TRANSPORTATION AND LAND USE THEORY

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ABSTRACT

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A graphical exposition is emphasized in attempting to draw together the areas of theory that are relevant to the understanding of transportation and land use interrelationships. Five partial models are developed from within a general framework, permitting each model to remain very simple but still generalizable. Factors considered in the general framework include aggregate demand for productive output, the supply of productive output, the supply of transportation services, land consumption by both types of activities, land rent and land use intensity, and location.

INTRODUCTION

The two topics -- transportation and land use -- have long been referred to in a single breath but never satisfactorily integrated, either in theory or practice. Traditional microeconomic theory breaks down as soon as a spatial dimension is added because this factor automatically eliminates competition in its pure form. Spatial monopoly has been of interest to some economists, but the results do not appear to have much direct policy application. To the extent that land use theory has developed at all, it has been accomplished outside the mainstream of economics and often by individuals of somewhat eccentric talent (1, 2). The aim of this paper is to bring land use theory and transportation theory into somewhat greater proximity, if not integration.

Throughout, the viewpoint taken is that of the individual entrepreneur or producer. The producer estimates and responds to market demand, acquires land and other factors of production, and makes decisions about inputs, pricing, and output based on profitability criteria. Occasionally a public enterprise enters the picture, but the public enterprise is assumed to behave like a competitive firm (equating marginal benefits with marginal costs) even though it may be, in fact, a monopoly.

The theory is both positive and normative. It is positive in the sense that it describes how the world works (generally in abstract and aggregate patterns) and explains why things behave the way they do; it is normative in the sense that it represents an ideal or optimum against which to measure and evaluate deviations. The norms are based on properly functioning markets (typically the perfectly competitive market, although some of the model assumptions preclude such markets in actuality), so that discrimination, regulation, negative externalities, administered prices, etc., are regarded as market distortions. The first four models are all static equilibrium models, the fifth includes time as a variable but no others, and some comparative static analysis is applied to the group of models in a concluding section.

General Framework

Since all of the models are partial, no single one employs all of the variables and relationships listed below, but the models are all limited to this set of variables and relationships. Optimization is based on market equilibrium, with no externalities or other forms of market failure.

Demand: D(p). Demand for productive output -- a single aggregate homogeneous commodity/service -- is expressed in a dimensionless market as a function of price alone. Some theory of consumer utility can be presumed, but does not need to be made explicit as long as it can be assumed that individual and social benefits are accurately revealed by aggregate demand.

Supply: Q(L, T, K); T(L, K). Two types of goods are supplied, one being "productive" (final) output and the other being transportation services. Productive output is a function of the amount of land used for that purpose (L_p), the level of transportation services provided (T), and the amount of non-land inputs (K) that are employed for production. Transportation services are produced with land (L_T) and non-land inputs, and all output of transportation is consumed by the producers of productive output, making transportation a derived intermediate good. Transportation output is always assumed to be priced at social cost, although only the price and demand for productive output are made explicit in most of the models. The price of non-land inputs is assumed constant (k) per unit. All production takes place, then, by consuming land as an input, while demand (final consumption) occurs at a dimensionless point.

Land Value: R(Q, p, t). The value, or rent (R) of land is a function of how much is produced on the land, the value of the output (market price p, for productive output), and the time at which the valuation takes place. Land is valued in terms of its contribution to the value of productive output; where the price of land is made explicit, it is the difference between total value product and total cost.

Location: x,r. Any of the variables mentioned above could also be given a specific location, measured in distance (x) from the single dimensionless market. In the models actually presented, only productive output (Q) and non-land inputs (K) (and hence rent) are ever given a location argument. The price of distance is taken, in some of the models, to be a constant (r) per unit of distance.

FIVE PARTIAL MODELS

1. Spatial Equilibrium in a Single Market

The assumptions of the simplest case produce a somewhat abstract world, and any conclusions drawn are contained implicitly in this set of assumptions:

(1) Production takes place on an infinite uniform plane, undifferentiated in all respects (fertility, transportation routes, etc.).

(2) Consumption takes place in a single dimensionless market.

(3) Product must be transported to the market in order to be sold.

(4) Transportation cost is constant per unit of distance, from any point on the plane and in any direction.

(5) Only one kind of output is produced, i.e., there is only one type of land use.

(6) Output per unit of land is constant.

Most of these assumptions will be modified, usually one at a time, in various versions of the general model.

