Economic Analysis of Highway Design in Developing Countries

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This paper deals with the selection of road transport technology for developing countries. By technology we mean a specific combination of such productive factors as labor, capital, and energy. The most efficient technology in one country such as the United States or Canada may not be the same as in another characterized by capital scarcity and the abundance of unskilled labor. In designing transportation facilities for underdeveloped countries, therefore, engineers should consider the whole range of technology available for producing transportation.

A framework for analyzing the choice of technology possible in producing a given output of transportation is formulated. By borrowing certain economic concepts such as the production function, it is possible to determine the degree to which expenditures on labor may be substituted for capital expenditures in producing a given output of road transportation. This framework is then used to determine the optimal combination of productive factors—that is, the best road design or choice of technology for a given set of conditions. In practical terms, this means finding the best trade-off among capital costs, road-user costs, and road maintenance costs under varying conditions of unemployment, interest rates, and foreign exchange rates.

A case study based on the author's research in Venezuela is presented to illustrate the data requirements for the suggested method of analysis. The example illustrates the usefulness of relatively scant cost information in making rational economic decisions. Using regression techniques, for example, estimating equations are derived which relate the cost of road construction to design standards for two types of terrain conditions. Road user cost data and maintenance cost data based on limited statistical information are also presented. In all cases, data are presented so as to permit determination of the labor, local capital, and foreign exchange components of each cost. The sensitivity of road investment decisions to change in both foreign exchange rates and labor costs is also illustrated by an example.

•THE COST of transporting goods from one point to another depends on the manner in which these goods are moved. The most efficient method in one country may not be the most efficient in another because of differences in production factors. In designing transportation facilities for underdeveloped regions, therefore, engineers should investigate the whole range of technology available for producing transportation. By technology we mean a specific combination of productive factors, such as labor, capital, energy, or any other resource which can only be obtained at a certain cost. With different technologies it may be possible to produce similar results, but at different costs.

Paper sponsored by the Department of Economics, Finance and Administration.

Thus goods may be moved over a given distance by human porters, pack mules, trucks, or railroad box cars. In each case, the technology is different, going from a very labor-intensive to a very capital-intensive method. In this instance, the changes in technology are very distinct, and it is often a simple matter to determine which technology is the most suitable. Where changes in technology are so distinct—where the medium by which the goods are carried changes—we define a change in mode.

Within a particular mode, further technological substitutions are also possible. Thus, goods may be carried in many small trucks or fewer large trucks. The mode is the same although in each case the choice of technology is different. Similarly, goods may be carried by railroads around a mountain or through it, each case involving a different combination of construction and energy costs. For each mode there will be some technology or some combination of productive inputs which is optimal in terms of its use of available resources. When intermodal comparisons are made, such as between road and rail, each mode should be compared using this optimal technology. It is important, therefore, to take a thorough look at the whole question of the substitutability of inputs, both as between modes and as between alternative technologies of a given mode. Some insight into the nature of this substitutability in transport can be gained by considering a simple model which describes the production of transportation.

TECHNOLOGICAL CHOICE IN TRANSPORTATION

Transportation involves the transfer of weight between non-coincident points. This weight has a certain bulk and follows a path between these two points which may be circuitous or direct, easy or difficult, safe or hazardous. Moreover, it may move over this path swiftly or slowly, in units which are large or small. All these factors affect the cost of moving this weight to a greater or lesser extent.

A model describing the production of transportation should at least take into account the more important of these factors. To some extent, the model should be sensitive to differences in (a) cargo characteristics—weight, bulk, density, and perishability, (b) route characteristics—circuity and difficulty, and (c) quality of transport—speed, safety, and reliability.

In the production of road transportation, for example, the major variables include road alignment, road surface, vehicle size, and energy input. Alignment, road surface, and vehicle size usually constitute the independent variables, whereas energy input is usually a dependent variable. How these factors affect the cost of transport and to what extent they are substitutable for one another can be described in the following manner.

Consider the problem of designing a road to carry a particular axle load. The load-carrying capacity or strength of a road depends primarily on the strength of the subgrade and the thickness of the pavement structure. The relationship between these three factors can be shown by a three-dimensional surface in which the vertical axis represents pavement thickness and the horizontal axes represent design axle load and subgrade strength (Fig. 1). By cutting this surface with a series of horizontal sections, strength contours are obtained, each of which indicates the various combinations of pavement thickness and subgrade strength which will safely support that load. These strength contours can be derived from theory and their shape is independent of local conditions (Fig. 2).

Local conditions become important in determining the costs of providing the pavement structure and of preparing the subgrade material. Subgrade strength, for example, can be improved by compaction or soil stabilization methods. The cost of improving the subgrade, however, will depend on such local conditions as the nature of the soil, the availability of labor, and the cost of equipment. As the subgrade is improved, total costs might vary in the general way shown in Figure 3. Similarly, the cost of increasing pavement thickness will also depend on local conditions.

The cost relationships of Figure 3 can be combined to form a series of equal cost contours or isocost curves as in Figure 4. Each isocost curve indicates the various ways in which a stated expenditure can be divided between improving the subgrade and providing additional pavement. At one extreme, the total amount can be spent on subgrade improvements leaving nothing for pavement expenditure, whereas at the other

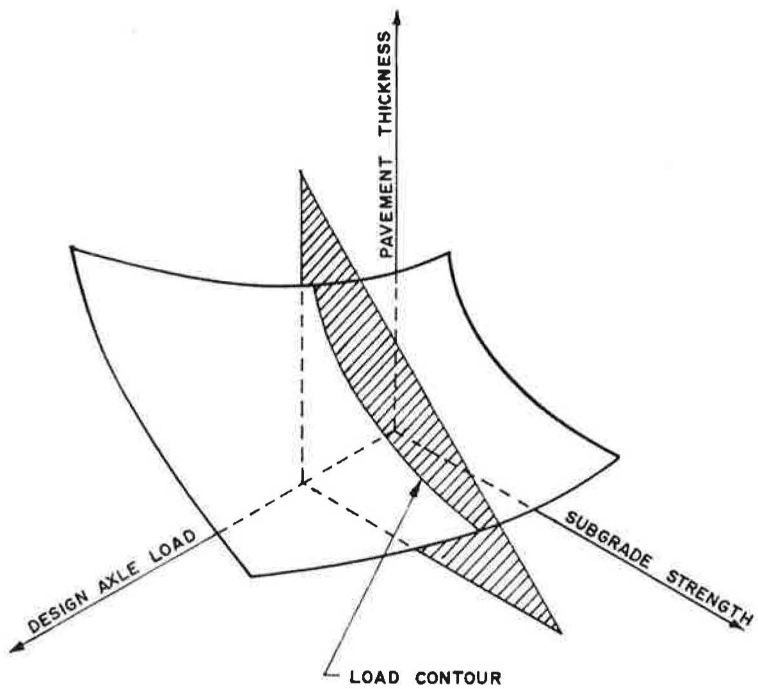

Figure 1. Relationship between axle load, subgrade strength and pavement thickness.

