

3 and 4 the surface layer (top layer) was increased and decreased by one third (33%) respectively. Lastly, simulations 5 and 6 were run by varying the middle layer (base and subbase) by plus and minus 50% the original, controlled thickness.

Upon establishing the trend set by these first six analyses, a straightforward iterative approach to choosing the next strategies followed, until an optimum strategy was located. In this particular case, the first six strategies revealed that thinner pavements generally resulted in lower total cost, thus the next strategies chosen used even thinner thicknesses.

An analysis of the results (see Table 3-3 and Figure 3-4) indicates that there exists a construction strategy associated with a set of pavement thicknesses, such that the total cost of the roadway discounted over its 20 year life will be a minimum. That is, the results indicate a minimum total cost point where spending an additional currency unit (i.e. dollar, peso, etc.) on construction saves less than a currency unit in maintenance. Conversely, it is noted that saving an additional currency unit in construction amounts to spending more than that currency unit in maintenance.

This optimum strategy occurs at a construction cost of about 11 million pesos per km ($33,000 per km). Also, quite coincidently, it is at this strategy where the construction

	20 Year Discounted Costs in Pesos per KM			
Run Number	Construction	Maintenance	Operating	Total
Base	25,212,700	4,024,242	103,481,306	132,718,200
1	23,912,600	4,301,800	103,030,400	131,244,800
2	25,992,000	3,295,100	103,377,500	132,664,600
3	26,411,600	3,156,604	103,511,806	133,080,000
4	24,407,500	3,888,300	103,189,375	131,485,200
5	30,994,100	3,027,200	103,157,800	137,179,100
6	19,431,200	5,113,700	103,096,700	127,641,600
7	13,158,600	8,931,700	103,396,100	125,486,400
8	10,540,600	11,660,000	103,407,600	125,608,100
9	9,341,400	15,110,200	103,699,200	128,151,000
10	8,142,400	18,765,600	103,700,100	130,608,100

Table 3-3: Costs for Pavement Thickness Analysis

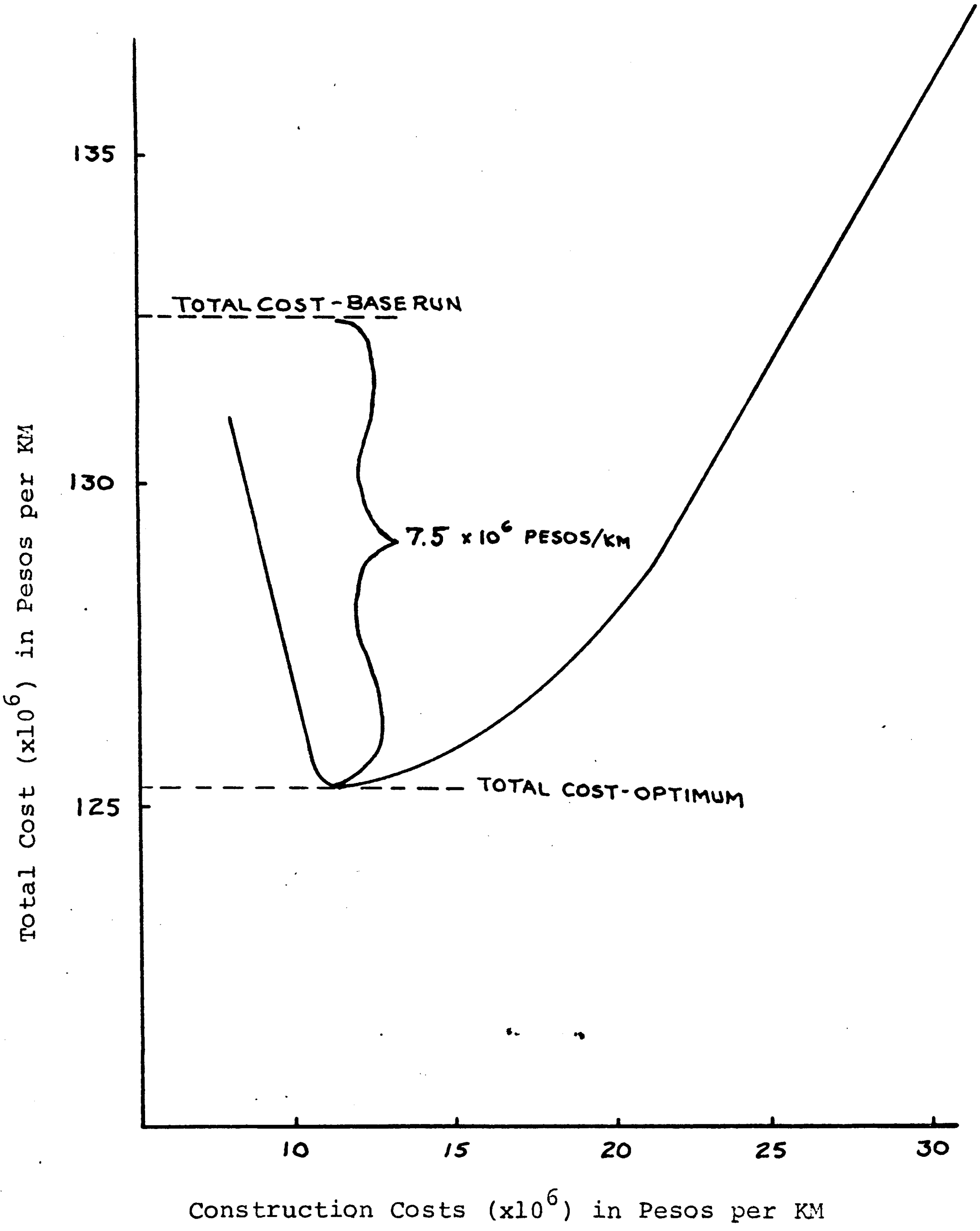


Figure 3-4: Pavement Thickness Tradeoff Analysis for Argentina Rte. 14

cost about equals the total discounted maintenance cost. Figure 3-5 shows the construction vs. maintenance costs for all the strategies. The shape of the curve typifies the earlier discussion on the relationship between thicker pavements and future savings in maintenance cost.

To give an example of the amount or magnitude of savings which can be realized by performing this type of tradeoff analysis, a comparison of costs between the optimal design and the base run were made. As shown in Figure 3-4, a savings of 7.5 million pesos per km ($22,500 per km) in total discounted cost can be realized by selecting the optimal strategy over the design presently considered. Thus, in this case, it is possible to save about 6% of the total discounted cost by using the results and knowledge obtained through performing this analysis.

A further result obtained from this analysis is that the operating or user cost (Table 3-3) discounted over the 20 year life of the road is almost constant for all strategies. This is mainly due to the fact that more effort is expended in maintenance in an attempt to compensate for the serviceability lost because of thinner pavements. In addition, the road is resurfaced as soon as it reaches a minimum level of serviceability to insure that deterioration and user costs will not become excessive.

From this analysis, planners should note that changes

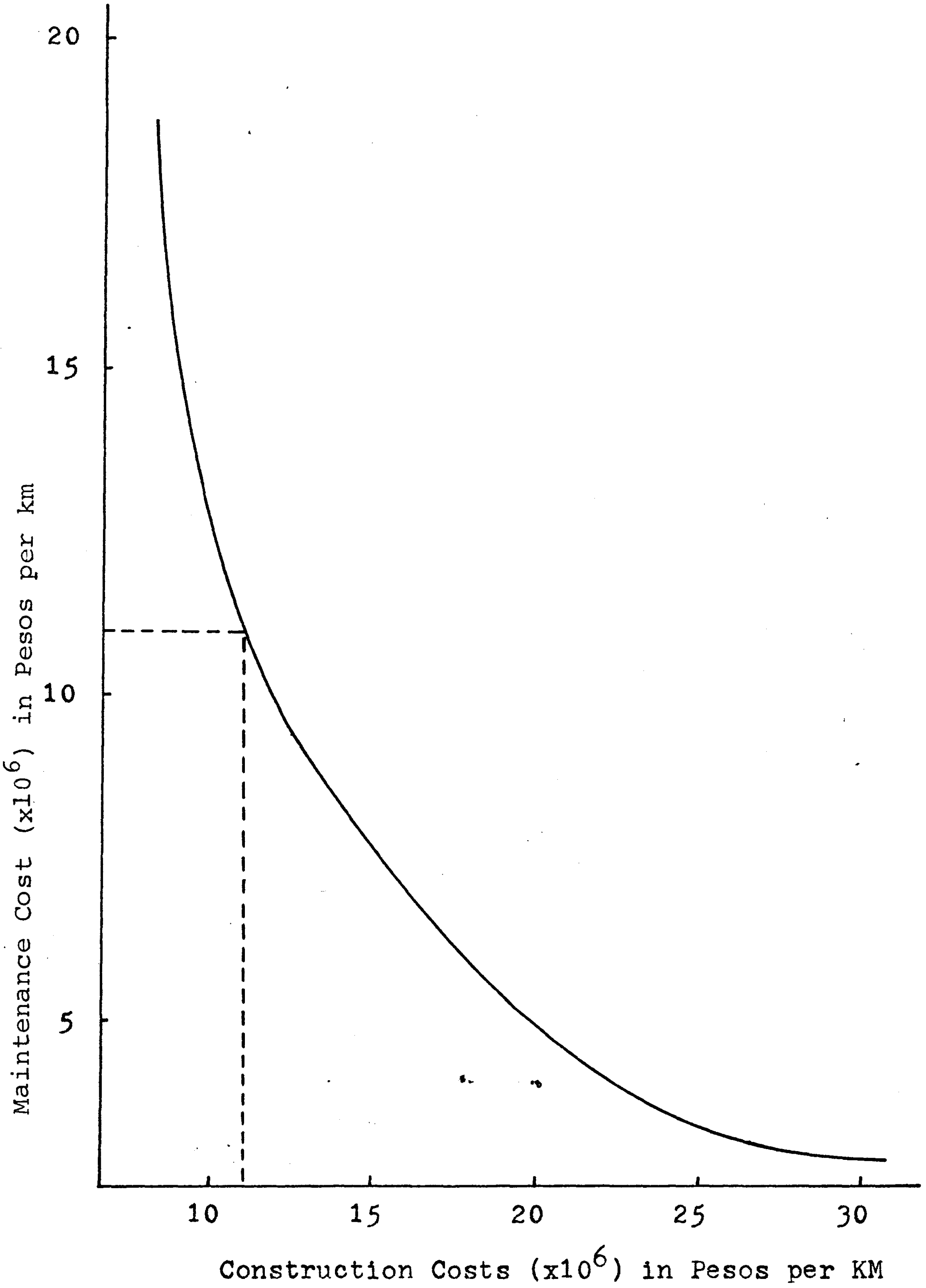


Figure 3-5: Effect of Construction Cost on Future Maintenance for Argentina Rte. 14

in pavement thickness represent a tradeoff between construction and maintenance cost only and that user cost is not significantly affected by variations in pavement thickness so long as it is recognized that maintenance effort and cost will be increased if thinner pavements are used.

3.3.2 Reconstruction Using Serviceability as a Criterion

When the PSI of an asphalt or surface treated road reaches 1.0, it was instituted in the model as a safeguard against complete and total roadway failure, that reconstruction be automatically initiated. Usually reconstruction implies a simple asphalt overlay with the thickness being specified by the designer. Since the choice of one as a minimum PSI was somewhat arbitrary, it was desireable to examine its consequences in more detail in addition to its importance as a policy or input variable.

The tradeoff to be examined in this analysis is argued in the following way. If the road is allowed to deteriorate to a low PSI level before reconstruction or resurfacing is performed, the construction cost (which in this case includes the reconstruction cost) will be low; however, the operating cost along with the sum of the yearly maintenance expenditures will be high because of the poor roadway condition allowed before resurfacing. Conversely, if the road is resurfaced when it still has a fairly high serviceability, which usually would occur early in its life, the construction cost will be high but the yearly maintenance and operating costs will be low. Thus, the purpose of this analysis was to evaluate the three-way tradeoff between construction, maintenance, and vehicle operating costs for different reconstruction policies based on serviceability.

For this analysis, reconstruction policy was defined as resurfacing a road when the serviceability of that road reaches a certain minimum PSI. Besides the initial condition where PSI equals 1.0,* the road was simulated so that reconstruction was performed when PSI equaled 1.5, 2.0, 2.5, and 3.0. At the present time, to vary the minimum PSI allowed before reconstruction, one DATA statement located in subroutine DETER (DET 200) has to be changed. If many tradeoffs of this exact nature are required it might be desireable to alter the program slightly making this data requirement a variable to be specified as an input variable. In this way, the routine would not have to be re-compiled each time a different value were to be specified.

As will be illustrated in the next section, however, the model has been modified to easily examine reconstructions in any year or combination of years as specified by the analyst. Using this criterion for examining the tradeoff for reconstruction is recommended because it is quite flexible and only requires changes in the input data. It

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*A PSI of two is considered unexceptable to most U.S. drivers (26).

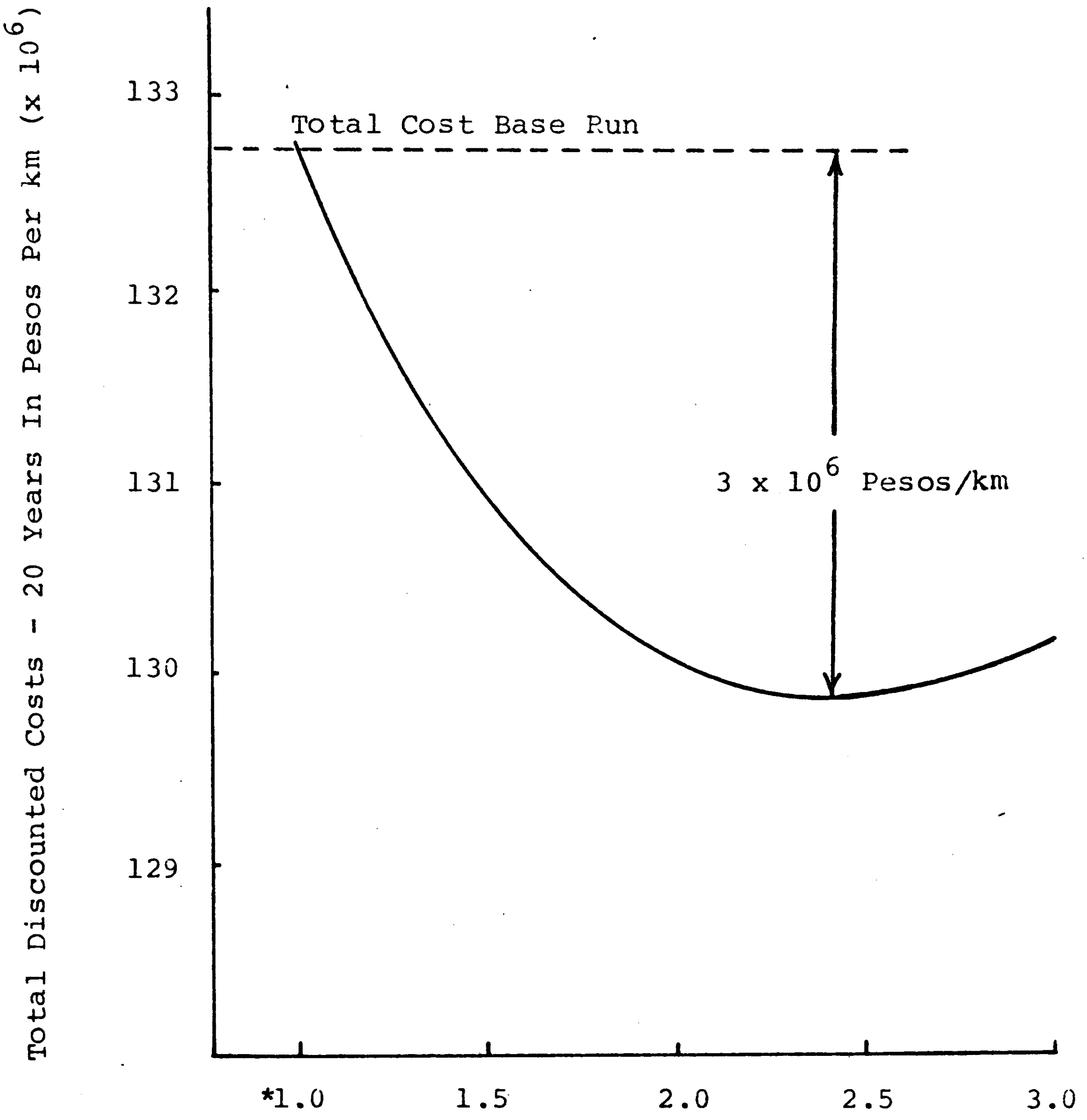
will be shown how both analyses produce about the same results, which signifies a level of consistency.

The results of the analysis using minimum PSI as the criterion for reconstruction, which are listed in Table 3-4, shows that a tradeoff between construction, maintenance, and vehicle operating costs does exist for various reconstruction strategies. The results can be shown graphically in Figure 3-6 which reveal that there is a reconstruction strategy such that the 20 year discounted total cost of the roadway will be a minimum. For the Argentine case study this optimum strategy occurs at a PSI of between 2.0 and 2.5. This means that in order to obtain the least expensive asphalt roadway, reconstruction of the road surface should occur as soon as the serviceability of the road reaches a PSI level in this range. With the Argentina roadway and with the present maintenance policy, this would require two reconstructions; the first occuring at year 10 and the second around year 18.

In addition, this analysis suggests that the lowest total cost is achieved by maintaining a roadway to a high level of serviceability. Although it is not completely obvious from this analysis alone, it will be shown that maintaining a road to a relatively high level of serviceability can be done more efficiently by the use of reconstructions than by yearly maintenance procedures. This

	20 Year Discounted Costs in Pesos per KM			
Minimum PSI	Construction	Maintenance	Operating	Total
1.0 (BASE)	25,858,600	3,378,342	103,481,306	132,718,200
1.5	26,003,960	2,600,016	102,355,119	130,939,000
2.0	26,182,040	2,097,557	101,720,144	129,999,700
2.5	27,091,340	1,567,880	101,181,013	129,840,200
3.0	28,395,900	1,121,600	100,631,500	130,148,900

Table 3-4: Costs for Reconstruction Analysis--PSI Criterion



MINIMUM PSI ALLOWED BEFORE RECONSTRUCTION

Figure 3-6: Reconstruction Tradeoff Analysis for Argentina Rte. 14

*BASE RUN

observation will become evident after analyzing and reviewing the maintenance policy and labor vs. capital tradeoffs presented in Chapter 4.

It should should be noted again that if the labor or equipment rates, relative to one another, or any other number of variables change, that the conclusions drawn from the use of this particular analysis might also change.

In a manner similar to the previous analysis, a savings of 3 million pesos per km ($9,000 per km) can be realized by selecting the optimal result of this tradeoff analysis (see Figure 3-6) over the design presently considered. Thus, it is possible to save about 2.3% in total discounted costs.

3.3.3 Reconstruction Using a Time Criterion

As a follow-up to the previous tradeoff analysis, which examined different strategies of reconstruction when the roadway reached a certain minimum level of serviceability, this analysis used time as the sole criterion for reconstruction. In particular, reconstruction was simulated for all possible five year intervals. Specifically, the seven different strategies and the years in which reconstruction occur are:

Strategy Number	Reconstruction during Year(s)
1	5
2	10
3	15
4	5 and 10
5	5 and 15
6	10 and 15
7	5, 10 and 15

The issues involved in this tradeoff analysis are similar to those for the previous analysis on reconstruction (i.e. the three-way tradeoff between construction, maintenance, and vehicle operating cost). Basically this analysis addresses the same question as before but by using another criterion to determine the best time reconstruction(s) should occur.

It has been shown (27) that the total discounted cost of a strategy involving reconstruction of a road usually varies only a small amount, generally within a couple of percentage points of total cost when reconstruction is delayed or advanced two or three years. Because of this theory it was possible to limit the interval between reconstruction to multiples of five years.* However, it might be desireable for the analyst to refine his time intervals after the first iteration to insure the accuracy of such an assumption.