If we start at the market and move in any direction away from it, the costs to the entrepreneur of production plus transportation are a function of distance from the market. Production costs are everywhere constant per unit of land, and the market price determines the distance from the market beyond which production is infeasible. Transportation costs rise linearly because the rate is constant. All producers earn the same price in the market for their output, so those located closer to the market receive a surplus as a result of lower transportation cost.

Because the supply of all factors of production is completely elastic except for the land at a specific location, all economic surplus is appropriated by landowners. Thus, the difference between what the producer incurs in costs at any distance from the market and the price obtained for the output becomes land rent, which forms a cone such as that in Figure 1. Land at the market earns a rent equal to market price net of production costs, and land outside the maximum distance x_m earns no rent at all. The slope of the cone is the transport rate.

Adding to the previous information about the supply side is the demand schedule in the market, the two combining to determine the equilibrium price

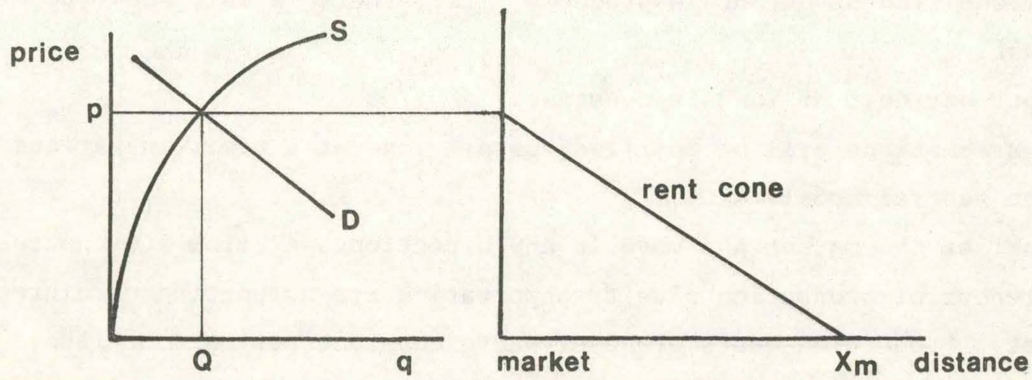

Figure 1. MARKET EQUILIBRIUM FOR SINGLE MARKET

and the amount supplied. Market output, Q, is the amount produced by a circle whose radius is x_m. Thus the extent of the market, the amount of output, and the market price, are determined by the parameters of the demand function and the transport rate.

2. Land Use Intensity

One abstract quality frequently referred to is "intensity," meaning the amount of activity or the level of capital investment per unit of land. The producer can combine two types of inputs -- land, and a general group of non-land inputs we will call capital -- at any location in the market area, to produce a single category of output. A mathematical representation of this production function might be

$$Q(x) = K^{\alpha}(x)L^{\beta}(x), \quad 0 < \alpha, \beta < 1, \text{ and } \alpha + \beta = 1$$

where K(x) is the capital invested at distance x, and L(x) is the land used for production at that distance. Constraining the parameters α and β to be between zero and one results in diminishing marginal returns for each factor at all levels of output, and constraining them to sum to one results in constant returns to scale. Views of what this production function might look like from different angles are given in Figure 2. The isoquants in the right-hand diagram are the result of looking down on contours cut horizontally through the three-dimensional surface, and the left-hand diagram shows vertical sections cut through the surface where indicated.

For the entrepreneur, on a given piece of land in a given location, additional applications of capital will increase output, but at a decreasing rate. Taking the cost of capital as constant, k, per unit, the interplay between costs (capital) and revenues (output times the constant price, net of transport costs) is shown in Figure 3. The producer who can pay the most for the land -- i.e., maximize rent-paying ability -- will get to use the land, so the rational entrepreneur will accomplish this by selecting an amount of capital equal to K* to complement the land inputs.

The slope of the capital cost function is the marginal cost of increasing production at the given location, and the slope of the revenue curve is the