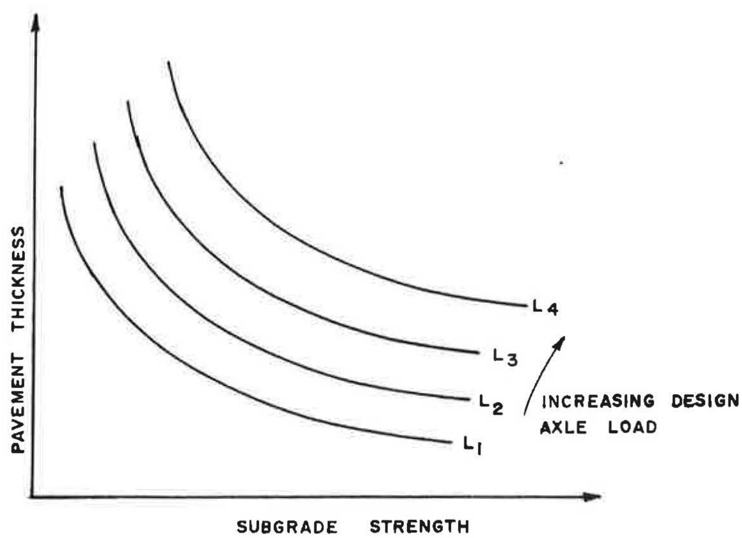

Figure 2. Road strength isoquants.

extreme, the total amount may be spent on pavement. In each, the intercepts are obtained from Figure 3 by observing what subgrade strength and pavement thickness, respectively, can be obtained for the given expenditure. In the intermediate range, the available amount of money is divided in varying proportions between the two alternative methods of increasing road strength. If the isocost map is now superimposed on the

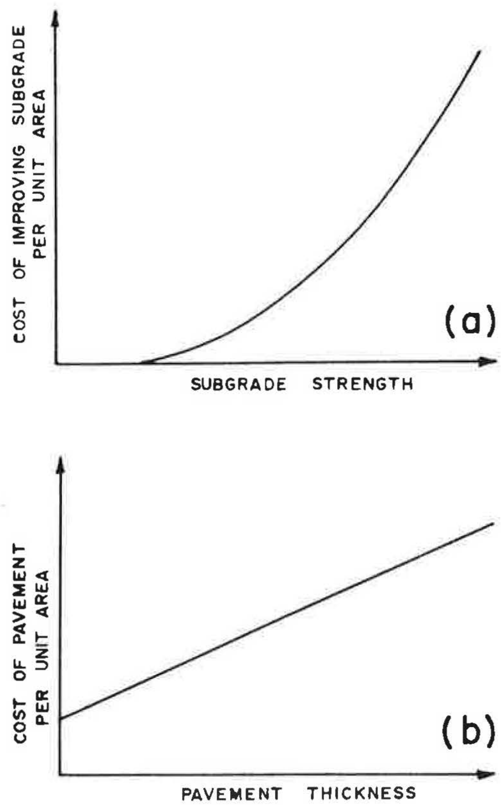

Figure 3. Subgrade strength and pavement cost function.

strength contour map (Fig. 2), the minimum cost of providing a specified road strength will be given by the isocost curve which is just tangent to the corresponding strength contour (Fig. 5). Moving in either direction from this point of tangency along the strength contour involves moving to a higher isocost curve.

In terms of the substitution relationships discussed, Figure 5 means that if a road is to be designed to carry a load, L, and if the initial design includes no pavement layer, expenditures for pavement thickness can be substituted advantageously for investments in improving the subgrade up to some point beyond which it will no longer be advantageous to continue the substitution. This point depends on the relative costs of improving the subgrade and providing additional pavement. If these relative costs change, the shape of the isocost curves will change and some new point of tangency will be indicated corresponding to a different combination of subgrade strength and pavement thickness. In other words, the proper design or choice of technology clearly depends on the relative factor costs.

Each point of tangency indicates a particular value of road strength and the minimum cost of providing this strength. The locus of all such points can be replotted (Fig. 6) to show the variation of minimum total road costs with increases in load-carrying capacity. As factor prices change, the shape of this cost curve will also change.

A similar technique can also be used to illustrate the substitution effects possible between road conditions and vehicle operating costs. For a vehicle of a given size, road conditions determine vehicle performance as well as the energy required to move the

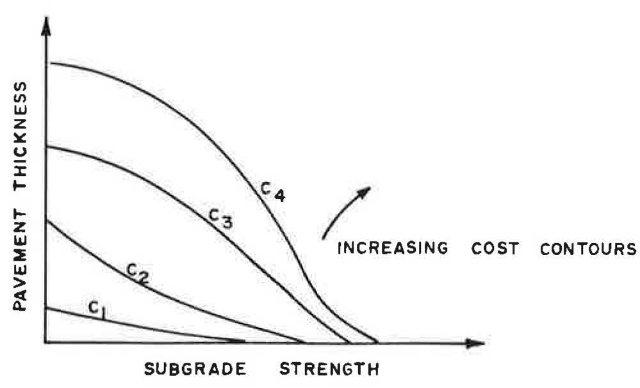

Figure 4. Road strength isocosts.

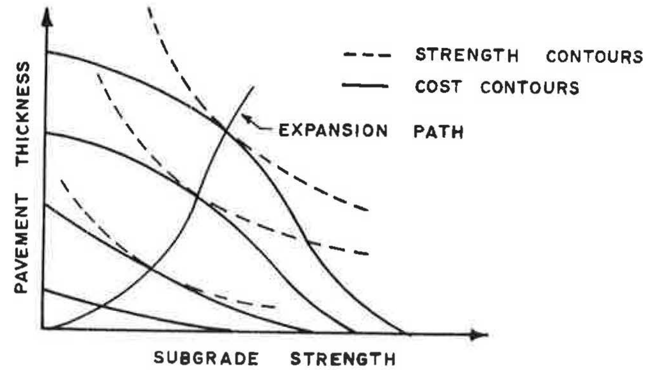

Figure 5. Road strength expansion path.

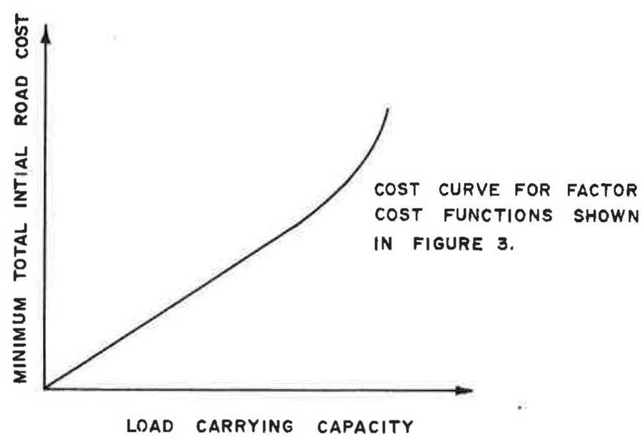

Figure 6. Minimum total road cost function.

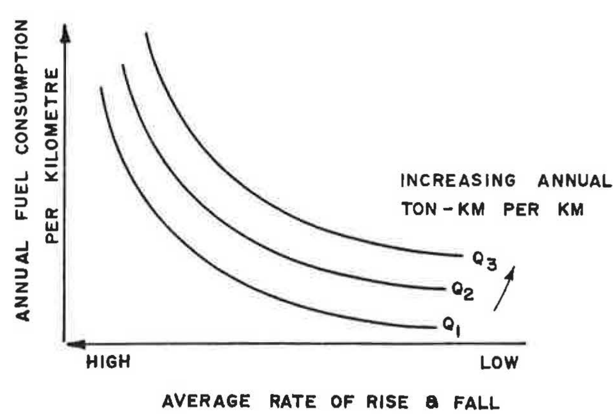

Figure 7. Transport output isoquants.