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*In addition, a five-year interval between reconstruction decision periods was chosen because it is well suited to the format used for input of construction strategies to the HCM.

Since this type of analysis is very similar to, and certainly more flexible than the previous analysis on reconstruction, a provision was incorporated in the model to easily examine this tradeoff. Presently this tradeoff can be analyzed quite simply by the addition of a few statements to the standard input deck (29).

As expected from the results of the previous analysis, the strategy that maintains the road to a relatively high level of serviceability has the lowest total discounted cost. For this particular analysis, referring to the results in Table 3-5, the strategy with reconstruction in years 10 and 15 had the lowest total discounted cost. This is consistent with the conclusions from the previous analysis which revealed that reconstruction in years 10 and 18 produced the minimum total cost for that series of strategies.

It should be noted however, that the last strategy with reconstructions in years 5, 10, and 15 reveals that there definitely is an upper limit in maintaining or resurfacing a roadway after which the additional cost associated with reconstruction outweighs any savings in maintenance and operating cost.

From the two analyses on reconstruction, two conclusions can be drawn with regard to the Argentine data. First, total roadway cost and its components are sensitive to the time when reconstruction is performed. Figure 3-7 illustrates

	20 Year Discounted Costs in Pesos per KM			
Recon. Year(s)	Construction	Maintenance	Operating	Total
19 (BASE)	25,858,600	3,378,342	103,481,306	132,718,300
5	26,846,700	2,108,191	101,883,294	130,838,000
10	26,400,700	1,697,363	101,197,619	129,295,700
15	26,057,700	2,318,418	101,690,631	130,066,700
5 & 10	28,035,000	1,223,592	100,699,700	129,958,200
5 & 15	27,691,700	1,292,193	100,661,788	129,645,600
10 & 15	27,245,700	1,366,242	100,632,838	129,244,700
5 & 10 & 15	28,880,100	946,495	100,205,675	130,032,300

Table 3-5: Costs for Reconstruction Analysis--Time Criterion

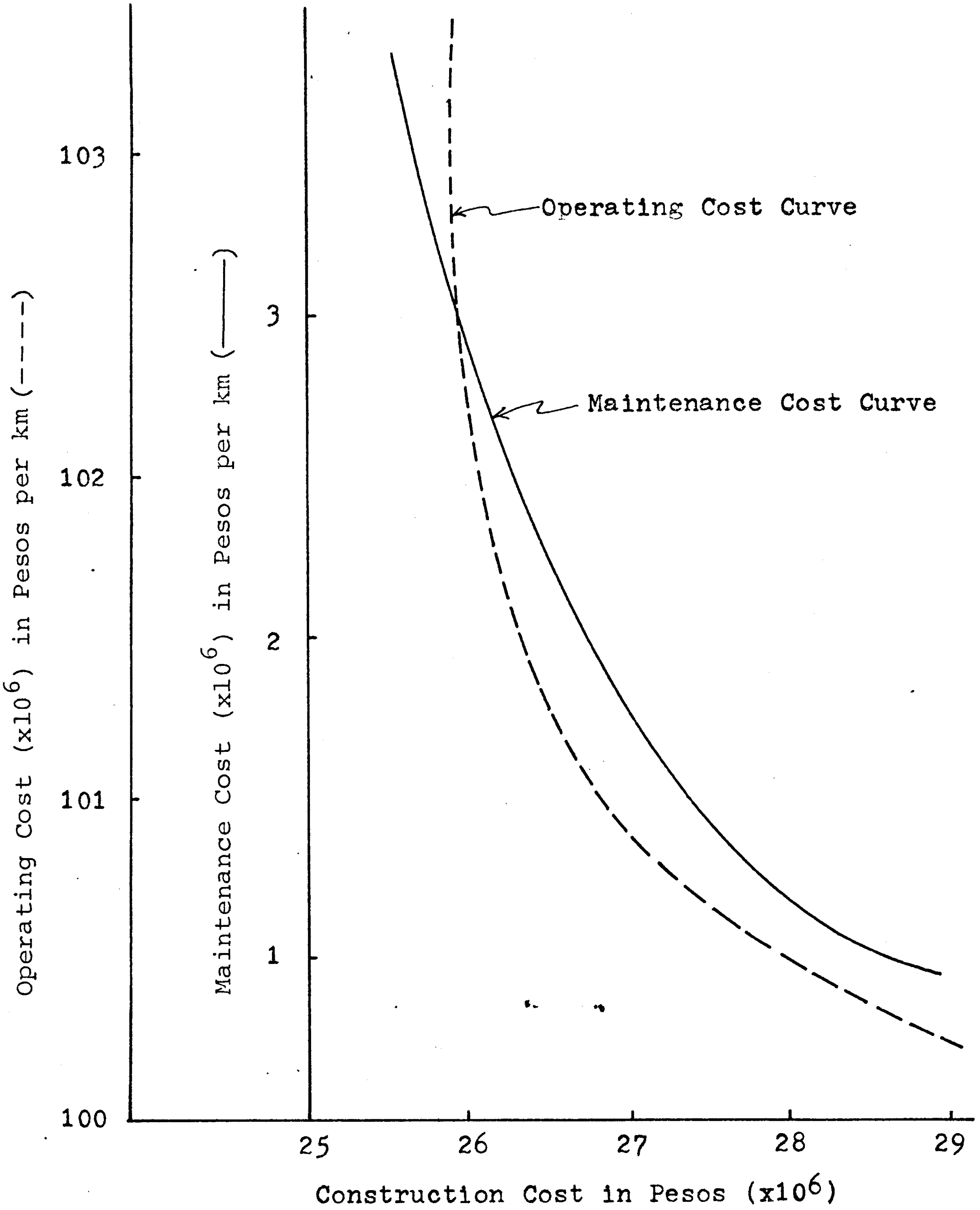

Figure 3-7: Effect of Reconstruction on Operating and Maintenance Cost for Argentina Rte. 14

the tradeoff or effect that increased construction cost (due to sooner or frequent reconstructions) has on maintenance and vehicle operating cost. Second, the savings in road user costs due to sustaining a road to relatively high levels of serviceability generally outweigh the cost of constructing and maintaining these roads to that serviceability, however, there exists an upper limit for which this is true. Furthermore if traffic levels are lower than those experienced in Argentina, the savings in road user costs may not be greater than the extra construction and maintenance expenditures.

Since both reconstruction tradeoff analyses predict far in advance the years in which reconstruction of the roadway should take place, planners are allowed an ample opportunity to schedule and distribute future maintenance work uniformly. In this way, periodic reconstructions of the road surface over a given network of roads won't unexpectedly occur all in one short time period. This procedure should allow for more efficient scheduling of available crews. Moreover, in certain instances, such advance forecasts would also allow governments an opportunity to organize and train maintenance crews which might be nonexistent at the time analyses are being conducted. Through use of the HCM scheduling of construction activities for a whole network of highways may take place in a planned, coordinated manner.

3.3.4 Maintenance Policy--Combined

This analysis examined the tradeoff between yearly maintenance procedures of the roadway surface and the subsequent longer term periodic reconstruction in an attempt to discover the best yearly strategy for road maintenance. In using the model the designer specifies the amount of yearly maintenance to be performed on the road surface in terms of the percentage of cracks that will be patched and sealed and of ruts which will be filled during any given year. Various maintenance policies were evaluated by changing the value for maintenance effort specified to the model in the standard data set. For this analysis, five policies corresponding to 0, 25, 50, 75, and 100 percent maintenance efforts were simulated.

The economic results from the analysis, corresponding with the simulated policies are tabulated in Table 3-6 and graphically illustrated by Figure 3-8. As can be observed, the strategy with the minimum total cost occurs with 0 percent annual maintenance (i.e. no yearly surface maintenance) being performed on the roadway. Consequently, the road is being improved only by the use of reconstructions. It should also be noted that the maintenance costs associated with the 0 percent maintenance policy (see Table 3-6) are for roadside mowing and the upkeep of drainage facilities and not for surface maintenance.

	20 Year Discounted Costs in Pesos per KM			
Maint. Effort	Construction	Maintenance	Operating	Total
0%	26,118,600	524,441	102,612,650	129,255,700
25%	26,003,960	1,727,607	102,860,313	130,591,800
50%	25,858,600	3,378,342	103,481,306	132,718,200
75%	25,212,600	4,725,521	102,967,663	132,905,800
100%	25,212,600	4,828,105	102,249,050	132,289,700

Table 3-6: Costs for Combined Maintenance Analysis

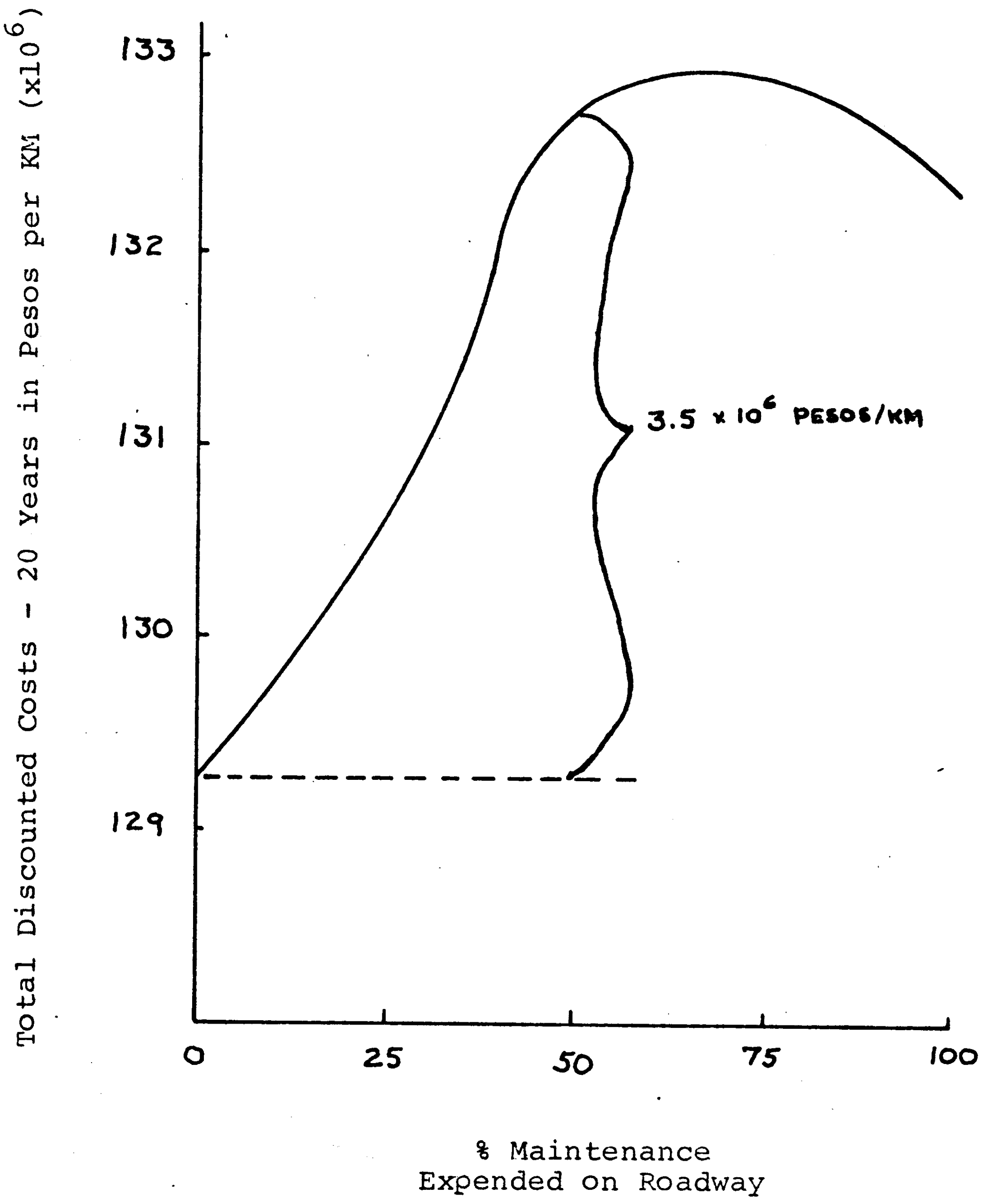

Figure 3-8: Maintenance Policy Tradeoff Analysis for Argentina Rte. 14.

Within the framework of maintenance policies that the HCM can simulate, the result confirms those of preceding tradeoff analyses that it is cheaper or more efficient in terms of total discounted costs, to maintain a road by the sole use of periodic, longer term resurfacings rather than by relying on smaller scale annual maintenance procedures.

As might be expected, the savings in total discounted costs realized through use of the optimum maintenance policy (3.5 x 10^6 pesos per km) is almost identical to the savings realized through use of the optimum reconstruction strategy (3.0 x 10^6 pesos per km). This simularity provides a check by which designers can gauge the degree of precision of the results obtained from tradeoff analyses performed on other data sets.

The vehicle operating costs are fairly constant for all of the strategies but contrary to the minimum total cost strategy, the minimum user cost occurs at the 100 percent maintenance policy, as expected. Even so, however, the 100 percent maintenance policy is not recommended because in order to save 26,000 pesos per km in user costs, 303,000 pesos per km must be expended in construction and maintenance costs.

As in all of these analyses, the results are characteristic of the relationships between the unit costs for the Argentine case study. If in other areas the relative unit cost of construction to maintenance, or maintenance to user cost changes, then the conclusions drawn here might also change.

In addition to costs, varying the maintenance policy affects the condition of the roads surface. Figure 3-9 graphically illustrates the effect that three different maintenance policies have on the rate in which roughness* increases, which is also a reflection of the deterioration rate of the roadway. As expected, in the early years of the life of a road, the deterioration rate is the same for the three maintenance policies. However, around year 10, the deterioration rate for the 0% policy increases quite rapidly until year 14 at which time the road must be resurfaced and reconstruction is initiated. Reconstruction reduces the roughness of the road (shown by the dotted line) and the deterioration process starts over again.

In examining the 20 year deterioration process for the 100% maintenance policy, the road surface never reaches a level where reconstruction must occur. Figures 3-10A and 3-10B show for two different vehicle types how velocity is affected by the various maintenance policies and by reconstructions. Vehicle type 1 is a passenger car, while vehicle type 2 is a light pickup truck.

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*Roughness, usually measured in inches per mile, is an indicator of the rideability or serviceability of a roads riding surface.

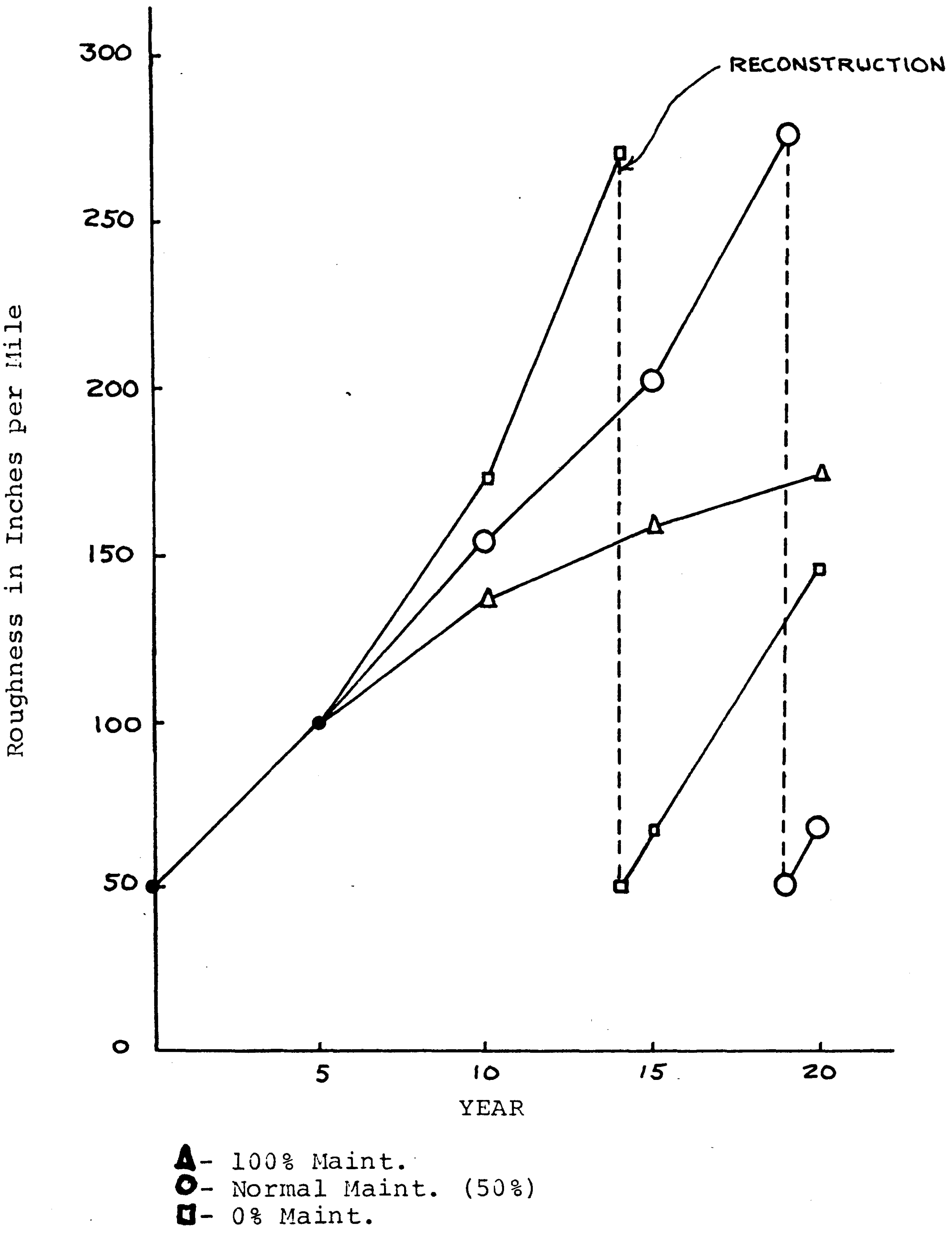

Figure 3-9 : Yearly Effect of Maintenance Policy on Road Roughness for Argentina Rte. 14