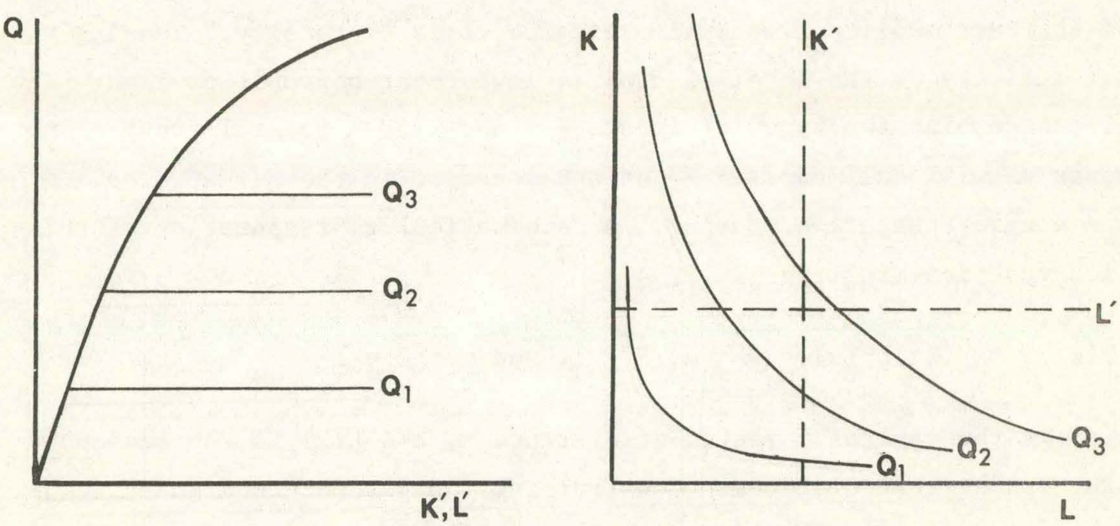

Figure 2. DIAGRAMMATIC REPRESENTATION OF COBB-DOUGLAS PRODUCTION FUNCTION

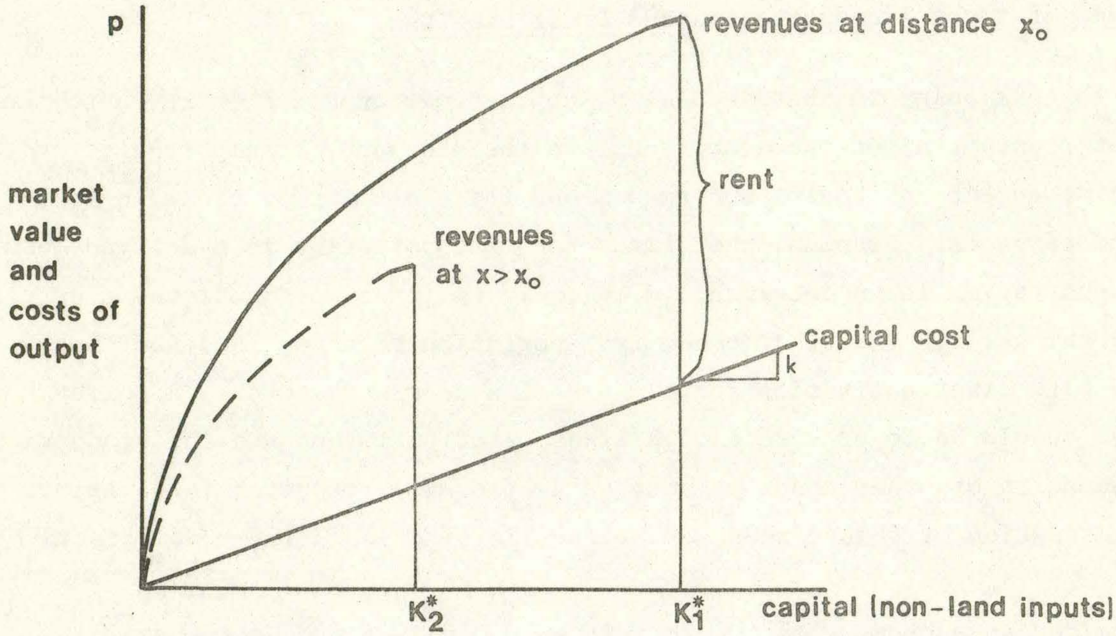

Figure 3. OPTIMIZING CAPITAL INPUTS AT A GIVEN LOCATION

marginal revenue earned by the last unit of capital; when these two slopes are equal, the difference between revenues and cost is maximized. For more distant locations, price is lower because of higher transportation charges while capital cost remains the same, so a lower level of capital input will maximize rent-paying ability. Mathematically,

$$R(x) = \left(\frac{\alpha}{k}\right)^{\alpha/1-\alpha} (1-\alpha)\ (p-rx)^{1/1-\alpha}$$

where R(x) is rent paid at distance x, and $1-\alpha = \beta$. Figure 4 shows a graph of this function, which has the same shape as K(x), the intensity function.

3. Balance Between Transportation and Other Land Use

Up to this point in the discussion, no recognition has been given to the fact that transportation takes up land. On the one hand, transportation is used not as an end in itself, but as a means for consuming or producing other goods and services. As such, the demand for transportation is a derived demand, and transportation is an intermediate commodity which complements the production of other things. On the other hand, transportation consumes land and thus competes with other activities for the use of a scarce resource. A policy objective should be to provide enough transportation to enhance the production and consumption of other goods without using too many resources in doing so. One formalization of this concept of balance is offered in the model described below.