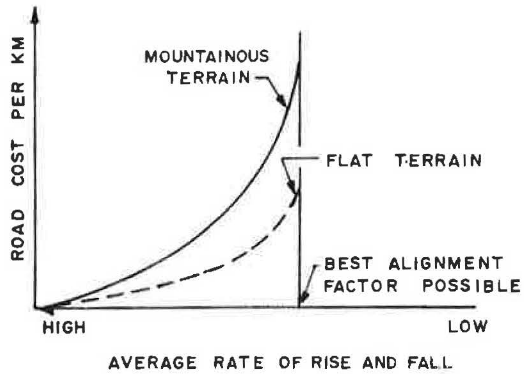

Figure 8. Aligment factor cost function.

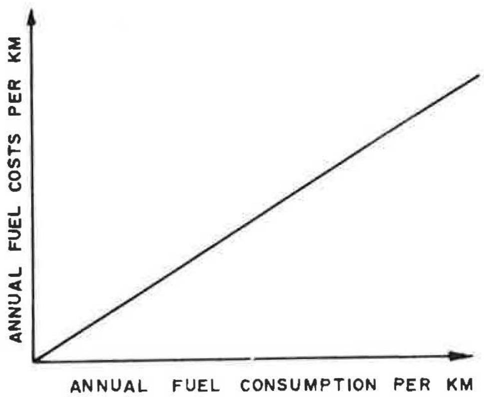

Figure 9. Operating factor cost function.

vehicle over a given distance. For purposes of illustration the major characteristic of road condition is considered to be the average rate of rise and fall; fuel consumption is taken as a measure of vehicle performance. Using these parameters, volume contours or isoquant curves can be drawn (Fig. 7), which indicate the quantity of goods that can be moved over a given distance for various combinations of fuel inputs and road conditions. If, for example, road conditions are improved by reducing the average rate of rise and fall, the quantity of fuel necessary to carry a specified tonnage will decrease correspondingly.

The cost of reducing the average rate of rise and fall of a particular road depends primarily on local topography. To a lesser extent the availability of labor and heavy earth moving equipment also influence this cost. With increasing expenditures, road conditions can be improved up to some point beyond which further expenditures will yield only slight improvements. Thus, for practical purposes, the cost curve can be considered as asymptotic to the lowest rate of rise and fall possible. As shown in Figure 8, the more rugged the terrain, the higher the cost of reaching this point. Figure 9 shows the cost curve for fuel consumption, assumed to be linear.

In Figure 4, the units of each axis represent initial or capital costs, thus allowing the costs to be combined in an isocost map. In Figures 8 and 9, however, the cost of road improvement represents an initial capital cost, whereas the cost of fuel represents a current cost related to the total quantity of transportation produced over a given time. To normalize these two axes, road improvement costs can be amortized on an annual basis (by means of the capital recovery factor), or alternatively, the present discounted value of future expenditures on fuel can be determined. In either case, the rate of interest and life of the facility must be specified.

If the costs of Figure 8 are amortized on an annual basis, an isocost map can be plotted and superimposed on the isoquant diagram (Fig. 10). Again, the tangency points indicate the degree to which operating inputs can advantageously be substituted for road improvements. At each point of tangency, both a total cost and a volume of transport output are indicated so that the expansion path through these points represents the minimum total cost curve.

In these considerations of alignment and operating factors vehicle size has been considered as given. Changing the vehicle size will change the shape of the isoquants (Fig. 7) and hence the location of points of tangency. Thus for each vehicle size a different cost curve will be obtained. When these curves are plotted

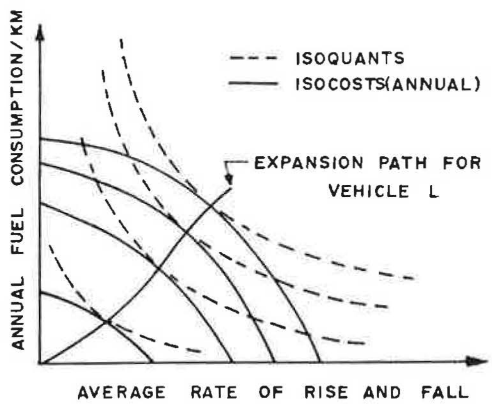

Figure 10. Transport output expansion path.

together (Fig. 11), the optimum vehicle size to be used is given as a function of transport output.

In the generalized case, however, vehicle size or load-carrying capacity of the roads can be taken into account by adding a third dimension to Figure 7. The isoquant curves would become surfaces of equal transport output and Figure 7 would represent a section through these surfaces taken perpendicular to the vehicle size axis. In other words, a particular surface would indicate the various combinations of energy input, vehicle size, and road conditions which would result in the production of the same output of transportation. This surface would be entirely independent of local conditions and would represent a relationship between physical inputs (or productive factors) and the quantity of transportation produced. The slope of the surface measured parallel to any axis would indicate the rate at which one factor could be substituted for another without changing the level of transport output. (Nothing has been said about the problem of measuring transportation output. A weight x distance measure has been used here for illustrative purposes. For a detailed treatment of output measures in transportation, see Wilson, 38.)

In a similar fashion, isocost surfaces could be found which are functions of the same physical parameters. These surfaces, however, would be entirely dependent on local conditions; they would represent particular solutions. Again, as in the two-dimensional case, points of tangency would indicate optimal points of production—optimal in the sense that output is maximized for a given cost or that cost is minimized for a given output. The expansion path through these points would specify, in addition to the best combination of road conditions and operating cost, the best vehicle size to be used.

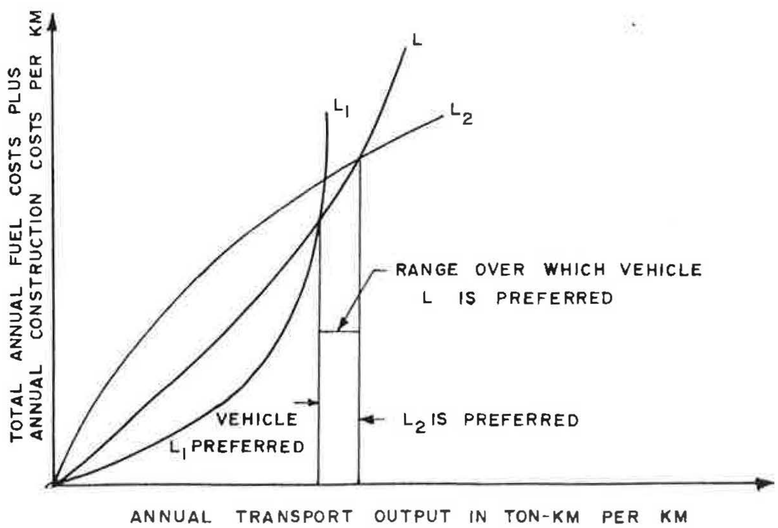

Figure 11. Minimum total transport output cost function.