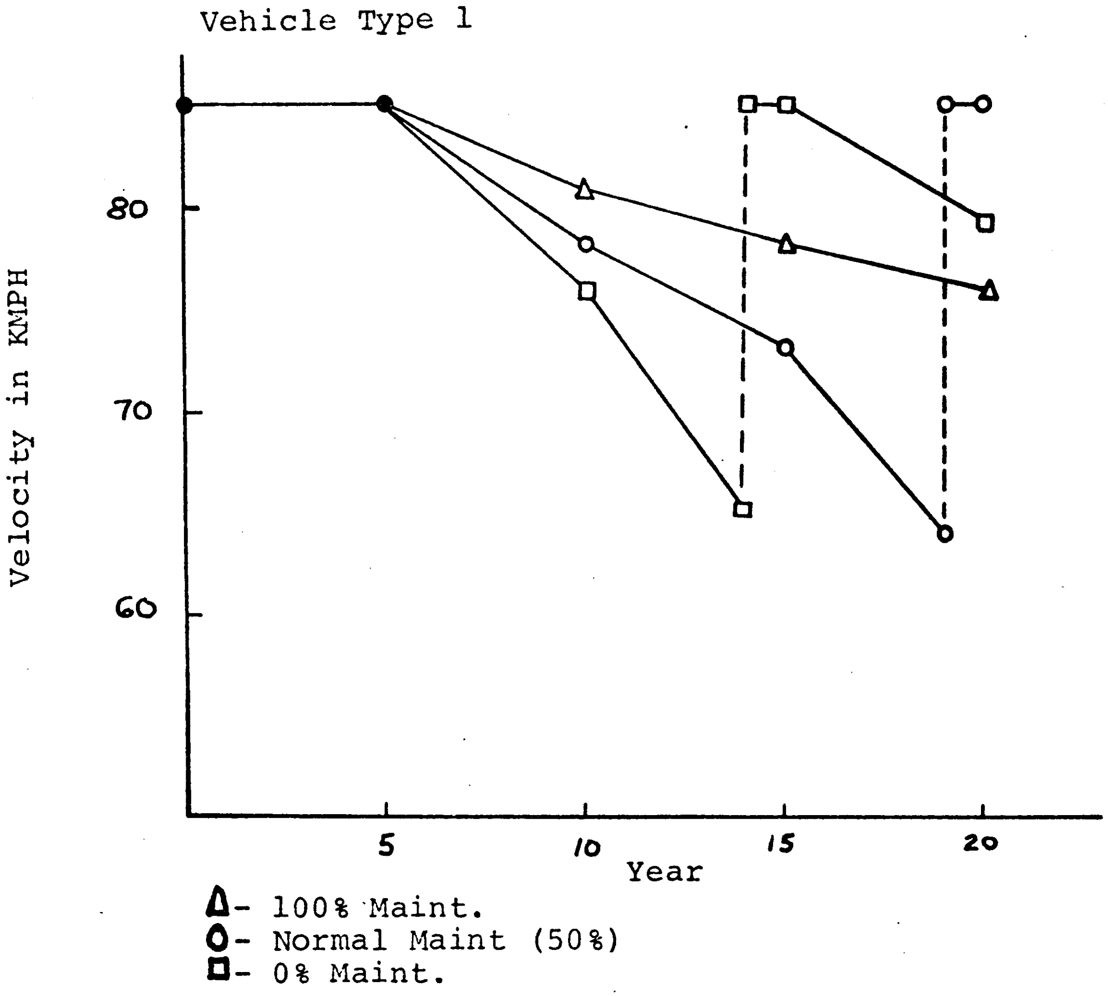

Figure 3-10A: Yearly Effect of Maintenance Policy on Velocity for Argentina Rte. 14

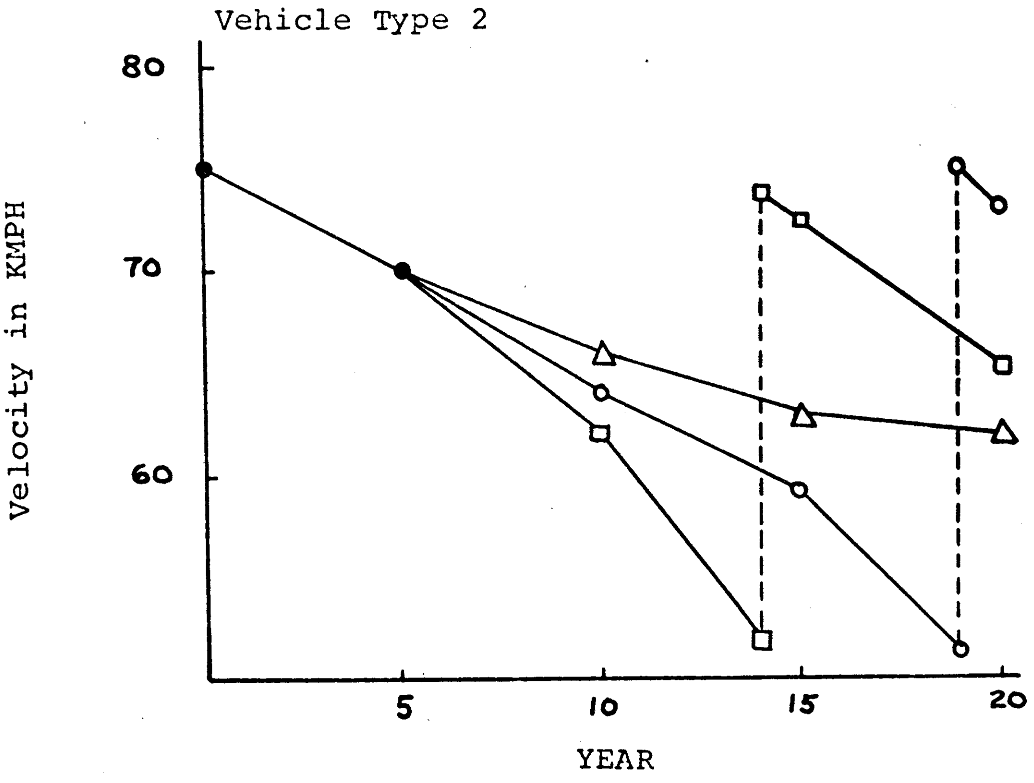

Figure 3-10B: Yearly Effect of Maintenance Policy on Velocity for Argentina Rte. 14

3.3.5 Maintenance Policy--Disaggregated

The previous set of maintenance analyses resulted in the knowledge that when considering all three maintenance policy parameters together (i.e. sealing, patching, rut filling) that performing no yearly maintenance was the optimum strategy. However, this result is based on a very aggregated collection of the maintenance policy variables. Thus, it might be possible that performing some amount of surface maintenance in the form of just one of the maintenance policies is desireable and that the other two should not be performed. (For example, perform some amount of sealing but no patching or rut filling; or any of the other possible combinations.)

The next step in this process therefore, was to determine the best (optimum) strategy while performing just one maintenance activity at a time, while keeping the other two constant at 0%, the optimum policy of the previous aggregated results.

For the first instance chosen, percent of cracks which are patched and the depth of ruts filled were held constant at 0% and the percent of cracks which are sealed was manipulated in much the same way as before by varying in increments of 25% (i.e. 0, 25, 50, 75, and 100 percent) the amount of maintenance performed.

Likewise, this same process was undertaken for the percent of cracks which are patched. In this case the percent of cracks sealed and the depth of ruts filled were kept constant at 0%, while the percent of cracks patched was varied. The resulting total costs of these two tradeoffs are presented in Tables 3-7 and 3-8 and graphically illustrated in Figure 3-11.

The first, obvious point which can be made is that performing no yearly maintenance in the form of sealing or patching resulted in the optimal strategy. This was not entirely unexpected due to what was found in the previous analyses.

Secondly, by examining the maintenance cost column in Table 3-8 one may acquire an understanding of the intensity of maintenance behind each policy. Specifically, one notes that patching cracks is a much more costly maintenance procedure in comparison to sealing cracks. Therefore, one should expect more "performance" for his money and this shows up in reduced reconstruction cost which is reflected by the slightly cheaper discounted construction costs.

The primary point of the analysis is that the extra annual maintenance effort is not worthwhile in terms of what is saved by later or delayed reconstructions or any change in vehicle operating costs.

	20 Year Discounted Costs in Pesos per KM			
Maint. Sealing	Construction	Maintenance	Operating	Total
0%	26,118,600	524,441	102,612,600	129,255,100
25%	26,059,400	564,800	102,949,700	129,573,900
50%	26,059,400	604,700	102,907,300	129,571,400
75%	26,059,400	643,900	102,901,300	129,604,600
100%	26,059,400	682,600	102,892,000	129,633,900

Table 3-7: Costs for Sealing Maintenance Analysis

	20 Year Discounted Costs in Pesos per KM			
Maint. Patch	Construction	Maintenance	Operating	Total
0%	26,118,600	524,441	102,612,600	129,255,100
25%	26,004,000	1,697,100	102,880,700	130,581,800
50%	25,858,700	3,340,200	103,544,500	132,743,300
75%	25,212,700	4,750,800	103,130,000	133,093,500
100%	25,212,700	4,951,500	102,370,800	132,535,400

Table 3-8: Costs for Patching Maintenance Analysis

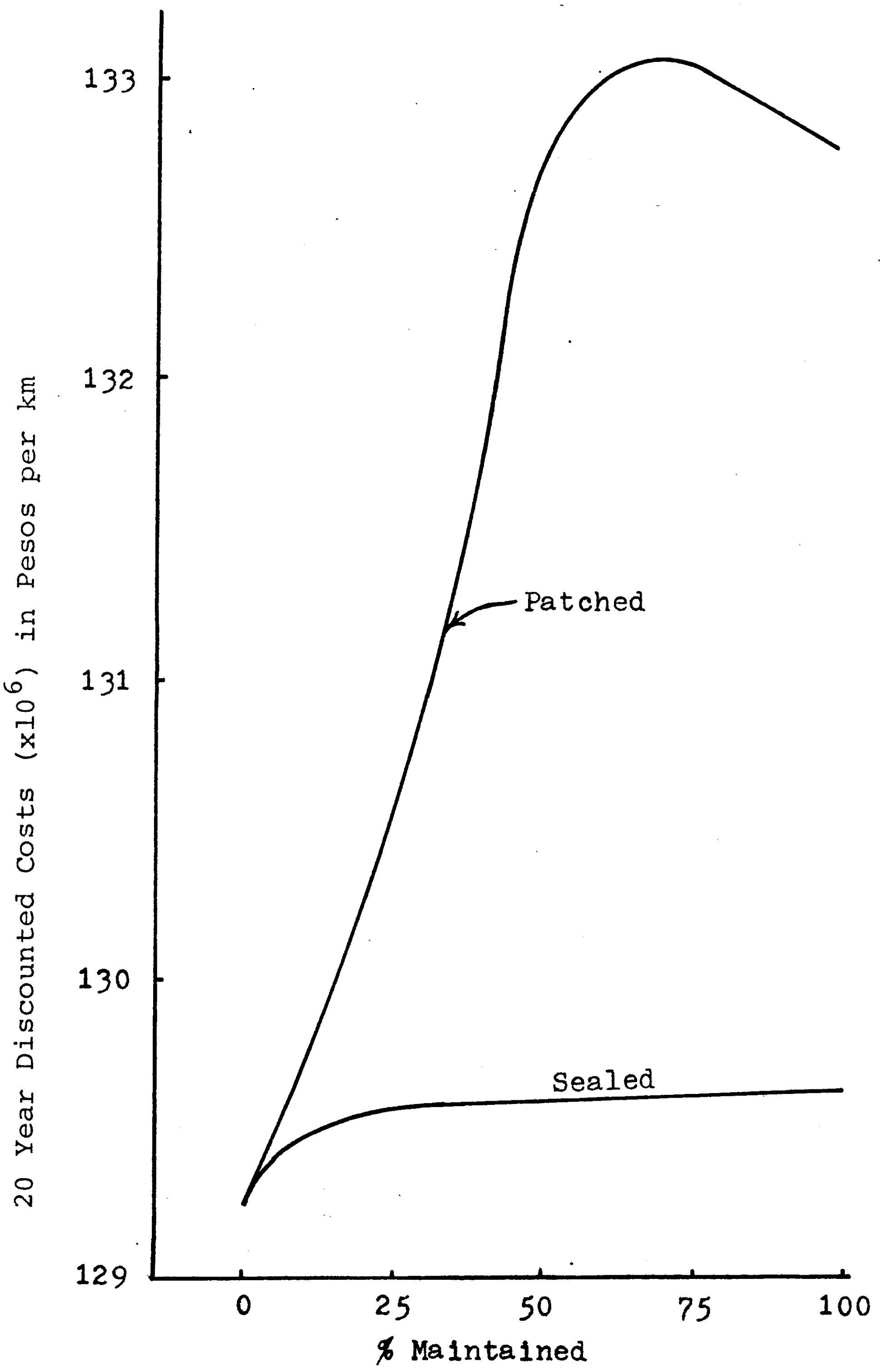

Figure 3-11: Patching and Sealing Tradeoff Analysis for Argentina Rte. 14

Finally it is also interesting to breakdown and compare the discounted maintenance cost by its component parts (labor, equipment, and material cost). In particular, the cost required for sealing cracks can be separated into 60% for labor and only 10% for materials while for patching cracks, which require, as a whole, a larger maintenance effort, can be separated into 45% for labor and a heftier 35% for materials. This result of a larger material cost for patching cracks, which is comprized of a type of bituminous cold mix, is typical of what one would expect because the material used for sealing cracks is the less expensive liquid asphalt.

The last of the 3 individual policies to be run separately was the depth of ruts which are to be filled yearly. This situation was approached in two ways.* In the first instance the percent of ruts filled was kept constant at 50% and the allowable mean rut depth was permitted to vary in increments of 0.10 cm. As before, the percent of cracks patched and sealed were held constant at 0%.

The results of this analysis is presented in Table 3-9 and shown in Figure 3-12. In examining the figure, one notes

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*In terms of background knowledge, this policy is specified both in terms of the mean rut depth allowed before ruts are filled and by the percent of ruts filled once the actual depth of ruts exceeds the allowable limit specified.

	20 Year Discounted Costs in Pesos per KM			
Maint. Ruts (cm)	Construction	Maintenance	Operating	Total
0.60	25,903,900	3,334,700	103,166,400	132,405,000
0.70	25,903,900	3,071,500	103,225,700	132,201,100
0.80	25,952,300	2,474,000	102,964,700	131,390,900
0.90	25,952,300	2,063,400	103,267,400	131,383,000
0.95	26,004,000	1,529,700	103,086,500	130,620,200
1.00	26,118,600	524,441	102,612,650	129,255,700

Table 3-9: Costs for Rut Depth Maintenance Analysis

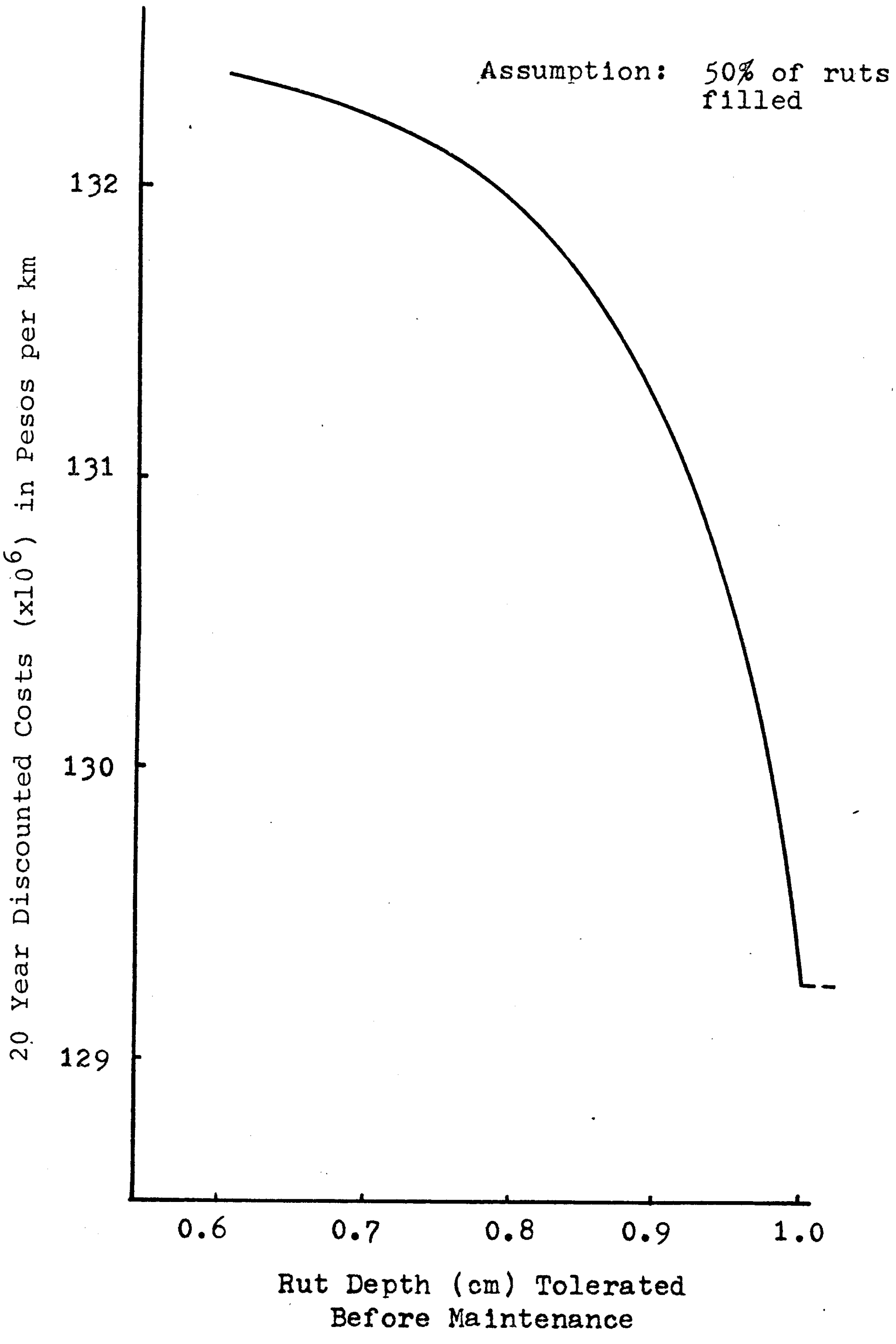

Figure 3-12: Rut Depth Tradeoff Analysis for Argentina Rte. 14

that the more the ruts are filled the more expensive the roadway becomes in terms of total discounted costs. This is consistent with previous analyses that performing more yearly maintenance is not economically efficient because the amounts of money saved both in later reconstructions and in user operating costs does not offset the increased maintenance cost.

In reference to Figure 3-12, the model was designed in such a way that ruts were never conceived to be able to progress to a depth of more than about 1.0 cm. One reason, among others, was the belief that it is unrealistic to have ruts (in the manner defined by AASHO (26)) so deep and still have what would be called a cohesive or uniform pavement surface. In other words, after ruts obtain a depth of 1 cm what would most likely happen is that the road would fracture and crumble and be considered a gravel surface.

Next, the analysis on rut depth was approached from another point of view. Specifically, the percent of ruts filled was allowed to vary in equal increments of 25% and the allowable mean rut depth was kept constant. In one instance it was held at 0.90 cm and 0.95 cm in another.