NATURE OF SUBSTITUTABILITY IN TRANSPORTATION

Despite certain oversimplifications, the model described gives some indication of the nature of the substitutability possible between factor inputs in producing transportation. For a more detailed description, see Soberman (31, Chap. III). For example, in addition to the substitutability between subgrade and pavement improvements, further substitution possibilities exist. In compacting the subgrade, alternative types of equipment, such as large, heavy-duty compaction equipment requiring only a few passes over the subgrade, or lighter equipment requiring many passes, might be used. In the first case, the capital component per unit area compacted will probably be greater, whereas in the second case the labor component is likely to be more important. Thus just as load contours were drawn showing the substitutability of pavement thickness for subgrade strength, contours of subgrade strength could be obtained showing the substitutability of labor for capital.

In a similar manner, pavement thickness contours could be drawn showing the substitutability of the same inputs for one another. High labor inputs might correspond to methods of construction employing hand mixers for asphalt or concrete, whereas high capital inputs might indicate the use of large automatic paving machines.

This type of substitutability is representative of the different levels of capital intensity possible in the construction of transportation facilities. For a given final design (specified in terms of road width, pavement thickness, etc.) it deals with the alternative methods of construction which can be used to arrive at this design. The degree to which labor can be effectively substituted for capital in the construction of transportation facilities is one of the key issues to be considered in planning transportation for underdeveloped countries. Basically, however, it represents a problem in engineering construction, and as such is beyond the scope of this work. (For further discussion of the choice of construction techniques in developing countries, see 7 and 9.)

Once the decision to build a transportation facility using certain methods of construction has been made, a second type of substitutability is possible within the operating phase. This is the substitutability which is possible at fixed levels of investment between the labor, material, and capital inputs necessary to produce transportation.

Highway maintenance, for example, affects vehicle life. By maintaining a road to a high standard, the capital input per unit of transportation (in the form of vehicle depreciation) can be reduced due to increased vehicle use. Furthermore, labor-capital substitutions within the maintenance operation itself are also possible.

Probably the most important substitutions within the operating phase (certainly for any resonable degree of traffic) relate primarily to vehicle size and use. Vehicle size, for example, determines the quantity of fuel, the hours of driver time, and the proportion of total vehicle maintenance and depreciation which must be charged against each ton-mile produced. For certain types of vehicles, the quantities of each of these input factors per unit weight moved will be higher than for other vehicles, and it would be clearly inefficient to use such vehicles. It is for vehicles where more of one factor and less of others is required that the nature of the substitutability becomes interesting. In other words, if for each vehicle type coordinates could be plotted corresponding to labor and capital components per unit of transportation, our interest would be confined to the substitution relationships defined by the curve passing through all points, none of which had x and y coordinates both larger than any other point.

Finally, a third type of substitutability can be considered representing a combination of the two types previously described. This concerns the substitutability of current or variable inputs for fixed capital inputs. For each type of road, corresponding to a particular fixed investment, alternative combinations of variable inputs can be used in producing a specified output of transportation. At one extreme, light, single-unit vehicles might be used over poorly graded, unpaved roads, whereas at the other extreme, heavy, multiple-unit vehicles traveling on superhighways might be employed. The problem which is of greatest interest concerns the substitutability within all possible combinations of both the construction and operating phases.

The number of such combinations of capital and current cost combinations can, of course, be extremely large. In the final analysis the judgment and experience of the

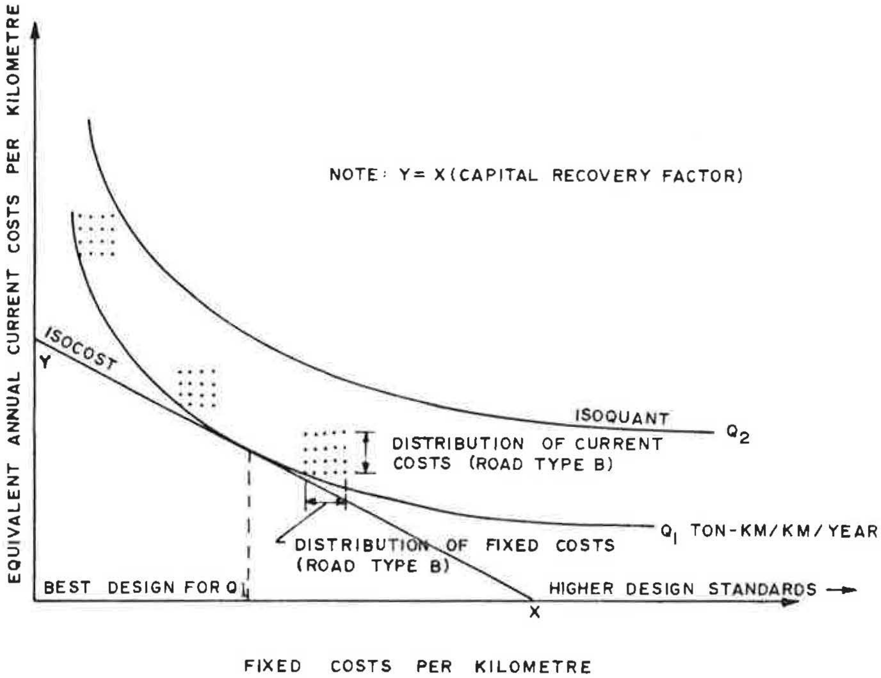

Figure 12. Substitutability between current and fixed inputs.

engineer will determine the set of alternatives which it seems feasible to consider.

For each level of fixed investment some combination of operating inputs will be optimal when the level of traffic volume to be accommodated is taken into account (Fig. 12). Several methods of construction can be used to provide a road of a given standard or design. Each method will involve different labor and capital components, leading to a distribution of fixed costs when each of these components is valued at its true cost.

In most underdeveloped countries a wide discrepancy may exist between the market prices of various factors of production and the real costs of these factors to the economy. These real costs are often referred to as shadow or accounting prices. They are fictitious prices attached to some factor inputs to give a better approximation of their relative importance to the economy. Usually they are applied to the labor, local capital, and foreign exchange components of an investment. (See 31, pp. 120-123; for methods of determining shadow prices, 35, p. 203.)

In Figure 12, this distribution of fixed costs is represented by rows of dots. Similarly, holding the traffic volume constant for each point in the distribution, a distribution of current costs is possible corresponding to various combinations of labor and working capital (local currency and foreign exchange). This distribution is shown by the columns of dots. Thus for each type of road, alternative combinations of fixed and current costs (at constant levels of traffic) are shown by a rectangular array of points on the graph. Each point in the array corresponds to a certain combination of labor and capital used in constructing the facility initially, and operating it thereafter. If these factors have been valued at their real costs, the curve passing through the lower left-hand corner of each array defines the substitutability of labor for capital for all lowest cost combinations of fixed and operating inputs. The curves of Figure 12 represent the labor-capital substitutions possible in providing road transportation. Were similar analyses to be carried out for other modes of transport, substitution relationships could be obtained showing the possible combinations of factor inputs over a much wider range of fixed and current costs.

SELECTION OF OPTIMAL TECHNOLOGY

Given the substitution possibilities described by this curve (or the family of curves for different levels of transport production), the question arises as to how to select the optimal combination of labor and capital, or current and fixed costs. In practical terms, this means selecting both the standards to be used in constructing a highway facility and the type of vehicle to be used. Here, however, the isocost curves indicate the combinations of annual current expenditures over a period of years and initial fixed investment which can be obtained for a specified sum of capital in the present. In other words, the isocost curve specifies the alternative ways of spending an available quantity of capital. On one hand, the entire sum may be invested in fixed expenditures, leaving nothing for future current expenditures. This case gives the X intercept of the isocost curve shown in Figure 12. On the other hand, the entire sum may be set aside to provide for an annual operating expenditure, denoted by the Y intercept, which is determined by the prevailing rate of interest and the assumed period of amortization. In the intermediate range a portion of the total sum is invested in capital expenditure, with the remainder set aside to meet current expenditures. As before, the optimal point of production or choice of technology is given where the isocost curves are tangent to the isoquants.

The expansion path obtained by connecting all such points of tangency indicates the minimum total cost of providing road transportation as output varies. The shape of this cost curve will vary according to the rate of interest. If several alternative modes of transport are analyzed in a manner similar to that described here for road transport, their final cost curves can be compared, thus showing over what ranges of traffic volume and for what prevailing interest rates each mode is to be preferred. In other words, once minimum total cost curves for each mode have been determined as suggested here, intermodal comparisons can be made.

DATA REQUIREMENTS—AN EXAMPLE

The diagrams previously presented are dimensionless, showing by argument alone the general shape of curves and the characteristics of the relationships involved. It would be logical to ask at this point how difficult it is to acquire the data necessary for the suggested method of analysis. The current fixed cost substitution curves (Fig. 12) suggest two basic types of data which are needed. The first relates to the variation in fixed costs as design standards are changed. In addition, some estimate of the variation in current costs for different vehicles operating on roads constructed to various design standards must also be known. How these data were acquired in the case of a newly developing region of Venezuela is discussed in the following.

Fixed Costs

To investigate the variation in fixed costs with changes in design standards, various road construction projects which had been completed in Venezuela were selected and classified according to terrain and geological factors. Within each classification attempts were then made to develop regression equations describing the relationship between construction costs and the design standards to which each road was constructed.

Because sufficient data were not available to consider the variation of each construction cost element for changes in design standards separately, all costs of construction exclusive of pavement costs were grouped together. Two terrain classifications were used: plains (llanos) which includes flat and gently rolling terrain, and mountain regions.

The major design variables taken into account were road width and design speed. The use of design speed takes implicitly into account the remaining standards which have significant effects on road construction costs (i.e., sight distances, curvature, and gradient).

Construction cost data were obtained from an analysis of approximately 2,100 km of road constructed in Venezuela before 1960. In some cases, cost data were available on a per kilometer basis, showing each of the component costs and even the division of

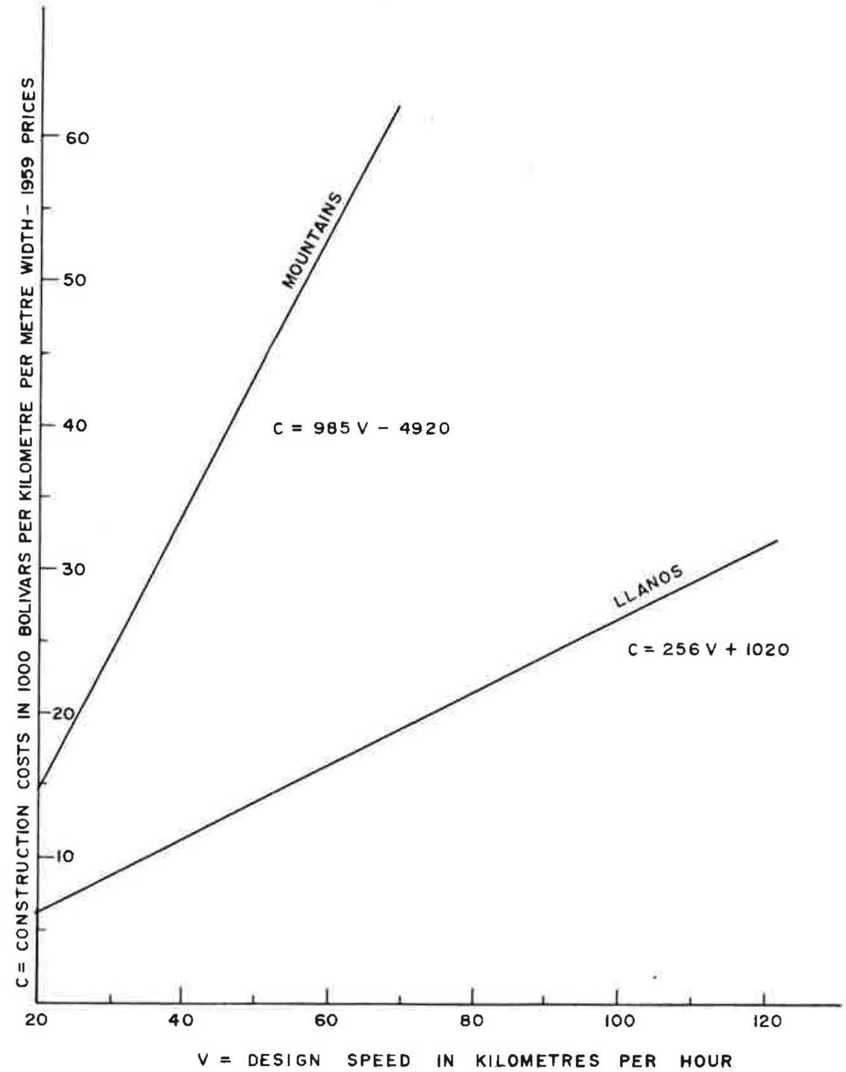

Figure 13. Effect of design speed on construction costs.

these costs between labor, imported materials, and depreciation of equipment. In other cases, cost data were expressed as lump sum figures for sections of road ranging up to 50 km in length.

Four types of two-lane highways (A, B, C, and D) are presently used, differing primarily with respect to design speed, pavement width, and width of shoulders. In flat terrain, road widths of 21.3, 14.6, 10.3, and 7.2 meters and design speeds of 100, 80, 60 and 50 kilometers per hour are usual for type A, B, C, and D roads, respectively. Examples of actual roads constructed corresponding to each of these road types could not always be found for both types of terrain considered. (Type A roads are generally rare in mountainous regions.) Therefore, in cases where actual data pertaining to a particular road type were lacking, it was necessary to use construction cost estimates prepared by the Ministry of Public Works.

Linear multiple-regression analysis was used to obtain construction cost equations for the two types of terrain considered.

$$C_L = 5,720\ W + 3,830\ V - 123,000 \qquad (1)$$

and

$$C_M = 57,900\ W + 5,860\ V - 490,000 \quad (2)$$

where

C_L, C_M = cost per kilometer in Bolivars for flat and mountainous terrain, respectively ($1.00 U. S. = 4.48 Bolivars);
W = design width in meters; and
V = design speed in kilometers per hour.

Least squares curve fits were also made with respect to design speed. In this case costs per kilometer were expressed per unit of road width.

$$C'_L = 256\ V + 1,020 \quad (3)$$

$$C'_M = 985\ V - 4,920 \quad (4)$$

in Bolivars per meter width. These equations are plotted in Figure 13.