Table 3-10 and Figure 3-13 exhibit the results of these two conditions. As one can note from both curves, performing no yearly rut filling was the optimum strategy. Again this is consistent with previous results. In addition, the policy

Maint. Strategy	20 Year Discounted Costs in Pesos per KM			
	Construction	Maintenance	Operating	Total
25% 0.90	26,004,000	1,230,000	103,135,600	130,369,500
75% 0.90	25,903,900	3,010,300	103,364,300	132,278,400
100% 0.90	25,858,700	4,057,300	103,467,700	133,383,700
25% 0.95	26,059,400	956,800	102,823,300	129,839,400
75% 0.95	25,952,300	2,229,500	103,382,100	131,563,800
100% 0.95	25,903,900	3,043,300	103,569,400	132,516,600

Table 3-10: Costs for Percent Rut Depth Maintenance Analysis

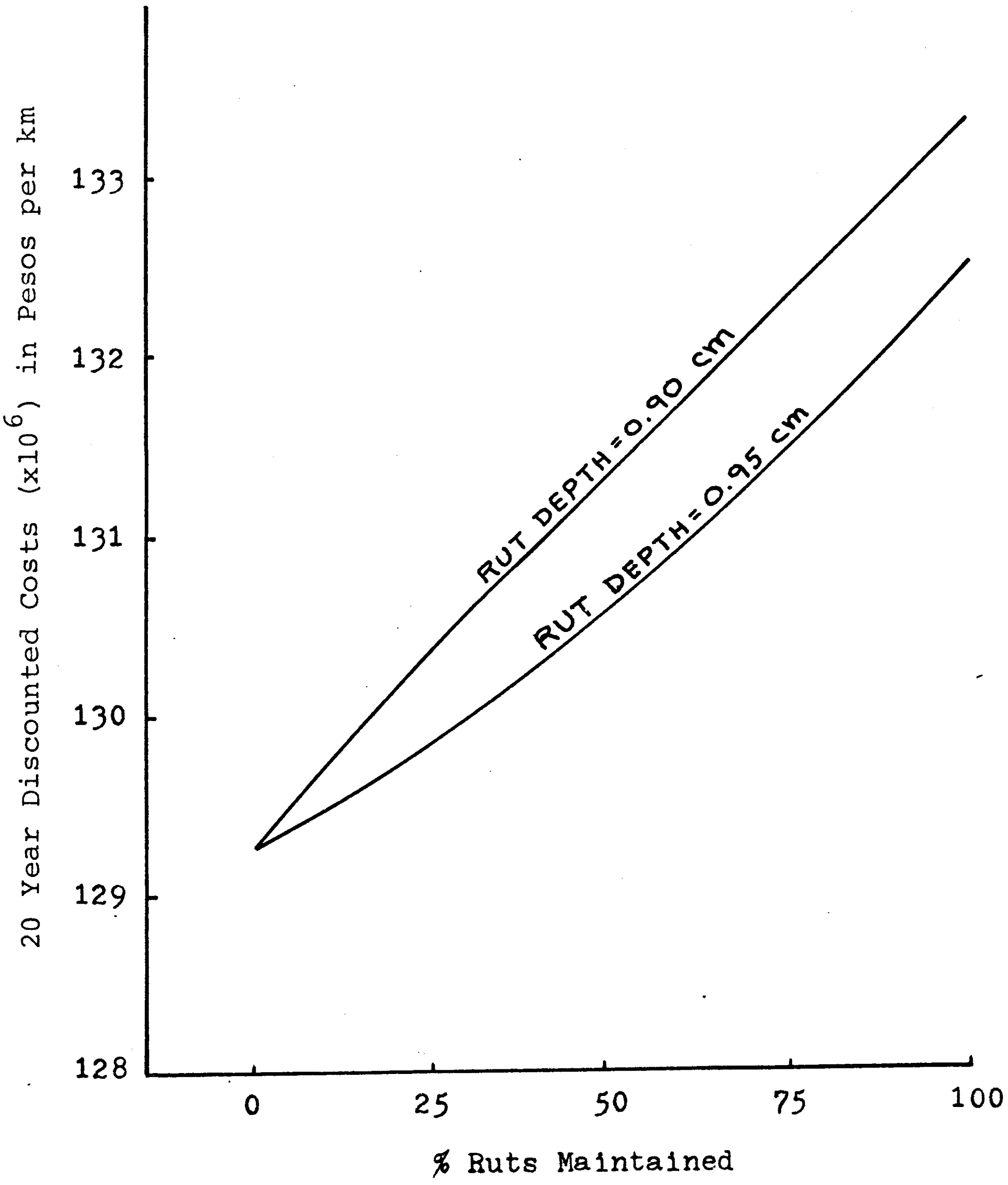

Figure 3-13: Percent Rut Depth Tradeoff Analysis for Argentina Rte. 14

that fills ruts after a depth of 0.95 cm is cheaper, strategy for strategy, than the policy that fills ruts after reaching a depth of 0.90 cm. This is synonymous with the results given in Figure 3-12.

3.4 Second Step Toward Optimality: First Iteration

The previous analyses could be labled as the introductory procedures in this heuristic process. They are equivalent to what is described as Step 1 in Figure 3-1. As previously described, the second step in the process is to examine the analyses and select that optimum which appears to be the most dominating or prevailing. This does not necessarily have to be from a cost viewpoint.

From the extensive tests and results on maintenance policies, it appears that the strategy of no (0%) yearly maintenance for all three maintenance policies is the most dominating of all the resulting tradeoffs. At the least, maintenance and its components have been approached and examined from many different angles with the resulting conclusions always being the same. Therefore, the third step in the process was to repeat some of the previous tradeoffs but first by changing the data structure to reflect the knowledge obtained from the maintenance policy variables.

3.4.1 Pavement Thickness

The first tradeoff analysis presented in this chapter on pavement thickness was the first analysis to be repeated. The same procedure as that described under the heading of "pavement thickness" was used for this new analysis. The numerical results are presented in Table 3-11. Figure 3-14 graphs the results from this analysis. For the sake of comparison, the results from the first analysis on pavement thickness are also plotted. As shown, with the new knowledge gained from the maintenance policy tradeoffs, there is a savings of about 7.0 million pesos per km ($21,000 per km) over the first optimum on pavement thickness. This represents a savings of about 6% over the previous optima and about 11% over the base run. The results of this new analysis are encouraging because they are consistently decreasing the total cost of the roadway.

3.4.2 Reconstruction Using the Minimum PSI Criterion

In the same manner that the pavement thickness tradeoff was re-analyzed with the optimum maintenance policies, the reconstruction tradeoff which uses minimum PSI as a criterion was also rerun using 0% yearly maintenance procedures. Also as before, the techniques and logic for performing this kind of tradeoff will not be repeated here for it is discussed under the heading "Reconstruction Using PSI as a

	20 Year Discounted Costs in Pesos per KM			
Strategy	Construction	Maintenance	Operating	Total
1	13,158,500	3,552,300	103,710,100	120,420,900
2	19,431,300	2,237,900	103,297,200	124,966,400
3	10,540,400	4,970,400	103,391,800	118,902,700
4	9,821,000	5,326,800	103,647,900	118,795,700
5	9,341,400	5,662,500	103,638,200	118,642,100
6	8,861,900	6,625,800	104,096,300	119,583,900

Table 3-11: Costs for First Iteration on Pavement Thickness Analysis

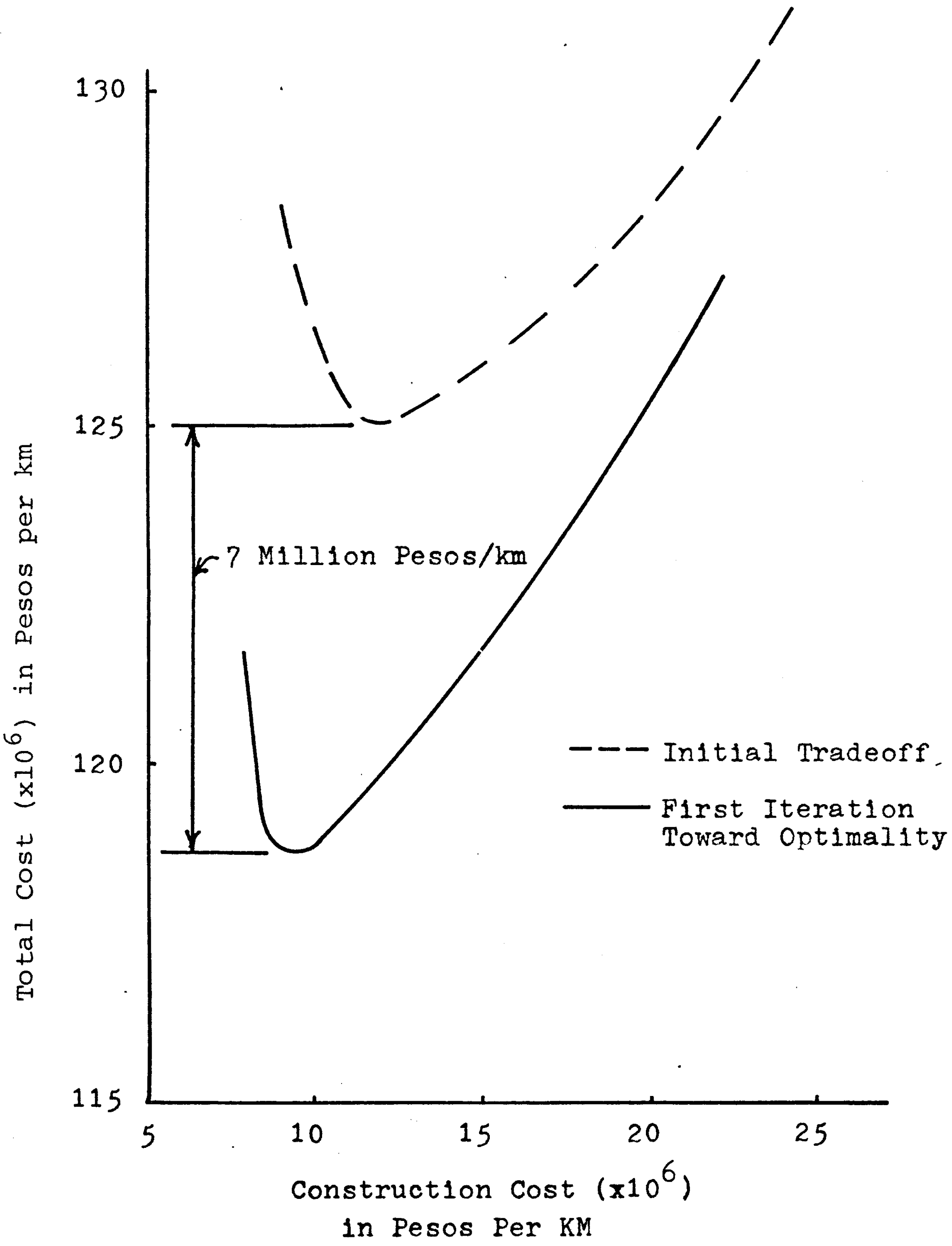

Figure 3-14: First Iterative Pavement Tradeoff Analysis for Argentina Rte. 14

Criterion" earlier in this chapter.

The numerical results of this new analysis are listed in Table 3-12. Figure 3-15 graphically illustrates the results of this re-analysis of reconstruction criterion along with those from the first analysis.

As one can see, the new analysis has improved on the previous solution to the extent of about 1 million pesos per km. Although this sum might not seem considerable as compared with previous reductions, it does illustrate the consistency of the model in the ability to reduce total roadway costs by employing previously obtained optimum policies.

3.4.3 Reconstruction Using a Time Criterion

Following the procedures previously described, the tradeoff that involves reconstruction using time as a criterion was also re-analyzed using the optimum yearly maintenance policies. Table 3-13 presents the results for this new analysis.

Two points can be brought out by this new analysis. First, in comparison to the initial tradeoff analysis the optimum strategy has shifted, by a very slight margin, from reconstruction in years 10 and 15, to a single reconstruction just in year 10. However, the margin is less than 100,000 pesos per km. Secondly, the optimum strategy has been reduced by about 1 million pesos per km over that of the

Minimum PSI	20 Year Discounted Costs in Pesos per KM			
	Construction	Maintenance	Operating	Total
1.0	26,118,600	524,441	102,612,600	129,255,100
2.0	26,926,300	524,441	101,962,900	129,413,500
2.5	27,274,700	524,441	101,073,600	128,872,600
3.0	28,444,300	524,441	100,594,400	129,563,100

NOTE: Data altered to reflect Optimum Maintenance Policy

Table 3-12: Costs for First Iteration on Maintenance Analysis--PSI Criterion

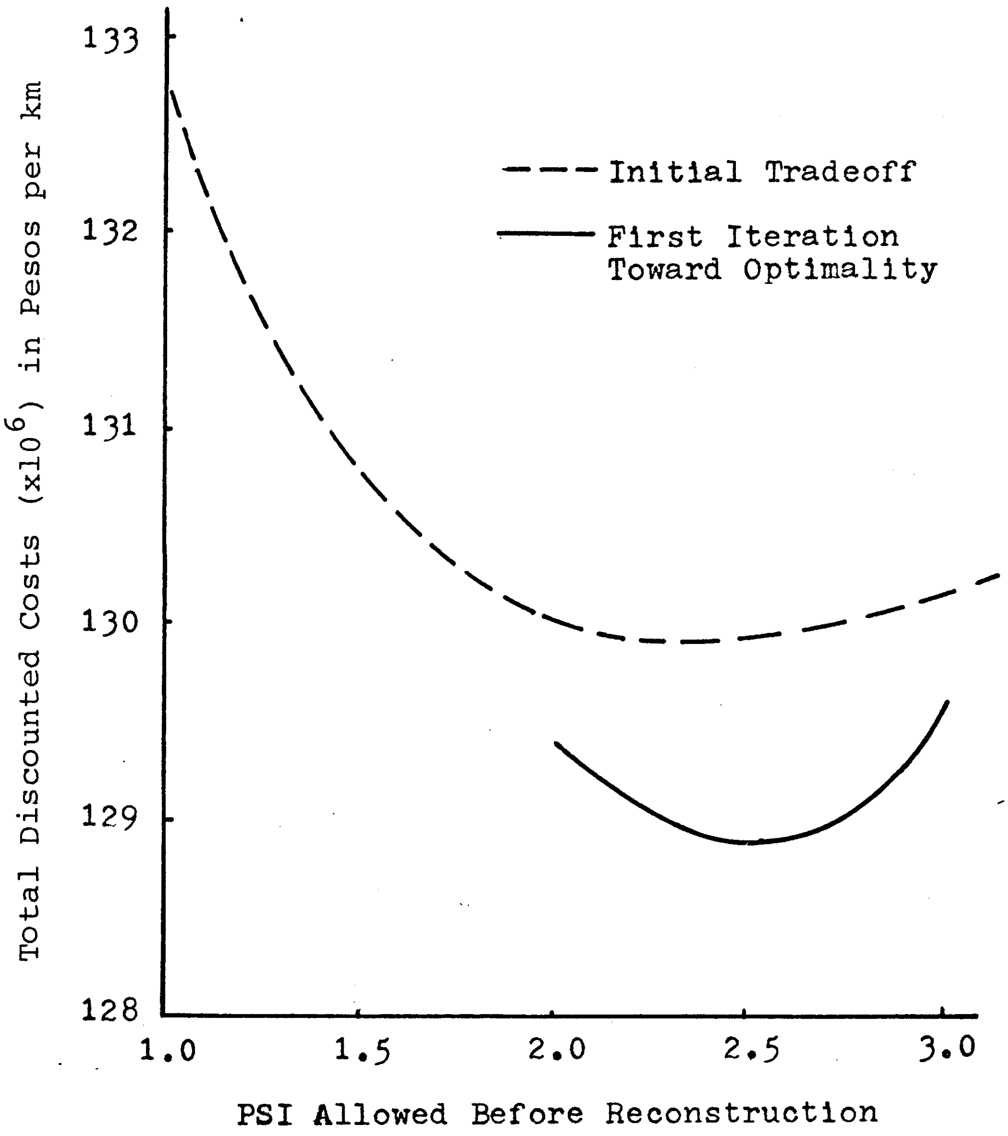

Figure 3-15: First Iterative Reconstruction Tradeoff Analysis for Argentina Rte. 14

	20 Year Discounted Costs in Pesos per KM			
Recon. Year	Construction	Maintenance	Operating	Total
5 (15)	27,524,200	524,400	102,412,300	130,460,900
10	26,400,300	524,400	101,466,100	128,390,700
15 (14)	26,118,700	524,400	102,398,900	129,042,000
5 & 10	28,065,800	524,400	100,889,200	129,479,600
5 & 15	27,725,000	524,400	100,777,000	129,026,400
10 & 15	27,247,000	524,400	100,706,800	128,478,200
5 & 10 & 15	28,912,500	524,400	100,205,700	129,642,600

Table 3-13: Costs for First Iteration on Maintenance Analysis--Time Criterion

initial optimum. This is very close to the results obtained using reconstruction with PSI as the criteria.

It should be noted here, that the model's simulation of the highway is approaching the point where it is not possible to simply reconstruct the road in a single year especially if the year is early in the road's life (for example year 5) and have the road withstand the constant deterioration process and still perform properly at year 20. Since the model is not simulating the performance of yearly maintenance the road cannot last long periods of time (15 years in the case when reconstruction is performed in year 5) and not violate the minimum PSI criterion of 1.0 that is always used as a check or safeguard by the model to prevent complete roadway failure. Thus, for the first reconstruction strategy listed in Table 3-13 (reconstruction in year 5) the road was resurfaced, although it wasn't called for, at year 15 because the roadway deteriorated, due to the absence of yearly maintenance, to a PSI level of 1.0. This additional reconstruction did not happen in the first tradeoff analysis because at that time some amount of yearly maintenance was being performed.

3.5 Third Step Toward Optimality: Second Iteration

The next and third step in this iterative process is to again select the most dominating of the previous three optima. Since the two tradeoffs dealing with reconstruction were mildly "unstable", the optimum pavement thickness was chosen as the next optimum to be controlled at its optimally determined value.

3.5.1 Reconstruction Using PSI as a Criterion

Using the same procedure as always, this tradeoff analysis was repeated but this time, the standard data deck was altered to include both the optimum yearly maintenance policy and the optimum pavement thickness. The new results are listed in Table 3-14 and are shown in Figure 3-16.

The most striking conclusion is the reduction in 20 year total discounted cost. Specifically, over the last reconstruction analysis, it represents a reduction of about 10 million pesos per km. More importantly, over the base run the savings amounts to 14 million pesos per km ($42,000 per km). This is equivalent to about a 10.5% reduction in total discounted cost; and as it should be, this is the largest reduction from the base run of all the analyses conducted. For a 72 km road, such as Section II of Argentina's National Route 14, this can be expressed as a $3 million savings ($42,000 savings/km x 72 km = $3.02 million) in total discounted costs over the design presently considered.

	20 Year Discounted Costs in Pesos per KM			
Minimum PSI	Construction	Maintenance	Operating	Total
1.5	9,841,500	6,227,300	102,761,200	118,829,900
2.0	9,341,500	7,233,200	101,972,600	118,547,200
2.5	9,341,700	9,273,600	101,099,900	119,714,900
3.0	9,341,500	11,513,300	100,641,200	121,495,900

NOTE: Data altered to reflect Optimum Maintenance Policy and Optimum Pavement Thickness

Table 3-14: Costs for Second Iteration on Maintenance Analysis--PSI Criterion

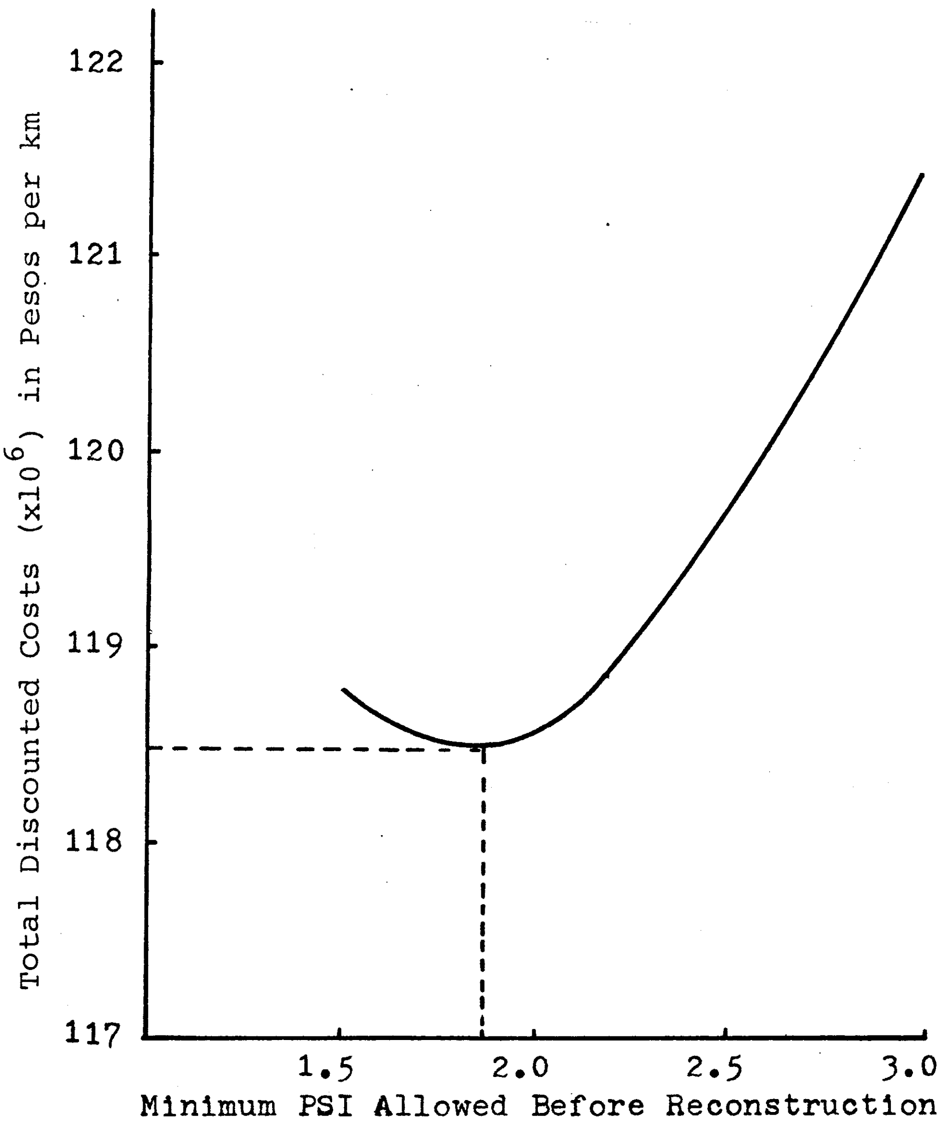

Figure 3-16: Second Iterative Reconstruction Tradeoff Analysis for Argentina Rte. 14

The tradeoff analysis for reconstruction that used time as a criterion was not repeated because of the excessive deterioration that results when the roadway is reconstructed only once in its lifetime. Therefore, the results from this analysis can be considered as the final concluding step in this iterative approach. From the variables selected to be used in this process we can safely say that this result represents a much more globally optima than all the previously reported tradeoffs.

3.6 Conclusions

It has been shown by the analyses undertaken in the first section of this chapter that the HCM can be effectively used by a planner or design agency in the evaluation of various tradeoffs between construction, maintenance, and vehicle operating costs. Also, in the context of a production process, the model was able to simulate various inputs to the process in an effort to determine which set of input parameters, variables, or policies would result in the lowest total discounted cost over the lifetime of a road.

The approach is heuristic in nature, in the sense that each new tradeoff analysis capitalizes on the results obtained in the previous step. The final analysis, using the previously determined optimum strategies, illustrates convincingly that this process does lead to an optima which is more "global" in nature than all of the previous optimum.

Only a selected number of variables and policies were chosen to demonstrate this process; that is, the procedures and results are truly illustrative of how the model can be extended and used beyond the mere simulation of construction, maintenance, and operating costs.

CHAPTER 4

LABOR VS. CAPITAL INTENSIVE MAINTENANCE

4.1 Introduction

This chapter examines the tradeoff between labor and capital intensive techniques for roadway maintenance. The two basic criteria used in the following analyses were to minimize total present worth and foreign exchange requirements. It is recognized, however, that there are other, possibly equally important factors affecting the choice of techniques than least total cost. For example, some work sites, especially in mountainous terrain, are not large enough to permit the use of oversized machines, furthermore the presence of skilled labor to maintain and operate equipment in developing nations is also an infrequent occurence (30). On the other hand, some jobs are located in remote areas where support of large labor forces; which must provide housing, food, transportation, and the elementary amenities of life are next to impossible. Also in areas which are experiencing chronic unemployment, a decision might be reached which favors labor intensive "make work" schemes and finally there is in some jobs the need for haste (31).

It is extremely difficult to develop a model which can properly judge the relative merits of various investment strategies based on social and political factors, it is, however, possible to evaluate both cheaply and quickly the economic consequences of various labor-capital policies associated with the construction and maintenance of a road project.

In general, computer simulation models are extremely useful in the rapid evaluation of costs and quantities required for physical facilities (for example, DTM, ICES COGO, ICES STRESS, ICES SEPOL, ICES STRUDL, etc.). It is in this respect that the HCM was developed to assist in the calculation of costs and quantities associated with the many facets of low volume road construction and maintenance.

The following analyses are presented to illustrate the manner by which the HCM can examine one aspect of road maintenance; in particular, the tradeoff between labor vs. capital intensive techniques. In order to demonstrate the sensitivity of this tradeoff to the type of road under consideration, two case studies, Argentina and Bolivia, are analyzed.

In contrast to the Argentine case study which has an asphalt surface and is located on relatively flat terrain, the Bolivian case study is composed of a section of gravel road located in very mountainous terrain. In addition, the Bolivian study has its own set of unit costs, productivities, design factors, vehicle composition, maintenance policy, etc. which are different from those in Argentina. Appendix A illustrates the data base used for both these scenarios.

4.2 The Argentine Case Study

4.2.1 Labor-Capital Tradeoffs

All six possible maintenance efforts available in the HCM, ranging from low labor intensive to high capital intensive were simulated and analyzed for the Argentine data. To properly examine the consequences of these maintenance activities, recollect that in Chapter 3, for the Argentine roadway, the strategy with frequent or sooner reconstructions coupled with no yearly maintenance was cheaper in terms of total discounted costs than strategies employing some amount of yearly maintenance with later reconstructions. Thus, it was not entirely unexpected to find much the same results for this analysis as shown by Table 4-1 and Figure 4-1. Specifically, the low yearly maintenance effort for both labor and capital intensive strategies resulted in the lowest total discounted cost for their respective strategy, with the low capital intensive strategy being the cheapest.

Again, just as in the previous tradeoff analyses, it

	20 Year Discounted Costs in Pesos per KM			
Strategy	Construction	Maintenance	Operating	Total
BASE	25,858,600	3,378,300	103,481,306	132,718,200
1 CI-Low	26,004,000	1,424,600	103,008,000	130,436,600
2 CI-Med.	25,903,900	2,744,100	103,406,600	132,054,500
3 CI-High	25,816,400	4,069,700	103,496,300	133,382,400
4 LI-Low	26,004,000	3,740,500	103,008,000	132,752,500
5 LI-Med.	25,903,900	4,968,000	103,406,600	134,278,400
6 LI-High	25,816,400	6,201,600	103,496,300	135,514,200

Table 4-1: Costs for Labor and Capital Intensive Strategies for Argentina Rte. 14

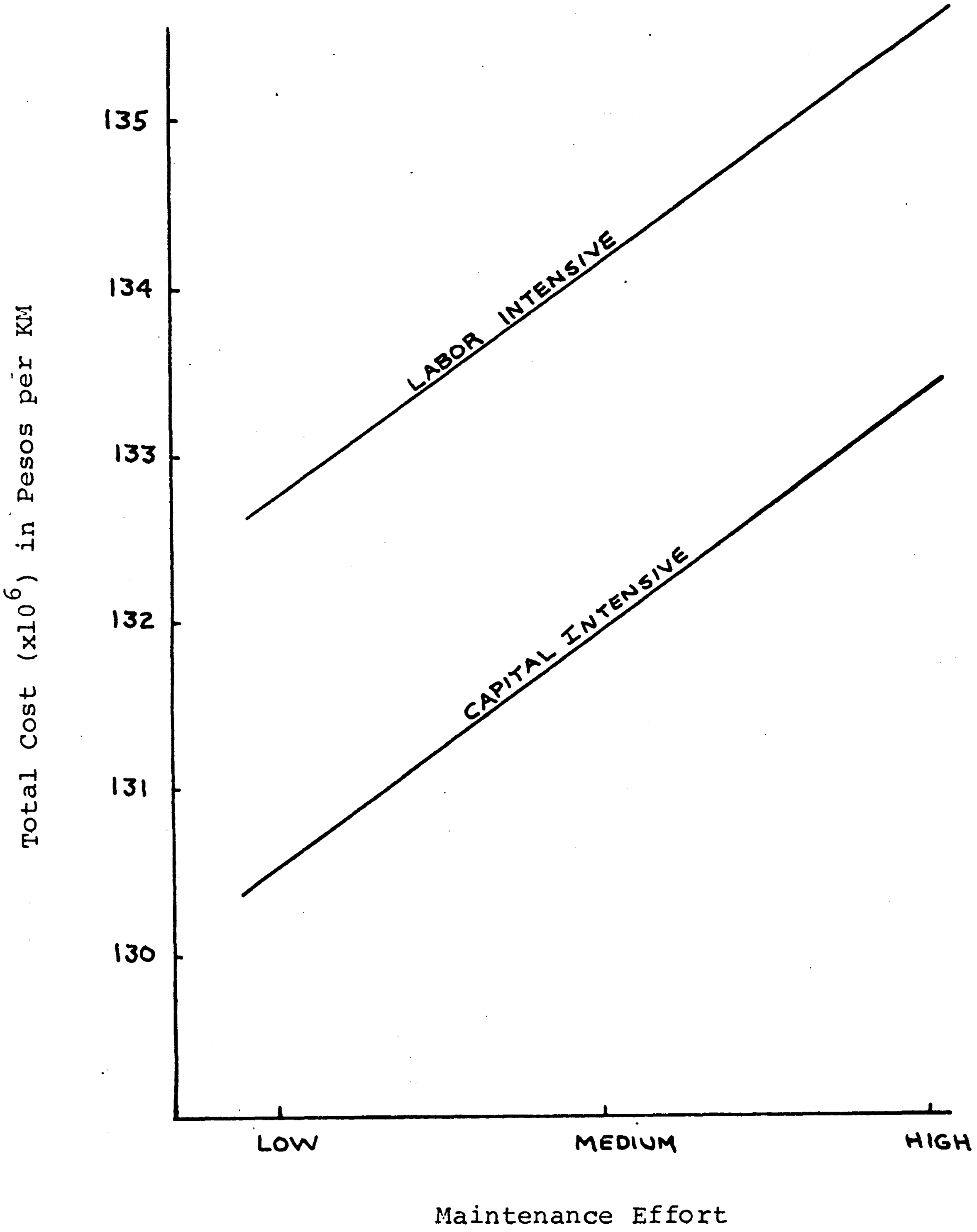

Figure 4-1: Labor vs. Capital Tradeoff Analysis for Argentina Rte. 14

is possible to reaffirm the conclusion that within the framework of policies the HCM can simulate, it is more efficient or economical to maintain an asphalt roadway by periodic reconstructions rather than using yearly maintenance procedures.

4.2.2 Components of Total Cost

Figure 4-2 illustrates the effect the various maintenance policies have on the three components of total cost. First, it is observed that as maintenance effort increases, construction cost, which includes the cost of reconstruction, decreases. Clearly the initial cost of construction is the same for all policies, therefore the reconstruction cost is the only variable. Basically, for larger maintenance efforts, reconstruction is delayed several years (in the case of Argentina, about 5 years by going from a low to a high maintenance policy) thus its discounted cost decreases. This effect is clearly exhibited in Figure 4-2.

As the amount of yearly maintenance increases, the total maintenance costs naturally become larger. Unlike the single curves for construction and operating costs, there are two curves for maintenance depending on whether labor or capital techniques are used. In this instance, because of the relative ratio of unit costs to productivity, equipment techniques are cheaper than labor intensive techniques.

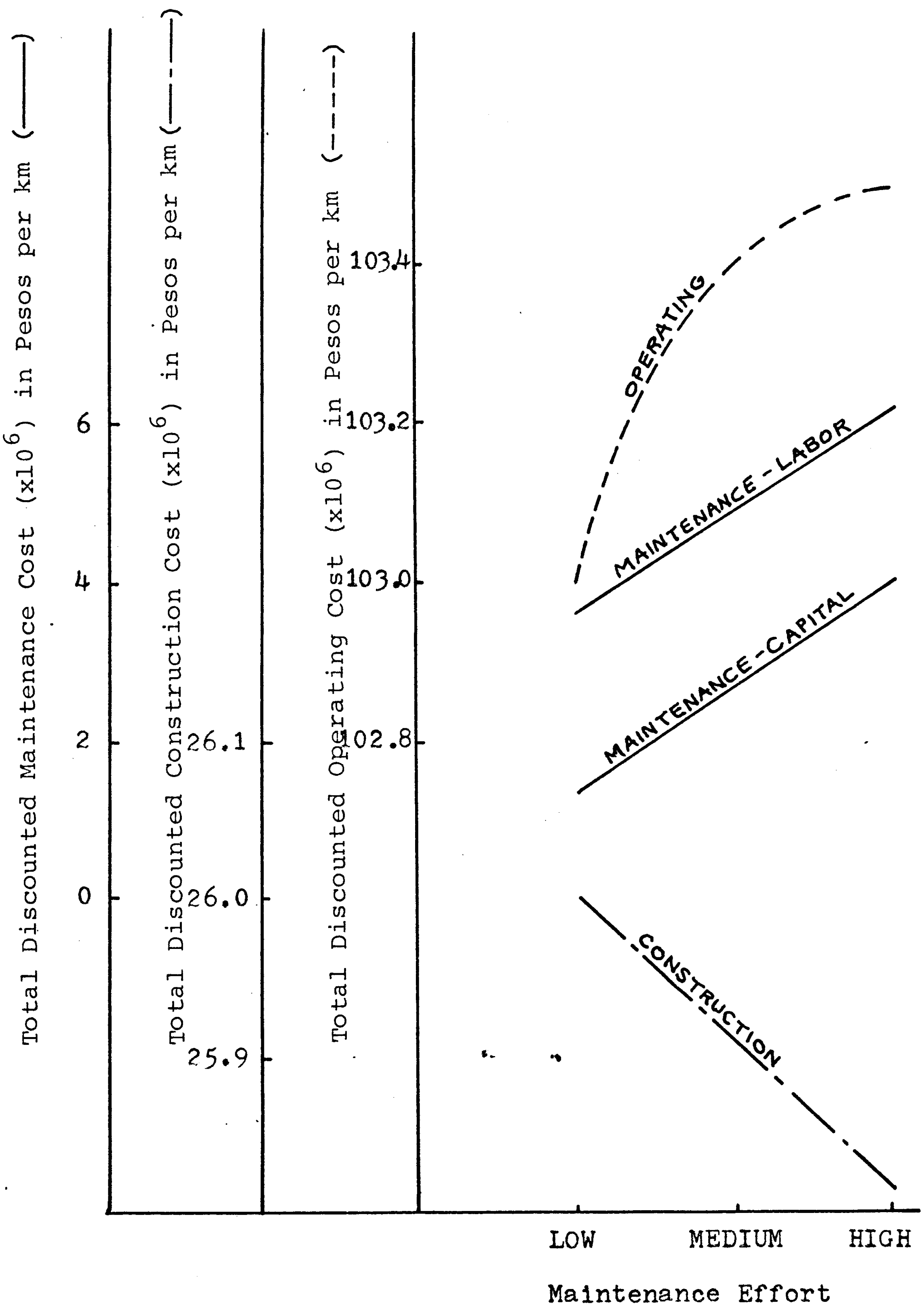

Figure 4-2: Effect of Maintenance Effort on Components of Total Cost

It will be shown later in the chapter that if this "ratio" changes, say in favor of labor, the cost curves will shift to favor labor.

Lastly, the operating cost curve appears to counter intuition. Generally one would think that as maintenance effort increases, operating costs would decrease. As shown later in this chapter for gravel roads, this is always true, but for paved roads which can be reconstructed, one cannot predict for certain, a priori, how operating cost will be affected. However, if the analysis horizon was shortened so that reconstruction does not occur, then it is true that higher yearly maintenance efforts would always result in lower operating costs. For example, the operating costs for low, medium, and high maintenance efforts in year 15 (before reconstruction) are: 81,359,700, 81,058,100, and 80,715,300 pesos per km respectively. This is consistent with what one would expect.

When the analysis horizon is increased, and reconstructions are considered, a low yearly maintenance effort forces reconstruction of the road to occur earlier than normal. Thus, as was shown by Figure 3-10, when the road is improved by an early resurfacing, velocity increases by such a significant amount that future operating costs decrease radically canceling out the earlier, more expensive operating costs.

4.2.3 Foreign Exchange

The six combinations of maintenance effort for labor and capital intensive techniques were evaluated in terms of both total cost and foreign exchange requirements. Table 4-2 lists the foreign exchange money that will be needed for the three sets of costs. It is observed from the table that strategy number 4 (low labor intensive) has the lowest total foreign exchange cost needed from foreign sources. However, since this strategy does not have the lowest 20 year total discounted costs, there is the tradeoff, which is presented in Figure 4-3 in graphical form, between foreign exchange and total cost.

In this particular case, the question the analyst must resolve is whether it is worth spending an additional 2.3 million pesos per km (see Figure 4-3) and use labor intensive techniques while only saving 100,000 pesos per km in foreign exchange.

Strictly on the basis of economics, it is better to spend the additional 100,000 pesos per km in foreign exchange and use capital intensive maintenance techniques. Not to do so and thus rely on labor intensive techniques would require spending 2.3 million pesos per km more of local funds. Of course, the final decision in this matter should also consider the social and political factors behind both strategies.

	20 Year Discounted Foreign Exchange Costs in Pesos per KM			
Strategy	Construction	Maintenance	Operating	Total
BASE	9,503,940	541,100	25,791,970	35,837,100
1 CI-Low	9,571,840	237,560	25,790,590	35,600,000
2 CI-Med.	9,525,060	453,300	25,790,320	35,769,000
3 CI-High	9,484,200	669,880	25,786,380	35,940,500
4 LI-Low	9,571,840	137,390	25,790,590	35,500,000
5 LI-Med.	9,525,060	307,360	25,790,320	35,622,700
6 LI-High	9,484,200	478,180	25,786,380	35,748,800

Table 4-2: Foreign Exchange Costs for Labor and Capital Intensive Strategies for Argentina Rte. 14

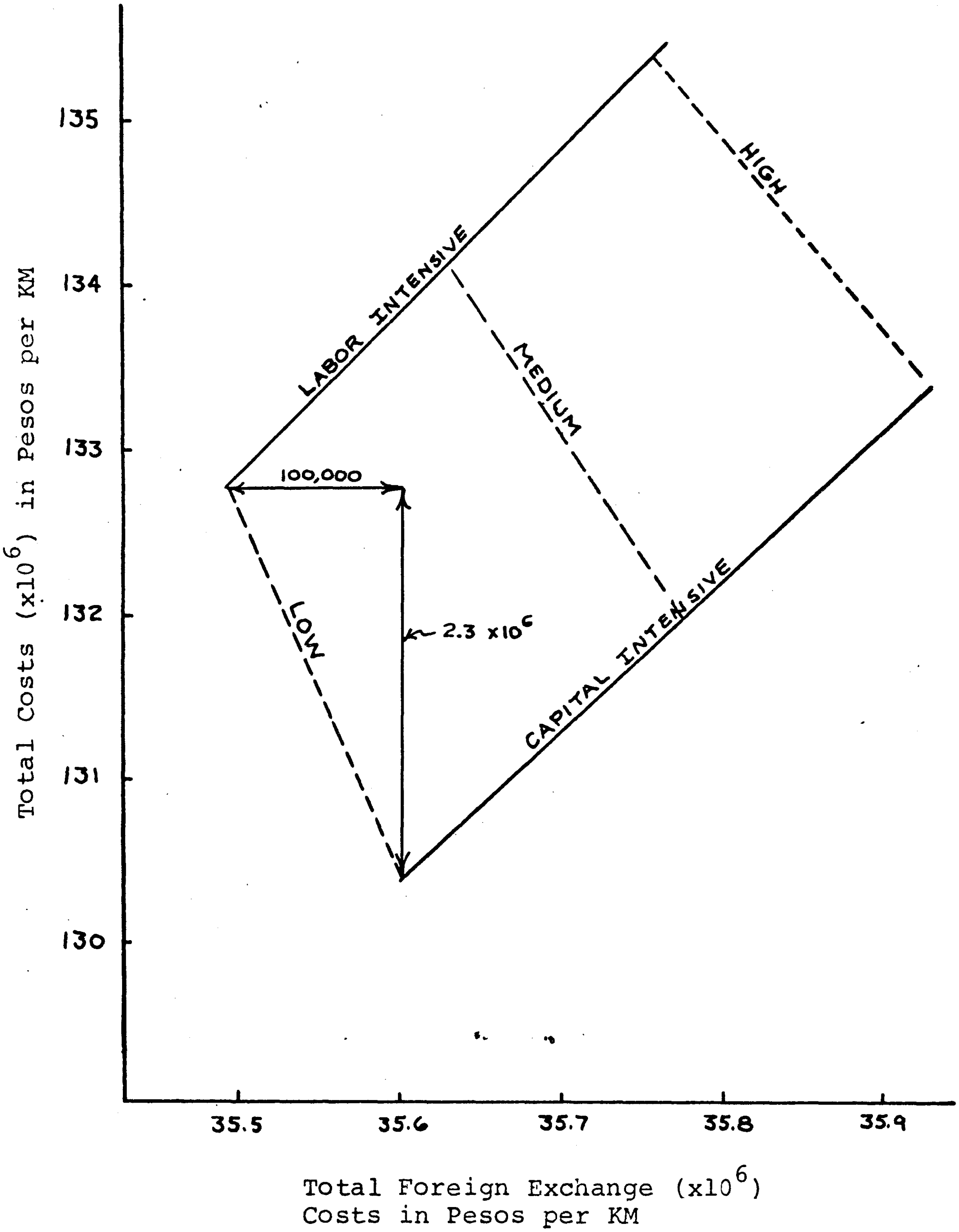

Figure 4-3: Effect of Labor vs. Capital Intensive Maintenance Policy on Foreign Exchange for Argentina Rte. 14

4.3 The Bolivian Case Study

4.3.1 Labor vs. Capital Tradeoffs

Due to the presumed importance of labor vs. capital tradeoffs in capital deficient countries, a section of gravel road from Bolivia was also examined under a variety of maintenance procedures.