TABLE 1

ESTIMATED RELATIVE IMPORTANCE OF ROAD CONSTRUCTION COST ELEMENTS FOR VARIOUS ROAD WIDTHS (FLAT TERRAIN)

Cost Element	Relative Importance (%)			
	7.2-m Width	10.3-m Width	14.6-m Width	21.3-m Width
Preparation of site	6.0	7.0	7.7	7.7
Earthwork	38.1	37.2	36.8	36.6
Culverts and drainage	11.1	16.0	19.7	21.7
Base	6.6	7.7	8.5	9.0
Bridges	35.2	30.1	26.0	24.1
Fencing	3.0	2.0	1.3	0.9
Total	100.0	100.0	100.0	100.0

TABLE 2

LABOR, LOCAL CAPITAL, AND FOREIGN EXCHANGE COMPONENTS OF ROAD COST ELEMENTS[a]

Cost Element	Detailed Breakdown (%)						Aggregate Figures (%)[c]		
	Labor[b]	Profits	Domestic Materials	Imported Materials	Fuels	Deprec. and General Expenses	Labor	Local Capital	Foreign Exchange
Preparation of site	28.2	10.4	-	22.0	7.1	32.3	28.2	33.6	38.2
Earthwork	28.2	10.7	-	25.1	5.8	29.6	28.8	31.3	39.9
Culverts and drainage	17.7	10.7	50.8	13.9	0.4	6.5	17.7	65.2	17.1
Base	29.7	10.7	12.0	20.0	3.9	23.7	29.7	38.5	31.8
Bridges	28.4	10.7	33.4	13.4	0.7	13.0	28.4	51.7	19.9
Fencing	24.3	10.7	35.0	-	-	-	24.3	75.7	-

[a]Data derived from construction projects obtained from Ministerio de Obras Publicas, Caracas; calculations based on 1959 prices.
[b]Includes 30 percent social benefits.
[c]Derived from detailed breakdown as follows: Labor = column 1; Local capital = columns 2 + 3 + 5 + 50 percent of column 6; and Foreign exchange = column 4 + 50 percent of column 6.

Estimates of the relative importance of the various construction cost elements were also made from the cost data available on a more detailed basis, and are indicated in Table 1 for flat terrain. Labor, fuel, domestic materials, imported materials, and depreciation components of these cost elements are indicated in Table 2.

The distribution of costs in Table 1 was then used to make estimates of labor, local currency, and foreign exchange components for each of the four road types considered, using the data in Table 2. Recognizing the limitations on data accuracy, the distributions as indicated in Table 3 remain remarkably constant with labor, local capital, and foreign exchange accounting for 27, 44 and 29 percent of total construction costs, respectively. These distributions can be used in conjunction with the regression equations developed previously to estimate labor and capital cost variations with changes in design standards.

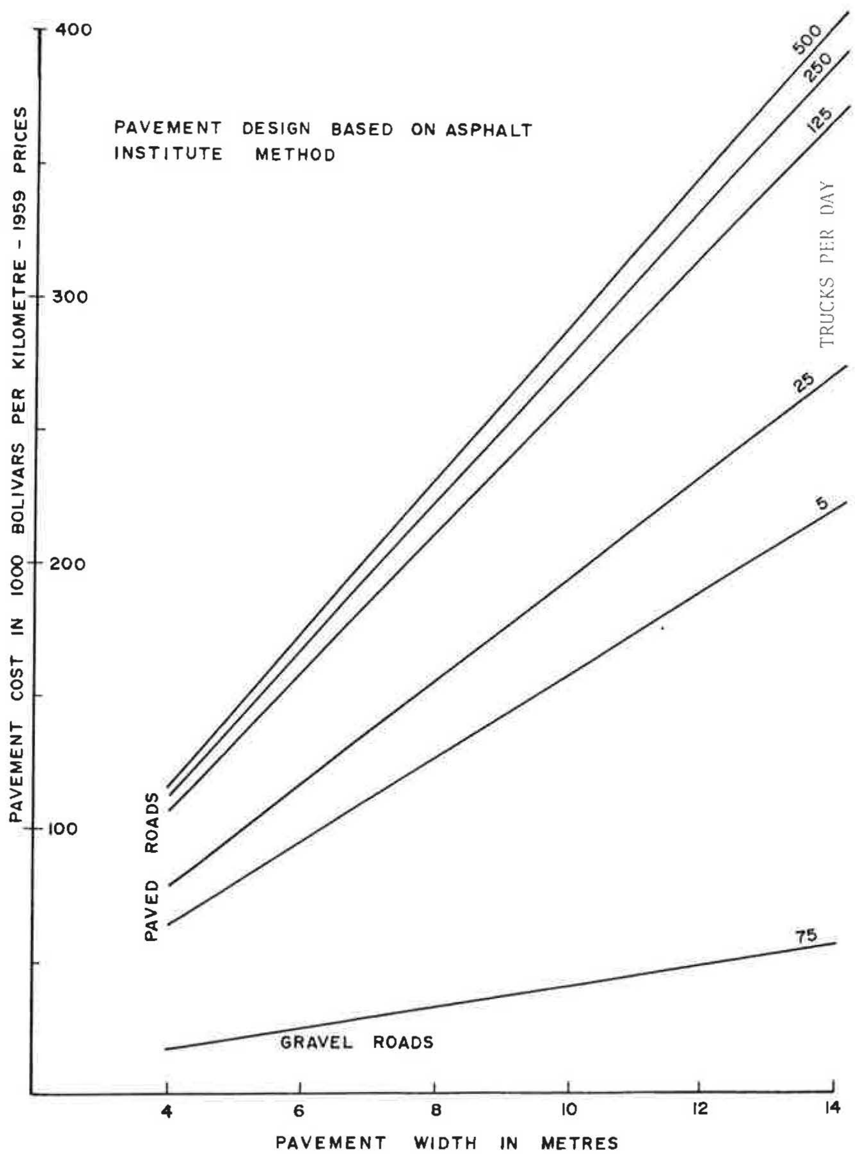

Figure 14. Effect of traffic volume and design width on pavement costs.

Estimates of pavement costs were made by designing flexible pavements for several different average daily traffic volumes and then applying local unit costs to quantities taken from these designs. The variation in pavement costs for changes in design width and traffic volume could then be determined (Fig. 14). Labor, local capital and foreign exchange components of these costs averaged 24, 58, and 18 percent, respectively.

Current Costs

Current costs include annual road maintenance and the cost of motor vehicle operation. Maintenance costs in turn include fixed and variable components. Fixed components are largely independent of traffic intensity, resulting from the deterioration of highway surfaces and structures caused primarily by climatic factors and the invasion of road margins by vegetation. In tropical climates rainfall is probably the most important climatic factor, particularly where wet and dry seasons are very distinct. During the rainy season, the cost of maintaining earth and gravel roads becomes so high that it is often cheaper to pave the road surface even where traffic volumes are very low. Variable maintenance costs, on the other hand, depend primarily on traffic intensity and the frequency of heavy trucks. In general, the relative importance of fixed costs increases from earth to gravel to paved roads, whereas variable costs decrease in importance.

Statistical information on total annual maintenance costs was available from the Venezuelan Ministry of Public Works. In addition, information on the length of various road types together with estimates of average daily traffic volumes on these roads were also available. By combining these data it was possible to develop maintenance cost estimating equations for three classes of roads.

$$M_P = 10,400 + 1\,(ADT) \quad (5)$$

$$M_G = 5,200 + 18\,(ADT) \quad (6)$$

$$M_E = 1,550 + 54\,(ADT) \quad (7)$$

where

M_P = annual cost of maintaining paved roads in Bolivars per kilometer (Bs/km);
M_G = annual cost of maintaining gravel roads in Bs/km;
M_E = annual cost of maintaining earth roads in Bs/km; and
ADT = average daily traffic.

For a more detailed explanation see Ref. 31, pp. 173-180.

No attempt has been made to take difference in road standards within the paved, gravel and earth categories used in the foregoing into account. Within each of these categories some variation in annual maintenance costs can be expected. In general, however, differences in design standards will not produce significant differences in the pattern of maintenance costs over the life of the road. For example, loads applied near the edge of a pavement produce more distress in pavements and shoulders than loads applied nearer to the centerline. Therefore, although the area to be maintained per kilometer increases as widths are increased, the relative frequency of edge loadings decreases and tends to offset increases in maintenance costs. For small increments of width (i.e., less than a lane) maintenance costs will be unaffected because the length of road for which each road gang is responsible does not change. In other words, total costs remain roughly the same and the productivity of the maintenance crew is forced to increase.

Costs of motor vehicle operation can also be divided into two groups, those which are fixed or independent of the degree to which the vehicle is used, and those which are variable or dependent on vehicle usage. In the former category are such costs as depreciation due to obsolescence, insurance, taxes and licenses, and garaging. Because the life of a vehicle is relatively short compared to the life of road facilities, these fixed costs can be considered as short-run fixed costs. The most important var-

TABLE 3

ESTIMATED LABOR, LOCAL CAPITAL, AND FOREIGN EXCHANGE COMPONENTS OF ROAD CONSTRUCTION COSTS FOR VARIOUS ROAD WIDTHS

Component	Cost (%)			
	7.2-m Width	10.3-m Width	14.6-m Width	21.3-m Width
Labor	27.3	26.8	26.5	26.3
Local capital	44.2	44.5	44.6	44.8
Foreign exchange	28.5	28.7	28.9	28.9
Total	100.0	100.0	100.0	100.0

iable costs are depreciation due to usage, fuel, maintenance, and wages paid to drivers and their helpers.

In the design of transport systems we are interested only in those elements of vehicle operation which can be affected by changes in system design. Normally, this excludes most of the elements of fixed costs. In underdeveloped regions, however, changes in system design can often affect unit fixed charges significantly by (a) increasing the useful lives of vehicles through improvements to road surfaces and alignment, and (b) improving the utilization of vehicles through overall increases in average running speeds possible. Therefore, both fixed and variable motor vehicle operating costs were considered here.

Operating cost estimates were made by supplementing available information on truck and tire prices, maintenance costs, and the price of fuel and lubricants, with United States data on fuel consumption, tire wear, and vehicle performance, obtainable from any one of a number of studies. (See, for example, the classic Oregon studies on motor vehicle operating costs by Beakey, 2; also Saal, 29.) In all cases where foreign data

TABLE 4

SUMMARY OF TRUCK OPERATING COSTS FOR OPERTION ON PAVED, GRAVEL, AND EARTH ROADS[a]

Item		Cost (Bolivars per veh-km)				
		7.8 Metric-Ton Cap.	11.4 Metric-Ton Cap.	15.9 Metric-Ton Cap.	21.0 Metric-Ton Cap.	23.5 Metric-Ton Cap.
Paved Roads[b]						
Drivers[c]		0.325	0.325	0.335	0.345	0.378
Maintenance[d]		0.055	0.063	0.085	0.104	0.107
Tires[e]		0.107	0.107	0.150	0.193	0.193
Gasoline[f]		0.051	0.063	0.075	—	—
Diesel oil[g]		—	—	—	0.021	0.023
Oil		0.010	0.016	0.022	0.025	0.025
Insurance[h]		0.036	0.042	0.050	0.069	0.075
Total		0.584	0.616	0.717	0.757	0.801
Gravel Roads[i]						
Drivers[j]		0.520	0.520	0.537	0.552	0.606
Maintenance[k]	(5.6)	0.308	0.353	0.477	0.582	0.599
Tires	(1.68)	0.199	0.199	0.252	0.324	0.324
Gasoline	(1.15)	0.059	0.072	0.086	—	—
Diesel oil	(1.15)	—	—	—	0.024	0.026
Oil	(1.51)	0.015	0.024	0.033	0.038	0.038
Insurance[j]		0.058	0.067	0.080	0.110	0.120
Total		1.159	1.235	1.465	1.630	1.713
Earth Roads[i]						
Drivers[j]		0.520	0.520	0.537	0.552	0.606
Maintenance	(10.0)	0.550	0.630	0.850	0.040	1.070
Tires	(1.24)	0.133	0.133	0.186	0.239	0.239
Gasoline	(1.11)	0.057	0.070	0.083	—	—
Diesel oil	(1.11)	—	—	—	0.023	0.025
Oil	(2.11)	0.021	0.034	0.046	0.053	0.053
Insurance[j]		0.058	0.067	0.080	0.110	0.120
Total		1.339	1.454	1.782	2.017	2.113

[a]All costs in 1959 Bolivars; depreciation costs not included.
[b]Annual truck utilization assumed to be 80,000 km.
[c]Base wage of Bs 2,170/month (including 45 percent benefits) increased by 3, 6, 16 percent, respectively, for 15.9, 21.0, and 23.5 ton trucks.
[d]Includes engine overhaul estimate of 7.7 Bs/HP every 60,000 km and monthly charges of Bs 150, 180, 300, 400, 350, respectively.
[e]Assumed tire life of 42,000 km and cost of Bs 450/tire.
[f]Average of empty and fully loaded fuel consumption computed for a rise and fall of 2.0 meters/100 meters, after Saal, (29), p. 39, and fuel costs of Bs 0.14/liter.
[g]Fuel consumption computed as in footnote 6 above and divided by 1.52 and 1.55 for 21.0 and 23.5 ton trucks, respectively, to allow for greater diesel efficiency. (Fuel adjustment factors taken from U.S. Congress, Final Report of the Highway Cost Allocation Study, House Doc. No. 54, Gov't. Pr. Off., p. 204, 1961. Diesel fuel costs assumed to be Bs 0.50/liter.
[h]Includes an annual charge of 3 percent of initial value of truck for collision.
[i]Truck utilization assumed to be 50,000 km/yr.
[j]Annual total remains constant while utilization is reduced from 80,000 to 50,000 km/yr.
[k]Figures in parentheses indicate adjustment factors applied to costs of operation on paved surfaces.

TABLE 5

TRUCK OPERATING COSTS ON PAVED, GRAVEL, AND EARTH ROADS SHOWING LABOR, LOCAL CAPITAL, AND FOREIGN EXCHANGE COMPONENTS AT 10 PERCENT INTEREST

Item	Cost (Bolivars per 1,000 ton-km)[a]				
	7.8 Metric-Ton Cap.[b]	11.4 Metric-Ton Cap.[c]	15.9 Metric-Ton Cap.[d]	21.0 Metric-Ton Cap.[e]	23.5 Metric-Ton Cap.[f]
Paved roads					
Labor	64.5	56.8	47.6	44.5	45.9
Local capital	39.9	38.9	40.0	37.4	36.5
Foreign exchange	21.1	24.6	25.9	32.6	36.1
Total	125.5	120.3	113.5	114.5	118.5
Gravel roads					
Labor	123.6	111.2	97.6	94.4	96.3
Local capital	74.8	71.8	71.7	71.9	70.0
Foreign exchange	42.0	47.0	49.9	60.8	65.8
Total	240.4	230.0	219.2	227.1	232.1
Earth roads					
Labor	144.7	132.4	121.6	120.1	120.9
Local capital	74.9	74.0	76.1	76.7	75.2
Foreign exchange	53.5	58.5	61.4	73.7	78.5
Total	273.1	264.9	259.1	270.5	274.6

[a]All costs in 1959 Bolivars.
[b]Two-way load factor, 70 percent.
[c]Two-way load factor, 55 percent.
[d]Two-way load factor, 50 percent.
[e]Two-way load factor, 42.5 percent.
[f]Two-way load factor, 40.0 percent.

were used, however, adjustments were made to take into account differences in unit prices, such as the price of fuel.