Figure 4-4 is a graphical presentation of the simulated labor-capital tradeoff results listed in Table 4-3 for the Bolivian case study. The figure illustrates that the best strategy utilizes a high maintenance effort for both labor and capital intensive techniques, with high capital techniques being the best to use in terms of total discounted costs. In one sense this is contrary to the results from the Argentina study which revealed that low maintenance procedures for both labor and capital techniques were optimal, but it is not contradictory simply because the kind of maintenance required for gravel roads is completely different than that needed by asphalt surfaced roads (i.e. bladings in the case of Bolivia vs. patching, sealing, and rut repair for Argentina). Analogous to the Argentine results, however, the three capital intensive techniques were also preferred, in terms of total discounted cost, to the labor intensive techniques for the Bolivian study.

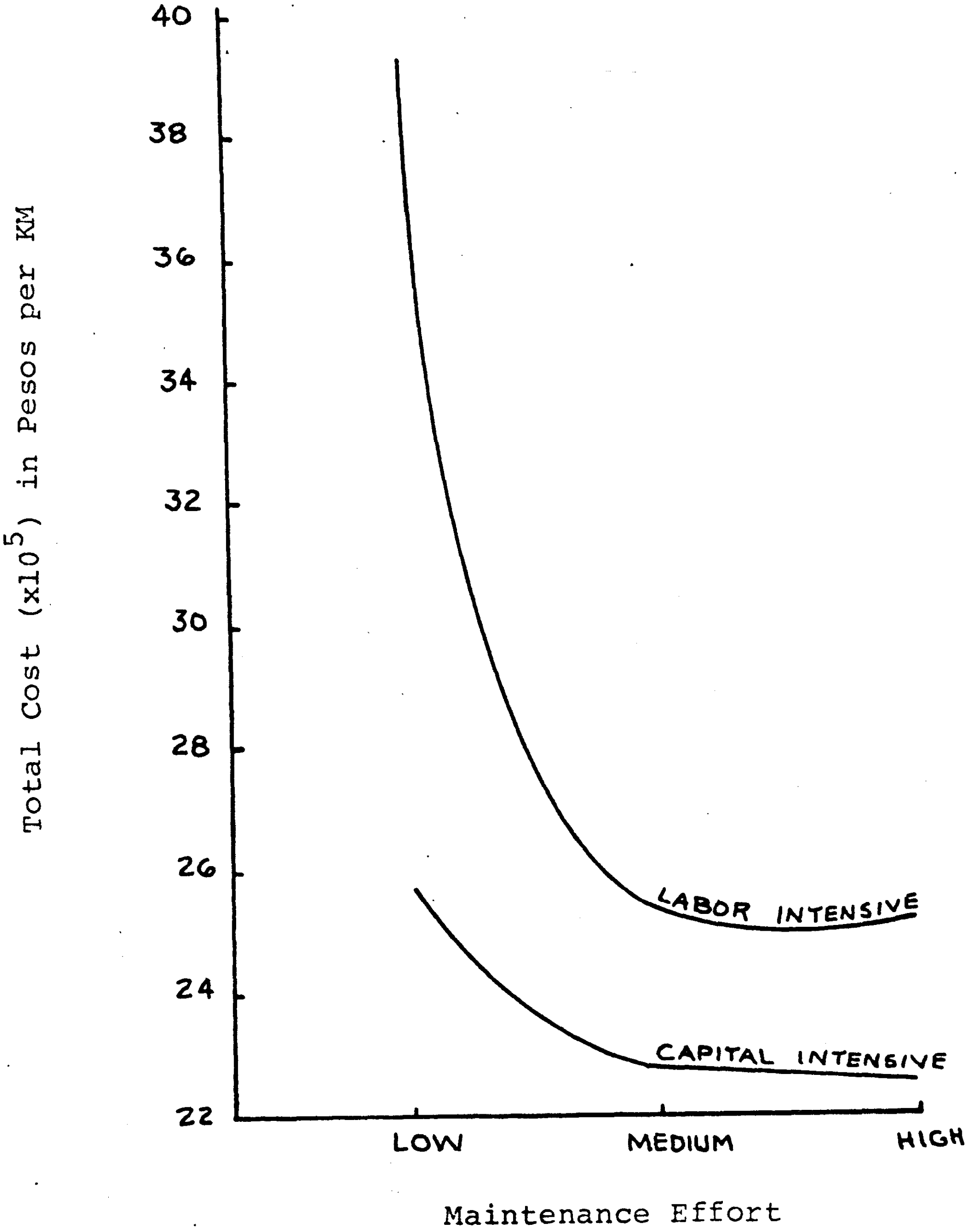

Figure 4-4: Labor vs. Capital Tradeoff Analysis for Bolivia

	20 Year Discounted Costs in Pesos per KM			
Strategy	Construction	Maintenance	Operating	Total
BASE	1,095,010	28, 825	1,127,163	2,250,998
1 CI-Low	1,095,010	11,871	1,482,615	2,589,496
2 CI-Med.	1,095,010	28,825	1,127,163	2,250,998
3 CI-High	1,095,010	50,264	1,081,101	2,226,374
4 LI-Low	1,095,010	106,751	2,744,704	3,946,465
5 LI-Med.	1,095,010	176,558	1,237,216	2,508,783
6 LI-High	1,095,010	308,536	1,089,300	2,492,845

Table 4-3: Costs for Labor and Capital Intensive Strategies for Bolivian Data

4.3.2 Foreign Exchange

As with the Argentine case study, it is important to also examine the tradeoff between total discounted cost and the amount of money needed from foreign sources. Figure 4-5 shows the foreign exchange requirements for the six strategies listed in Table 4-4.

It is observed that for all three maintenance efforts, capital intensive techniques are cheaper than the corresponding labor intensive techniques. These results can be compared to those from Argentina in the following way:

	Criterion	
Scenario	Total Cost	Foreign Exchange
Argentina	Low <u>Capital</u> Intensive	Low <u>Labor</u> Intensive
Bolivia	High <u>Capital</u> Intensive	Low <u>Capital</u> Intensive

For the Bolivian scenario, it is entirely clear-cut that capital intensive maintenance techniques are cheaper in both total cost <u>and</u> foreign exchange requirements. Thus, the only existing tradeoff of further interest is between capital intensive <u>low</u> and capital intensive <u>high</u>. While on the other hand, the tradeoff with the Argentine data is between low <u>labor</u> intensive and low <u>capital</u> intensive techniques, possibly resulting in a decision of greater dimensions (i.e. involving socio-political factors).

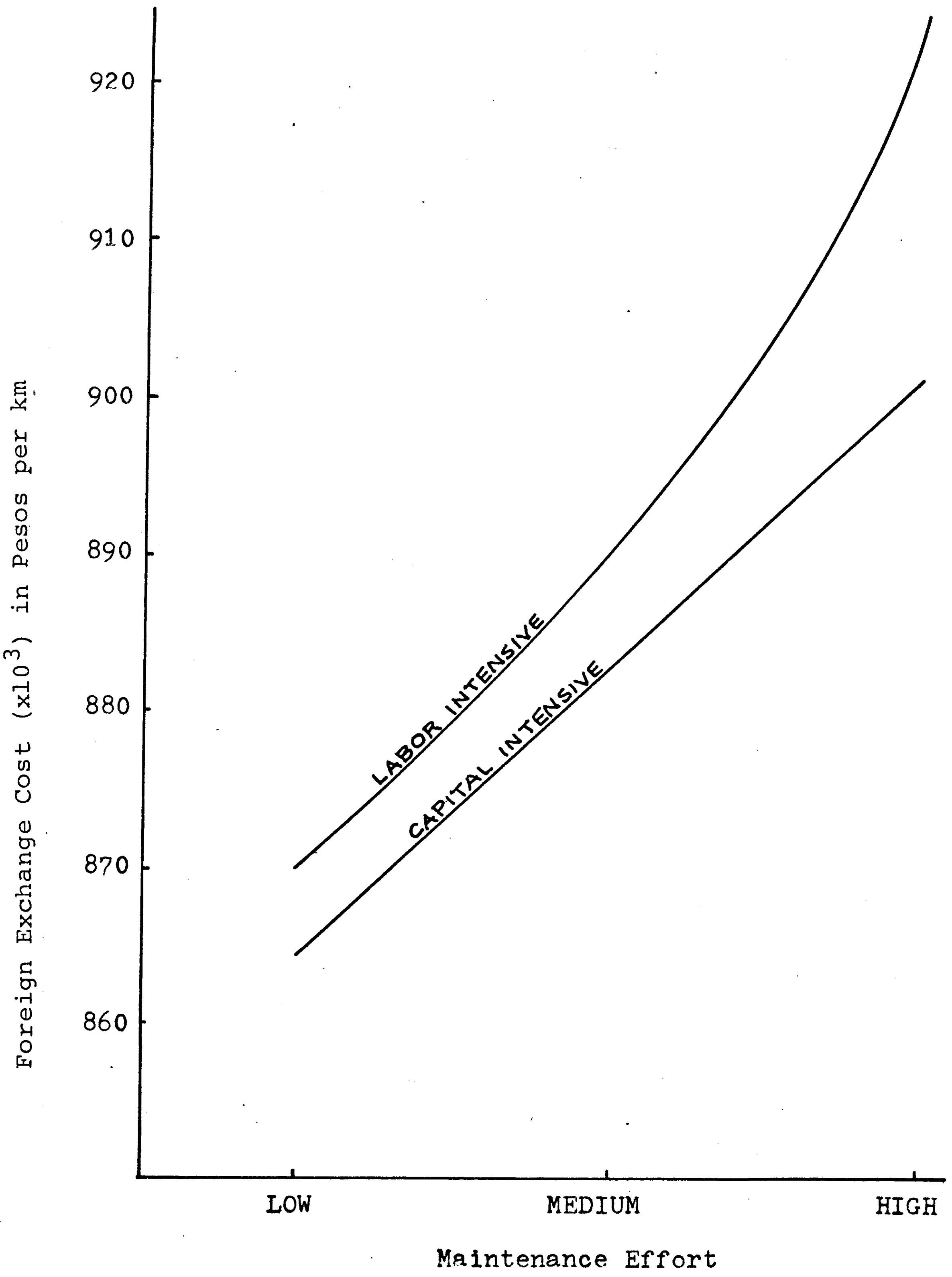

Figure 4-5: Effect of Labor vs. Capital Intensive Maintenance Effort on Foreign Exchange for Bolivian Data

	20 Year Discounted Foreign Exchange Costs in Pesos per KM			
Strategy	Construction	Maintenance	Operating	Total
BASE	600,724	26,456	256,032	883,212
1 CI-Low	600,724	10,772	253,029	864,525
2 CI-Med.	600,724	26,456	256,032	883,212
3 CI-High	600,724	45,915	254,312	900,950
4 LI-Low	600,724	16,408	242,674	859,806
5 LI-Med.	600,724	34,285	255,144	890,153
6 LI-High	600,724	68,850	255,110	924,684

Table 4-4: Foreign Exchange Costs for Labor and Capital Intensive Strategies

Certainly, however, in other situations where labor unit prices are much lower than unit prices for comparable equipment; labor intensive techniques could be the most economical. Such would also be the case if productivity rates for machinery were to decrease because of inadequate equipment maintenance, lack of experience on the part of the operator, scarcity of spare parts, mountainous terrain, a large unemployed labor force, and a number of other equivalent reasons. An excellent discussion on what may result if these conditions exist is given in reference 32.

4.4 A Re-Analysis of the Argentine Case Study

4.4.1 Labor-Capital Tradeoffs

In all the analyses discussed so far, the input to the HCM for common labor is the actual labor wage rate which is presently being paid. However, one question frequently asked, especially in areas where high unemployment exists, is to what extent would labor-capital tradeoffs be affected if the opportunity cost--to the government--of maintenance wages for common laborers were used in the analysis instead of the present labor wage scale. Stated in another way, what common labor rate would have to prevail so as to make labor intensive techniques cheaper or more desireable to use than capital intensive maintenance techniques.

Basically, two methods are possible in initially calculating what might be called the "break-even" labor wage rate for maintenance. First, one could use the trial and error approach which would consist of simply trying various labor rates in the model until the proper one is found. However, without some kind of initial calculations, this approach, although simple, could result in many runs before the break-even rate is located.

Therefore, the second method, and the one initially used, was to determine what percent of the total discounted maintenance cost is comprized of labor. From the earlier runs it was determined that on the average, for labor intensive techniques, 76% of the total discounted maintenance cost is composed of labor (the remaining being material and equipment cost) while for capital intensive techniques, the figure drops to 48%. Thus, a reduction in maintenance labor rates reduces the cost of labor intensive techniques by about 50% more than the cost of capital intensive techniques.

A simplified illustration of this second method follows. Figure 4-6 graphs the various components (labor, material, and equipment) of the 20-year total discounted maintenance cost for both maintenance strategies. The A and B components for each strategy is comprized of material and equipment cost and thus will not be affected by any changes in the labor rate.

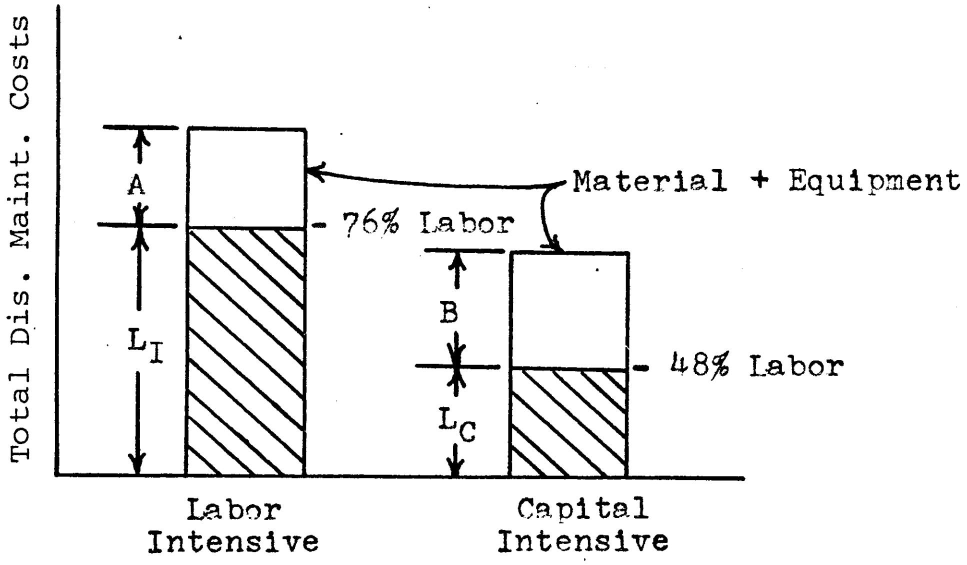

Figure 4-6: Components of Cost by Percent for Labor and Capital Intensive Strategies

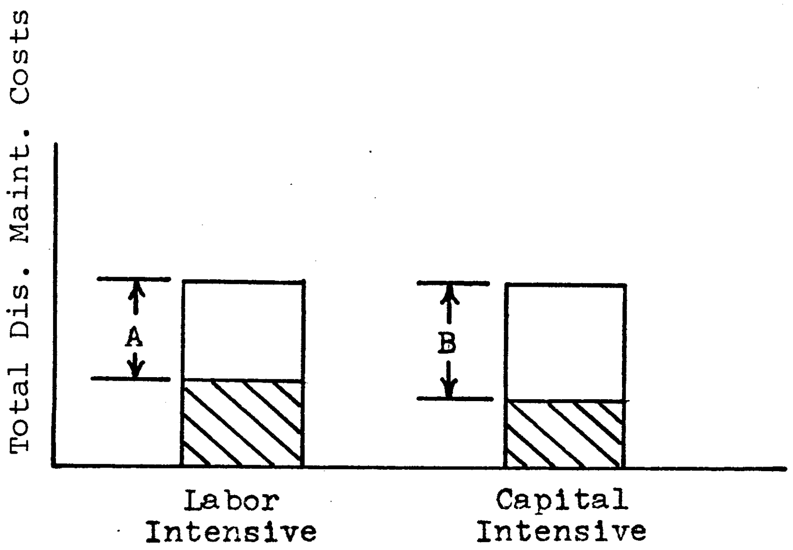

Figure 4-7: Effect of Reducing the Labor Wage Rate on Total Discounted Maintenance Cost

Figure 4-7 illustrates in bar graph form how the labor component of total maintenance cost will have to change so that the two strategies will each be equally desireable. Since material and equipment cost do not change, the A and B components remain the same in both Figures 4-6 and 4-7. Thus, the following equation can now be written:

$$A + L_I(X) = B + L_C(X)$$

Where: A = Material and Equipment cost for labor techniques
B = " " " " " capital "
L_I = Labor Cost " labor "
L_C = " " " capital "
X = Fraction that labor rate will have to be reduced

With one equation and one unknown X can be solved for.

Using this rough guide it was determined that at a wage rate for common laborers of 65 ¢/day* labor intensive maintenance techniques would become competative with capital intensive techniques. The Argentine common labor rate for maintenance was changed to 65 ¢/day in the standard or base data set and the labor-capital tradeoff analysis repeated as before.

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*The wage rate for common laborers is about one-third of what foreman and skilled workers receive. The original wage rate for common laborers in Argentina is about $6.40 per day.

Table 4-5 lists the resulting total discounted cost which are graphically shown in Figure 4-8. As can be observed, the model confirms the rough, first-cut analysis that for certain maintenance policies, the labor intensive techniques are in fact more economical to use than capital intensive techniques.

Although 65 ¢/day seems extremely low by U.S. standards, it has been reported (32) that in one project in Africa, for instance, the common labor rate used in the given analysis was 66 ¢/day. This is typical of what is experienced in other developing countries as well.

4.4.2 Foreign Exchange

Following the pattern set by the previous analyses, the foreign exchange requirements of this re-analysis of the Argentine data will be examined. First, however, it is appropriate to briefly review here how the maintenance labor component of foreign exchange is handled by the model.

Basically, the HCM implicitly assumes that maintenance labor will entirely be performed by local workers thus the amount of money originating from foreign sources is 0%. Although it might be argued that one or two foreman or supervisors could become involved with maintenance work early in the life of a road, either in an advisory capacity or until a pattern of maintenance operations can be estab-

	20 Year Discounted Costs in Pesos per KM			
Strategy	Construction	Maintenance	Operating	Total
1 CI-Low	26,004,000	756,800	103,008,000	129,768,700
2 CI-Med.	25,903,900	1,559,000	103,406,600	130,869,400
3 CI-High	25,816,400	2,365,000	103,496,300	131,677,700
4 LI-Low	26,004,000	872,800	103,008,000	129,884,800
5 LI-Med.	25,903,900	1,612,600	103,406,600	130,923,000
6 LI-High	25,816,400	2,356,100	103,496,300	131,668,700

Table 4-5: Costs for Labor and Capital Intensive Strategies for Argentina Rte. 14 and Reduced Labor Wage Rate

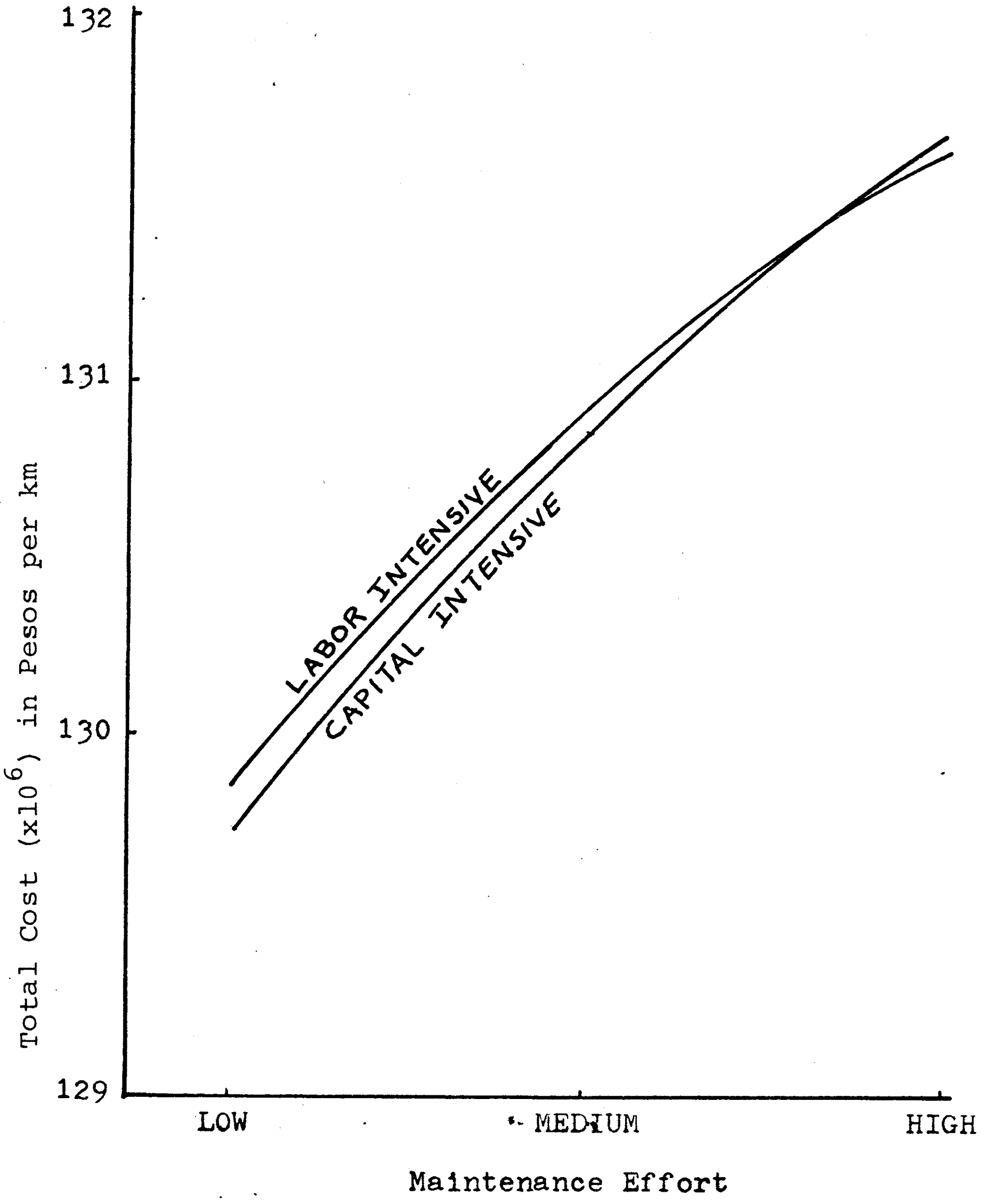

Figure 4-8: Effect of Maintenance Effort on Total Cost for Argentina Rte. 14 with Reduced Labor Wage Rate

lished, it is assumed that on the whole, the effective percent of maintenance labor cost from foreign sources over a 20-year period will approximate quite closely the zero percentile figure. Therefore, in this re-analysis, a change or reduction in maintenance labor rate should not affect the magnitude of foreign exchange requirements.

The 20 year total discounted foreign exchange cost are listed in Table 4-6 and are shown schematically in Figure 4-9. As one can see from the table, the amount of foreign exchange did in fact remain the same as that of the first labor-capital tradeoff analysis (see Table 4-2). Only discounted maintenance and total cost were affected by the reduction in the maintenance labor rate. Consequently, the tradeoff between foreign exchange and the new, revised total discounted cost is presented in Figure 4-10.

The graph brings together in one figure the important points of this re-analysis. First, one notes that for each maintenance effort, either low, medium, or high, labor intensive techniques require less in foreign exchange cost than their counterparts for capital intensive techniques. But more importantly, in terms of total discounted cost some labor intensive techniques are cheaper to use than capital intensive techniques.

	20 Year Discounted Foreign Exchange Costs in Pesos per KM			
Strategy	Construction	Maintenance	Operating	Total
1 CI-Low	9,571,800	237,560	25,790,590	35,600,000
2 CI-Med.	9,525,100	453,300	25,790,320	35,769,000
3 CI-High	9,484,200	669,880	25,786,380	35,940,500
4 LI-Low	9,571,800	137,390,	25,790,590	35,500,000
5 LI-Med.	9,525,100	307,360	25,790,320	35,622,700
6 LI-High	9,484,200	478,180	25,786,380	35,748,800

Table 4-6: Foreign Exchange Costs for Labor and Capital Intensive Strategies for Argentina Rte. 14 and Reduced Labor Wage Rate.

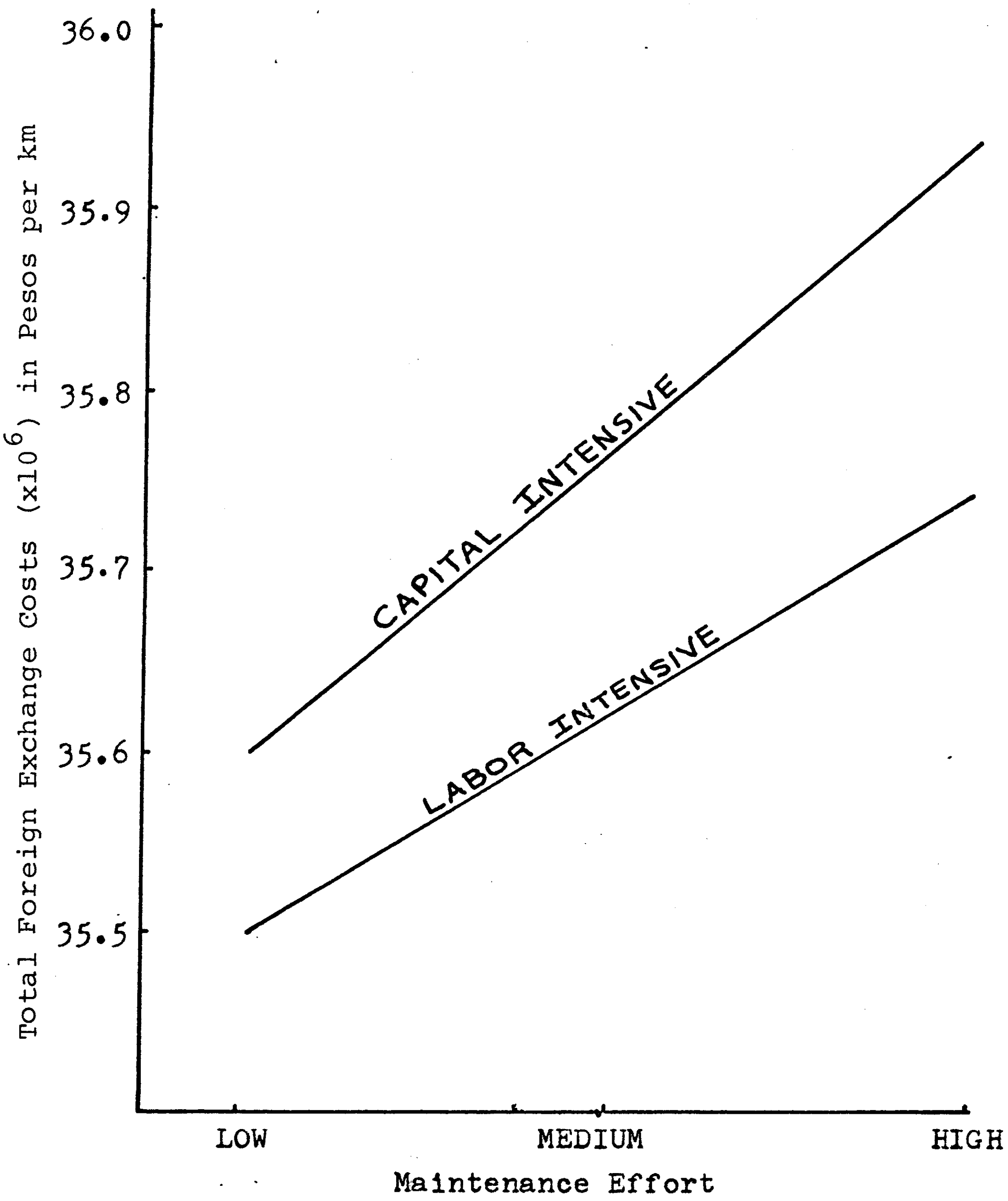

Figure 4-9: Effect of Maintenance Effort on Foreign Exchange for Argentina Rte. 14 with Reduced Labor Wage Rate

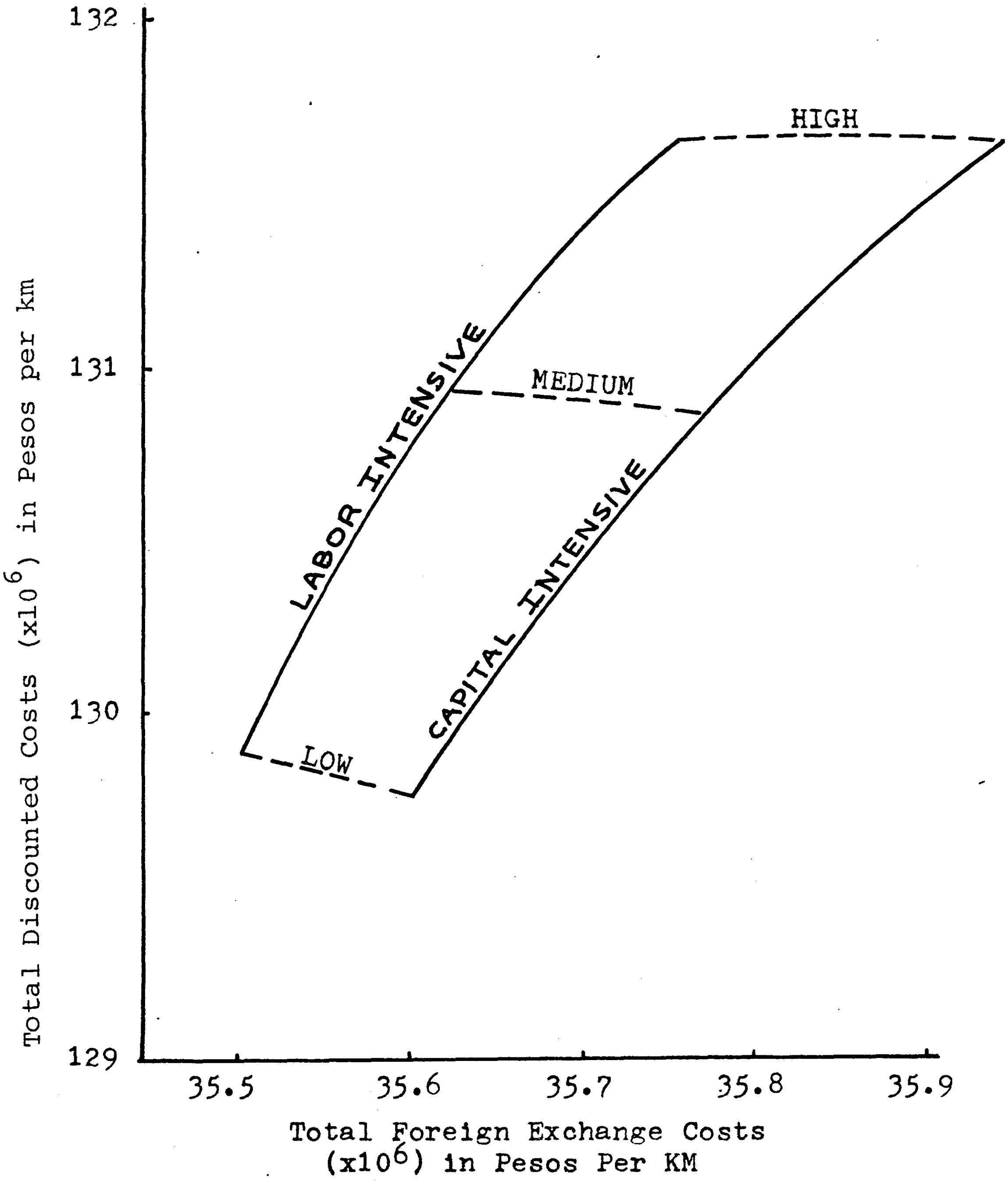

Figure 4-10: Relationship between Foreign Exchange and Total Discounted Cost for Argentina Rte. 14

This conclusion culminates the stated purpose of this re-analysis, specifically that it is possible for labor intensive techniques to be cheaper or more economical to use than capital intensive techniques if the ratio between labor and equipment costs with respect to their productivities is altered by the use of the opportunity cost for common laborers.

4.5 Summary

The analyst can use the HCM to simulate the effect labor or capital intensive strategies in highway maintenance will produce on total discounted cost and on foreign exchange. This capability is especially helpful in those developing countries which are faced with high unemployment and low foreign exchange reserves.

Data from the Argentine and Bolivian case studies were used in conjunction with the HCM to illustrate typical results and functions that the model can handle. From an analysis of the results on maintenance activities, it was observed, among other conclusions, that:

1) Capital intensive maintenance techniques were cheaper in terms of total discounted costs than labor intensive techniques and,
2) When foreign exchange was the primary criterion, low labor intensive maintenance techniques could

be used although this significantly adds to total discounted costs. (Note: this result applies to the Argentina case study with its asphalt surface only.)

Next, the notion of using the opportunity cost of maintenance labor was introduced and its effect on total cost analyzed. It was estimated that on the basis of a daily wage rate of 65 ¢/day some labor intensive strategies were more economical to use than capital intensive strategies.

Again, it should strongly be suggested that the model should be the tool in evaluating various strategies and the results presented here are only illustrative of the use of the model and might not apply to a wide range of conditions not simulated. This statement is especially true when the ratio between labor-capital wage and productivity rates change either from site to site or over time.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The various analyses presented in Chapters 3 and 4 demonstrate that the HCM can definately be used as an effective tool by planners in the initial decision and policy phases of transportation planning for highways in developing countries. The analyses in particular illustrate the manners by which planners can improve their decisions by using results previously obtained from the model in what may be described as a dynamic approach to highway transportation planning.

In terms of the constraints which limit development (i.e. scarce capital resources, low foreign exchange reserves, aboundance of common or unskilled labor), the research reported shows that it is possible to use the HCM in such a fashion that the constraints can be considered explicitly in decision making.

This study has shown that an iterative analysis framework can be used to interact closely with the HCM in an effort to obtain the "best" or most "desireable" (from a viewpoint of total discounted cost) set of design decisions and maintenance policies. In examining the final results it was concluded that this approach is quite successful in its iterative search and evaluation of optimal strategies. The final set of policies should not be accepted as "handbook" results but instead it should be clearly understood that the approach is illustrative of how designers may use the model with their own data and local conditions.

Finally the labor-capital tradeoffs including the analysis of foreign exchange requirements illustrate the model's ability to easily examine the consequences of different maintenance strategies. As unskilled labor is generally plentiful in developing nations, these kinds of analyses can trace out, simply and cheaply the consequences of using labor intensive techniques with their lower productivity and lower foreign exchange requirements versus the use of higher productive but more expensive (i.e. unit costs) capital intensive techniques.

Based on an analysis of the results, it was concluded that for the Argentine and Bolivian labor wage and productivity rate, capital intensive techniques are cheaper to use than labor intensive techniques. However, if the opportunity cost of unskilled labor (which is usually much lower) is replaced in the analysis, labor intensive techniques then become preferable.

Again, the analyses are illustrative of only one set of conditions and might not be applicable to other areas.

Consequently it is stressed and emphasized that the model be used only as a tool in decision making.

Recommendations for Further Work

A general recommendation which can be made based on the work presented in this thesis is the use of the HCM in conjunction or in parallel with an actual engineering feasibility study, or probably simultaneously with existing evaluation techniques. Once the model completes this stage of testing it should then be re-evaluated in terms of its accuracy, assumptions, usefulness etc. At this time another decision should be made to determine whether the model is considered "eligible" to be used in a much broader capacity.

Although the "ground breaking" research has been done on labor intensive techniques for roadway maintenance, there is still a great need for research into all aspects of the problem. In particular, the feasibility of using intermediate technologies involving a mixture of modern equipment and manual methods appears promising and should be investigated further. That is, instead of comparing the most labor intensive to the most capital intensive methods one could establish various ranges or grades of intermediate levels of technologies. This should provide a wider, more realistic range of possible strategies.

In a manner similar to the above, the model should be expanded so that one could specify the intensity of labor and equipment for each maintenance activity that is to be performed. For example, reconstruction may be undertaken by capital-equipment techniques, while sealing and patching is performed by hand labor. This entire area would rely or hinge on the development of better productivity rates for labor in addition to some kind of assessment of the quality of work performed. If this recommendation is followed, it would be adviseable to concentrate on countries where there is a specific need for these technologies.

Next, the model could be adjusted so that road maintenance in the early years of a road's lifetime may be done by labor intensive techniques, say at a low level of effort but gradually over time, as skill in the area of maintenance improves, it can be phased into equipment oriented techniques which might be used at a larger level of effort. It is not implied here, however, that these are necessarily better strategies but that if they were at least incorporated in the model it would allow an analyst to investigate their effects cheaply and quickly so that it is possible to evaluate for certain whether they are preferable or not.

Finally, at the present time only one standard or typical labor-capital mix is used for all aspects of road construction. Although the analyst can alter it to his own conditions, it involves changing DATA statements in the model. Thus, it is recommended that in a manner similar to the way in which various labor and capital intensive efforts for roadway maintenance were incorporated into the model, various labor-capital intensities and mixes be established for all components of road construction. Not only would this open up a wider range of alternative strategies for road construction* but it would make available many alternatives that could be combined with various maintenance policies. As an example, a labor intensive work force could be used in certain areas of road construction which could gradually shift to more capital-equipment techniques for roadway maintenance.

In total, these recommendations could eventually result in an extremely flexible model which would be able to simulate large sets of construction and maintenance policies, efforts, and labor-capital mixes.

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*For example, employing labor intensive techniques for site preparation, drainage, and surfacing; while using capital intensive techniques for earthwork.

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APPENDIX A

ARGENTINE AND BOLIVIAN DATA

Figures A-1 and A-2 reproduce the input data needed by the Highway Cost Model for the Argentine and Bolivian scenarios respectively.

The case studies were taken from two engineering feasibility studies. The first, performed by Louis Berger, Inc., investigated, among others, Provincial Route 14 in Argentina (28). The second study, by Baker-Wibberly and Associates, Inc., reported on the Sapecho-Puerto Salinas road in Bolivia (33).