These cost estimates have been itemized in Table 4 for five different truck sizes. Adjustments (shown in brackets) made for operation on unpaved earth and gravel surfaces have also been included. (Adjustments are based on data from Daftary and Ganguli, 11, p. 251, and Moyer and Winfrey, 21, pp. 23, 43.) These variable costs are stated in terms of costs per vehicle-kilometer for line-haul operation. They have been recalculated on a ton-kilometer basis in Table 5. Labor, local currency, and foreign exchange components for an interest rate of 10 percent have also been estimated.

Once the variation is fixed and current costs for changes in design standards and vehicle size have been determined, these data can be applied to the framework developed earlier for choosing the optimal road transport technology. For example, estimates of total annual current costs for a particular route in Venezuela were computed for each year from 1966 to 1975. Operating costs were based on the foregoing cost data for 15.9-ton trucks and the maintenance cost equations developed previously for various road types. For each of several road types construction costs were estimated using the previously given equations. Discounting the current costs for each year and expressing them as an equivalent annual volume (39), it was then possible to describe the substitutability possible between current and fixed expenditures (Fig. 15). To make the axes comparable, fixed costs have been amortized on an annual basis at an interest rate of 10 percent. The substitution relationship is shown by curve 1, and the optimal technology is determined by the point of tangency between this isoquant and the Bs 59,000 isocost.

Figure 15 also shows the effect of using accounting prices on the selection of final design standards. For each of the three isoquants, the optimum level of fixed investment (corresponding to a particular set of design standards) is different. Lowering the real wage rate, for example, improves the position of the higher current cost alternative since current expenditures (vehicle operation and road maintenance) have higher labor components than construction expenditures.

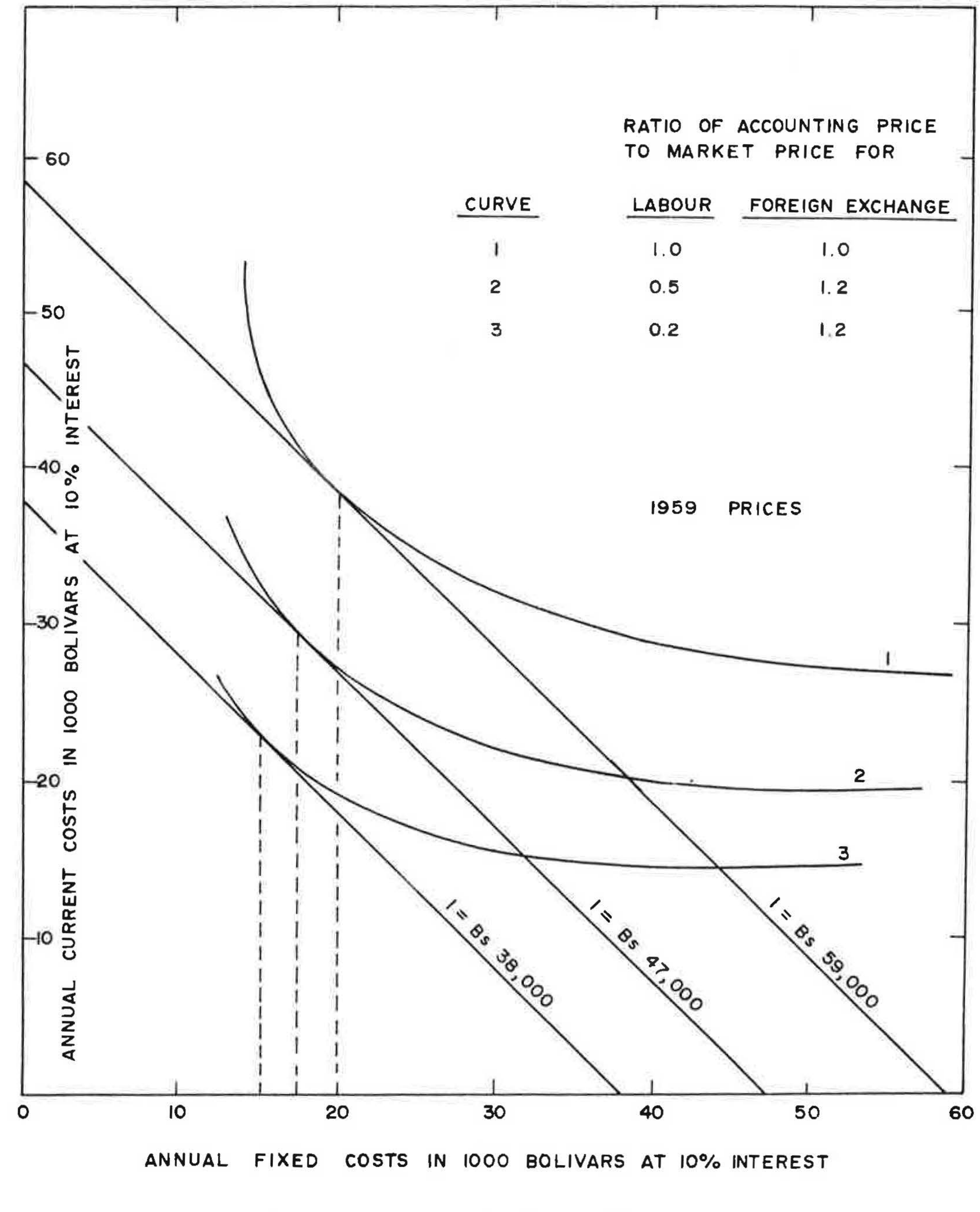

Figure 15. Selection of optimal road investment.

CONCLUSIONS

A conceptual framework for analyzing the degree of factor substitutability possible in producing transportation has shown that different transport technologies can be represented by different combinations of fixed investment and current costs. The optimal level of investment changes with changes in factor prices. Thus the level of transportation investment (as expressed by the choice of design standards) which is in keeping with best engineering practice in one country may not be justified in another characterized by different relative factor prices. Because these differences in relative factor prices are more pronounced among underdeveloped countries, the method of determining optimal investment levels suggested here is likely to be more meaningful in such countries.

The Venezuelan case study illustrates how relatively scant cost information can be used to estimate the cost relationships relevant to the method of analysis. These cost data were collected over a 3- to 4-month period. A national, familiar with local practice and working in his own country, could undoubtedly seek out the best sources of data in even less time. Moreover, a much wider range of data could readily be obtained in a shorter period of time by using some of the vehicle simulation and computer techniques available for evaluating construction and road user costs (19, 27). Recognizing that any sort of economic analysis requires some estimate of highway costs, the data requirements of this method of analysis do not appear to pose special problems.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support of the Joint Center for Urban Studies of the Massachusetts Institute of Technology and Harvard University and of the Corporacion Venezolana de Guayana. The author is also indebted to the Ministry of Public Works, Caracas, Venezuela, for permission to use much of the road construction data presented.

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