As the figures indicate, the two roads differ in many respects, including traffic volumes, terrain, alignment, maintenance policies, and proposed design. The Argentine road, comprized of asphaltic concrete, was designed to carry relatively high levels of traffic on a straight, flat embankment on a floodplain north of Buenos Aires. On the other hand, the gravel surfaced Sapecho-Puerto Salinas road, was expected to carry relatively little traffic through the Andes, about 300 km (185 miles) northeast of LaPaz.

```
 OUTPUT SWITCHES FOR THIS RUN ARE  CONSTRUCTION  0       MAINTENANCE  3   USER  0
 OUTPUT IS PRINTED FOR YEARS THAT ARE A MULTIPLE OF 20  UNLESS THIS NUMBER  0  IS POSITIVE
THE TRAFFIC GROWTH SWITCH IS -1 AND THERE ARE  1 SETS OF   INITIAL TRAFFIC CONDITIONS ASSOCIATED WITH THIS PROJECT

        RUN 50C                                                    DATE 1/ 1/72


TYPICAL ARGENTINA PAVED ROAD
 ALIGNMENT DATA-ALIGN
  LENGTH   DEG-CURVE
    73.42      0.10
PROFILE DATA- PROF
TYPE-SWITCH AVE-GRADE MAX-GRADE NO-VPIS
    -1.00      C.32      3.13     49.00
VPI STA   VPI ELEV  VPI STA   VPI ELEV  VPI STA   VPI ELEV  VPI STA   VPI ELEV  VPI STA   VPI ELEV
    0.0       4.90   1300.00      6.95  12500.00      7.10  14650.00      9.10  15500.00      9.10
 16650.00     7.95  20900.00     11.90  23600.00     17.80  25300.00     30.66  27900.00     32.22
 28650.00    42.55  28850.00     43.95  29750.00     41.33  31050.00     46.93  31250.00     46.03
 32000.00    37.20  33750.00     40.70  35300.00     52.37  37200.00     41.10  37900.00     41.94
 38100.00    41.40  39200.00     34.62  40200.00     34.90  41850.00     26.63  43000.00     24.00
 43850.00    23.00  45000.00     25.20  45750.00     31.00  46600.00     37.00  48050.00     43.50
 48750.00    41.17  49700.00     45.45  51200.00     36.75  52750.00     39.30  53800.00     32.30
 55650.00    33.60  57250.00     24.00  58200.00     29.68  59700.00     19.70  61000.00     21.40
 62750.00    15.06  64300.00     21.40  64700.00      8.86  66900.00     10.07  68450.00     19.84
 70900.00    30.20  71450.00     24.98  72800.00     25.90  73420.00     20.30
ROADWAY CROSS SECTION(HORIZONTAL)-TEMPL
    WIDTH     SLOPE    SHLD-WD   SHLD-SL    DTH-WD    DTH-SL    DTH-WD    DTH-SL    CUT-SL   FILL-SL   PAVE-WD   SIDE-CL
     3.65      0.02      1.20      0.05      4.00      4.00      3.00      0.03      2.00      4.00      7.30     22.70
ROADWAY DESIGN DATA(VERTICAL)-PAVE
   PAVE-CD    LAYERS   MAT-TPE  THICKNESS  MAT-TPE     THICK   MAT-TPE     THICK  SHLD-TPE    THICK1    THICK2    THICK3
     3.00      3.00      6.00      0.20      5.00      0.48      1.00      0.07      1.00      0.20      0.48       0.0
ECONOMIC DATA
NO OF PERIODS,DISC. RATE, NO OF VEHICLE TYPES
       20      7.00          5
   FOREIGN RATE OF EXCHANGE
        1 PESOS        =    0.00300 DOLLARS
   PERCENTAGE OF COSTS THAT ORIGINATE FROM FOREIGN SOURCES
         PER CENT OF VEHICLE COST =  80.00        PER CENT OF FUEL COST =  70.00PER CENT OF TIRE COST =  80.00
         PER CENT OF  LABOR COST =    0.0         PER CENT OF CONSTRUCTION EQUIPMENT COST =  93.00
         PER CENT OF SOURCE COST =  25.00         PER CENT OF MAINTENANCE  EQUIPMENT COST =  90.00
MAINTENANCE POLICY-MAPOL
   DRAIN-SW  RGRVLSW  SHLD-SW    MOW-SW    BLAD-SW    BLAD-DRY  BLAD-WET    MOW-FRQ   RUTFFL    CRKDTH    CRKFSLD   RUT-DTH   SUR MNT
     1.00     1.00      1.00      1.00      -1.00    5000.00   5000.00      3.00      0.80      0.50      0.50      1.50      0.0
RECONSTRUCTION SCHEDULE- RBLD
   NO-UPGRAD
       0
TOPOGRAPHY- TOPOG
NO. OF STATIONS          90
TYPECODE  FLAT       ROLLING    MOUNT      NSTA
    -1.00   100.00       0.0        0.0      90.00
STATION   ELEV.      STATION   ELEV.      STATION   ELEV.      STATION   ELEV.      STATION   ELEV.
    0.0       4.00   1300.00      6.50   5500.00      6.50   5600.00      5.50   8000.00      6.00
 10000.00     5.50  11000.00      5.40  12500.00      4.20  13500.00      4.00  14650.00      5.00
 15500.00     6.10  16650.00      7.40  20900.00     10.20  23600.00     17.60  25300.00     29.30
 25750.00    30.00  26400.00     27.30  27050.00     34.00  27900.00     29.00  28650.00     45.50
 29750.00    40.00  30250.00     40.00  31050.00     48.30  32000.00     35.40  32500.00     41.00
 33200.00    38.00  34900.00     53.40  35300.00     48.50  35700.00     52.50  36300.00     44.50
 36650.00    44.00  37200.00     40.00  38100.00     41.40  38750.00     35.20  39200.00     34.40
 39550.00    31.20  40200.00     37.70  41150.00     27.40  41500.00     29.00  41850.00     26.70
 42000.00    26.00  42500.00     24.00  43000.00     24.00  43500.00     23.70  43650.00     22.80
 43850.00    23.00  44370.00     24.00  45500.00     25.40  45750.00     31.00  46600.00     37.00
 47100.00    37.00  47700.00     45.00  48050.00     44.20  48750.00     42.17  48850.00     40.00
 49300.00    41.00  49700.00     48.00  50000.00     43.50  50750.00     41.50  51000.00     37.00
```

Figure A-1: Argentine Base Scenario Data

```
 51200.00     37.50  51450.00     34.50  52350.00     40.70  52750.00     39.30  53800.00    30.80
 55000.00     29.50  55650.00     36.00  57250.00     22.00  57800.00     29.90  58200.00    29.68
 58600.00     29.50  58900.00     24.70  59700.00     16.70  60500.00     19.00  61000.00    22.60
 61675.00     15.50  62100.00     17.00  62780.00     12.00  63600.00     15.60  65100.00     8.00
 65500.00      3.00  68450.00     20.40  69075.00     21.60  69500.00     15.90  70000.00    22.00
 70400.00     22.50  70900.00     33.50  71600.00     20.30  72800.00     28.60  73420.00    18.10
SOIL + GROUNDCOVER-CBR,GRDCV
     CBR     EASY    NORMAL    DIFFICULT
     6.00  70.00      30.00        0.0
DRAINAGE RELATED DATA-DRAIN
  WATR-BLDE   IMPASS   AVERAIN   MT-RAIN  FLT-MED     FLT-LGT
     1.00     1.00     120.00      0.0       1.00      1.00
HAUL DISTANCES,CONSTRUCTION
                                               PAVEMENT                MAINTENANCE
    %-BOR    HAULDIST   LAYER1    LAYER2   LAYER3   SHOULDER    WATER    GRAVEL    PATCH    CULVERTS
    10.00     36.00    644.00    380.00      0.0     380.00      2.00     15.00    40.00    142.00
CONSTRUCTION PRODUCTIVITIES + COSTS-PROD
SITE PREPARATION
     EASY     NORMAL     HARD    LCOST    EQCOST
     0.50      0.40      0.20     20.36     63.40
EARTHWORK
   BORROW   TRANSPORT    PROD    LCOST    EQCOST
     1.26      0.06    250.00     95.94    417.34
PAVEMENT
     PROD     SOURCE   TRANSPORT   LCOST    EQCOST
   400.00      1.86      0.00     67.52    147.20
   163.00     22.30      0.01     96.23    207.77
   387.00     65.70      0.0     151.61    451.16
   163.00     22.30      0.01     96.23    207.77
DRAINAGE
    NO. OF CULVERTS =      3.00
    SCOST    WEIGHT     TCOST
    67.10     55.00      0.00
   107.41    110.00      0.00
   168.37    160.00      0.00
OTHER COMPONENTS
    %TCOST   %LABOR    %TCOST    %LABOR
     0.0       0.0       0.0       0.0
MAINTENANCE COSTS AND PRODUCTIVITIES-MUC
    BITDIS   DUMPTRK   TRALDR   MOTORGD    ROLLER    TRACTOR   WTRTRK
    15.05      9.30     25.00     23.65      9.68      9.00     9.90
    CLABOR   ECOPER    FOREMAN  TDRIVER    LIQASHP   PATMIX    COVSEAL
     2.65      5.80      6.70      4.80      0.16     42.20     1.00
  DIESELFUEL GRCOST    GASCOST  WATERC
     0.16      1.00      0.37      0.0
USER COSTS,ECON. AND MARKET- ECONO,MARK
    LABORC   DRIVER    GASCOST    DIESEL
     1.50      1.90      0.18      0.15
     3.00      3.90      0.37      0.16
     INITIAL COST          TIRE COST         VEHICLE COST       CARGO COST
   ECONOM    MARKET    ECONOM    MARKET    ECONOM    MARKET    ECONOM    MARKET
 10000.00  15000.00     87.00    130.00      2.70      3.10     0.0       0.0
 11000.00  16000.00     97.50    160.00      1.40      1.50     0.0       0.0
 26000.00  40000.00    400.00    570.00      7.23      7.25     0.0       0.0
 41000.00  63000.00    588.00    860.00      7.99      8.10     0.0       0.0
 79000.00 112500.00    535.00    790.00      7.00      7.10     0.0       0.0
VEHICLE DATA- VEH
 DEWEILLE    VEHWT   WTDRWLS   HRSEPWR   DSNSPEED            CHPVEHH   VEHWDTH   VEHHT   AIRCOEFF   FUELTYPE
 0.10E 01  0.10E 04  0.60E 03  0.45E 02  0.85E 02            0.0       0.18E 01  0.19E 01  0.17E-01  0.0
 0.20E 01  0.30E 04  0.15E 04  0.10E 03  0.80E 02            0.0       0.20E 01  0.22E 01  0.24E-01  0.0
 0.30E 01  0.10E 05  0.50E 04  0.11E 03  0.75E 02            0.10E 01  0.23E 01  0.37E 01  0.25E-01  0.0
 0.50E 01  0.24E 05  0.11E 05  0.12E 03  0.65E 02            0.10E 01  0.24E 01  0.38E 01  0.27E-01  0.10E 01
 0.40E 01  0.50E 04  0.30E 04  0.10E 03  0.75E 02            0.10E 01  0.24E 01  0.36E 01  0.27E-01  0.10E 01
```

Figure A-1 (Con't): Argentine Base Scenario Data

```
 OUTPUT SWITCHES FOR THIS RUN ARE  CONSTRUCTION  0       MAINTENANCE  0   USER  0
 OUTPUT IS PRINTED FOR YEARS THAT ARE A MULTIPLE OF 20  UNLESS THIS NUMBER  1  IS POSITIVE
THE TRAFFIC GROWTH SWITCH IS -1 AND THERE ARE  3 SETS OF   INITIAL TRAFFIC CONDITIONS ASSOCIATED WITH THIS PROJECT

          RUN 170                                                   DATE 0/ 0/ 0

  BOLIVIA TEST OF 25 YEAR ANALYSIS
 ALIGNMENT DATA-ALIGN
  LENGTH   DEG-CURVE
     6.10      15.00
PROFILE DATA- PROF
TYPE-SWITCH AVE-GRADE MAX-GRADE NO-VPIS
    -1.00       6.72       9.29     15.00
VPI STA   VPI ELEV  VPI STA   VPI ELEV  VPI STA   VPI ELEV  VPI STA   VPI ELEV  VPI STA   VPI ELEV
     0.0     896.00    140.00    896.00    600.00    900.00   1300.00    835.00   2100.00    750.00
  2900.00    720.00   3140.00    722.00   3660.00    702.00   3900.00    714.00   4100.00    700.00
  4270.00    712.00   4680.00    680.00   4900.00    672.00   5520.00    619.00   6100.00    670.00
ROADWAY CROSS SECTION(HORIZONTAL)-TEMPL
    WIDTH      SLOPE     SHLD-WD    SHLD-SL    DTH-WD     DTH-SL     DTH-WD     DTH-SL     CUT-SL    FILL-SL    PAVE-WD    SIDE-CL
     2.25       0.03       0.82       0.25       1.00       2.00       0.0        1.00       0.75       1.50       4.50      20.00
ROADWAY DESIGN DATA(VERTICAL)-PAVE
   PAVE-CD     LAYERS    MAT-TPE  THICKNESS  MAT-TPE      THICK     MAT-TPE      THICK    SHLD-TPE    THICK1     THICK2     THICK3
     2.00       3.00       4.00       0.18       0.0        0.0        0.0        0.0        2.00       0.19       0.0         0.0
ECONOMIC DATA
NO OF PERIODS,DISC. RATE, NO OF VEHICLE TYPES
      25       6.00        3
   FOREIGN RATE OF EXCHANGE
       1  PESO       =     0.08330 DOLLARS
   PERCENTAGE OF COSTS THAT ORIGINATE FROM FOREIGN SOURCES
        PER CENT OF VEHICLE COST =  80.00          PER CENT OF FUEL COST =  70.00PER CENT OF TIRE COST =  80.00
        PER CENT OF  LABOR COST =  43.00           PER CENT OF CONSTRUCTION EQUIPMENT COST = 100.00
        PER CENT OF SOURCE COST =   0.0            PER CENT OF MAINTENANCE  EQUIPMENT COST = 100.00
MAINTENANCE POLICY-MAPOL
   DRAIN-SW  RGRVLSW  SHLD-SW     MOW-SW    BLAD-SW    BLAD-DRY  BLAD-WET    MOW-FRQ    RUTFFL     CRKDTH     CRKFSLC    RUT-DTH    SUR MNT
     1.00      1.00      1.00       1.00      -1.00    5000.00   5000.00       3.00       0.80       0.50       0.50       1.50        0.0
RECONSTRUCTION SCHEDULE- RRLC
   NO-UPGRAD
       0
TOPOGRAPHY- TOPOG
NO. OF STATIONS          77
TYPECODE  FLAT        ROLLING   MOUNT      NSTA
    -1.00      0.0        0.0     100.00      77.00
STATION   ELEV.      STATION   ELEV.      STATION   ELEV.      STATION   ELEV.      STATION   ELEV.
     0.0     896.00     50.00    888.00    110.00    888.00    140.00    880.00    200.00    893.00
   250.00    887.00    290.00    896.00    350.00    890.00    400.00    898.00    430.00    891.00
   460.00    900.00    490.00    895.00    550.00    908.00    630.00    888.00    710.00    858.00
   740.00    898.00    760.00    888.00    840.00    886.00    860.00    880.00    920.00    864.00
   940.00    870.00   1050.00    843.00   1130.00    868.00   1300.00    835.00   1520.00    823.00
  1630.00    820.00   1720.00    806.00   1860.00    816.00   2030.00    795.00   2080.00    802.00
  2100.00    790.00   2150.00    778.00   2210.00    790.00   2280.00    786.00   2360.00    765.00
  2420.00    782.00   2610.00    740.00   2830.00    714.00   2900.00    714.00   3060.00    719.00
  3140.00    722.00   3220.00    730.00   3300.00    714.00   3530.00    710.00   3570.00    704.00
  3620.00    708.00   3660.00    702.00   3770.00    704.00   3870.00    716.00   3900.00    714.00
  3930.00    705.00   3970.00    710.00   4000.00    718.00   4070.00    688.00   4100.00    700.00
  4270.00    712.00   4350.00    712.00   4430.00    696.00   4460.00    710.00   4580.00    690.00
  4680.00    664.00   4770.00    682.00   4840.00    665.00   4900.00    675.00   5000.00    666.00
  5060.00    682.00   5120.00    646.00   5200.00    658.00   5290.00    631.00   5400.00    640.00
  5460.00    614.00   5520.00    623.00   5610.00    626.00   5790.00    636.00   5960.00    670.00
  6080.00    674.00   6100.00    670.00
SOIL + GROUNDCOVER-CBR,GRCCV
     CBR       EASY     NORMAL     DIFFICULT
     6.00       0.0        0.0     100.00
```

Figure A-2: Bolivian Base Scenario Data

```
DRAINAGE RELATED DATA-DRAIN
  WATR-BLUE    IMPASS    AVERAIN    MT-RAIN  FLT-MED      FLT-LGT
    1.00        1.00      40.00      1.00      0.0         0.0
HAUL DISTANCES,CONSTRUCTION
                                                  PAVEMENT                        MAINTENANCE
    %-BOR     HAULDIST    LAYER1     LAYER2   LAYER3   SHOULDER     WATER      GRAVEL  .   PATCH      CULVERTS
    10.00       1.00       2.00       0.0      0.0       2.00        0.0        2.00        0.0       200.00
CONSTRUCTION PRODUCTIVITIES + COSTS-PROD
SITE PREPARATION
     EASY      NORMAL      HARD      LCOST     EQCOST
     0.0        0.0        0.19     127.20     854.40
EARTHWORK
    BORROW   TRANSPORT     PROD      LCOST     EQCOST
     0.0        0.0       825.00    1057.00   7464.00
PAVEMENT
     PROD      SOURCE    TRANSPORT    LCOST     EQCOST
    348.00      0.0        0.0       495.70   3446.40
     0.0        0.0        0.0         0.0       0.0
     0.0        0.0        0.0         0.0       0.0
    348.00      0.0        0.0       495.70   3446.40
DRAINAGE
    NO. OF CULVERTS =        5.00
    SCOST     WEIGHT       TCOST
    384.00     55.00        0.03
    523.00    110.00        0.02
    715.00    160.00        0.02
   1065.00    210.00        0.02
   1480.00    290.00        0.02
OTHER COMPONENTS
    %TCOST    %LABOR      %TCOST    %LABOR
     0.0        0.0         0.0        0.0
MAINTENANCE COSTS AND PRODUCTIVITIES-MUC
    BITDIS    DUMPTRK     TRALDR    MOTORGD     ROLLER     TRACTOR     WTRTRK
    150.00     96.00      90.00      77.00      77.50      75.00      71.00
     CLABOR    EQOPER     FOREMAN   TDRIVER    LIQASPH     PATMIX      COVSEAL
     6.00       8.00      13.40       6.00      0.0         0.0         0.0
  DIESELFUEL GRCOST      GASCOST   WATERC
     0.0        0.0        0.0       0.0
USER COSTS.ECON. AND MARKET- ECONC,MARK
     LABORC    DRIVER     GASCOST     DIESEL
     6.00       6.00       0.0        0.0
     6.00       6.00       0.0        0.0
      INITIAL COST             TIRE COST           VEHICLE COST          CARGO COST
    ECONOM     MARKET     ECONOM     MARKET      ECONOM     MARKET      ECONOM     MARKET
  36000.00  54000.00     313.00     468.00       9.70      11.20         0.0        0.0
  39600.00  57600.00     351.00     576.00       5.00       5.40         0.0        0.0
  93600.00 144000.00    1440.00    2052.00      26.00      26.10         0.0        0.0
VEHICLE DATA- VEH
DEWEILLE     VEHWT     WTDRWLS    HRSEPWR    DSNSPEED                  CHPVEHH    VEHWDTH    VEHHT     AIRCOEFF    FUELTYPE
0.10E 01   0.84E 03   0.45E 03   0.40E 02   0.12E 03                  0.10E 01   0.17E 01   0.18E 01  0.17E-01    0.0
0.20E 01   0.27E 04   0.16E 04   0.14E 03   0.95E 02                  0.10E 01   0.20E 01   0.19E 01  0.24E-01    0.0
0.30E 01   0.31E 04   0.20E 04   0.11E 03   0.90E 02                  0.10E 01   0.24E 01   0.25E 01  0.34E-01    0.0
```

Figure A-2 (Con't): Bolivian Base Scenario Data