Consider an economy with two activities. One is a productive activity requiring land and transportation as inputs, according to some production function,

$$Q = Q(L_p, T)$$

where the productive output, Q, is a function of the amount of land used for production, L, and the level of transportation service available, T. The second activity is the production of transportation services, represented by

$$T = T(L_T)$$

where L_T is the amount of land used for transportation. No specific shapes for

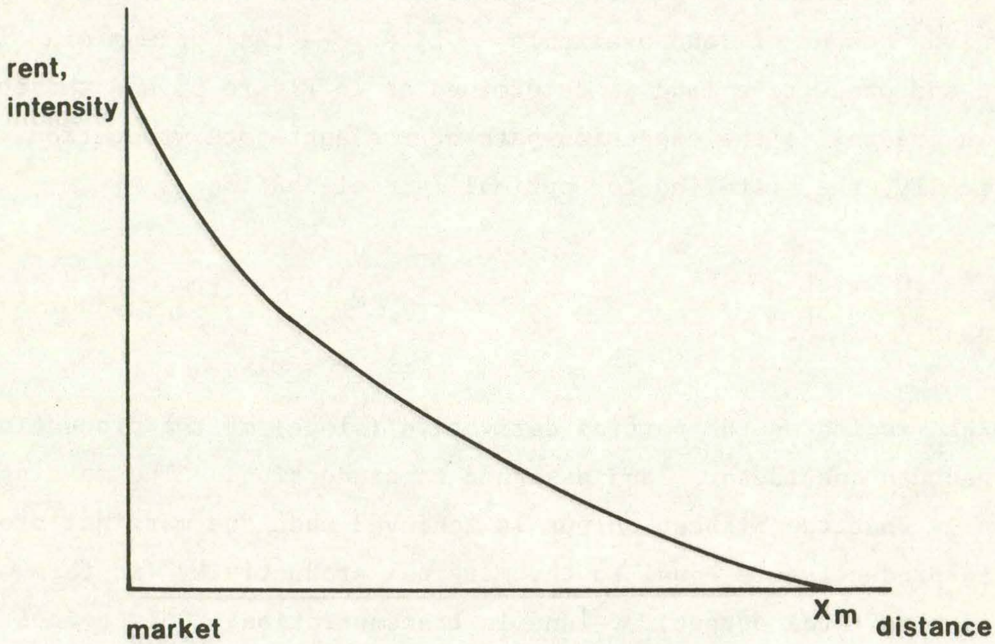

Figure 4. RENT GRADIENT AND LAND USE INTENSITY GRADIENT

these two production functions are assumed.

Intensity of land use in both sectors is ignored, i.e., held constant, as well as the spatial arrangement of the two types of land use. Implicitly, then, we are assuming that however the interaction takes place between transportation and land use it is worked out in an optimal manner and is properly reflected in the two production functions.

Although three distinct inputs are indicated as arguments in the production functions, there is only one basic factor, land. The problem is to allocate the single factor to the two sectors in such a way that output of the aggregate production function is maximized, represented diagrammatically by a function similar to the one shown in Figure 2 (not necessarily a Cobb-Douglas function). For any given amount of land available -- $\bar{L}$, say -- the optimum mix of transportation and productive land is determined as in Figure 5, and the optimum balance in general is the expansion path of the aggregate production function. Mathematically, the criterion for optimal land allocation is

$$\frac{\partial Q}{\partial L_p} = \frac{\partial Q}{\partial T} \cdot \frac{\partial L}{\partial L_t}$$

where $\partial Q/\partial L_p$ indicates the partial derivative (slope) of the production function with respect to one factor, land assigned to production. The meaning of this criterion is that the highest output is achieved when the marginal productivity of land in production is equal to the marginal productivity (in terms of contribution to total output) of land in transportation. Only points lying along the expansion path satisfy this criterion. The scale along the horizontal axis of the lower diagram in Figure 5 can be regarded as the percentage of the total land available that is allocated to transportation, ranging from zero on the left to one hundred on the right.

At the moment, we have no empirical knowledge of the production functions proposed in this model, and so we cannot estimate the share that should be given over to transportation. We can observe, however, the actual balance: in built-up areas of cities the street system occupies about thirty percent of the land area, and if parking lots and garages, filling stations, repair garages, spare parts outlets, auto and truck sales, etc. are added in, the total is said

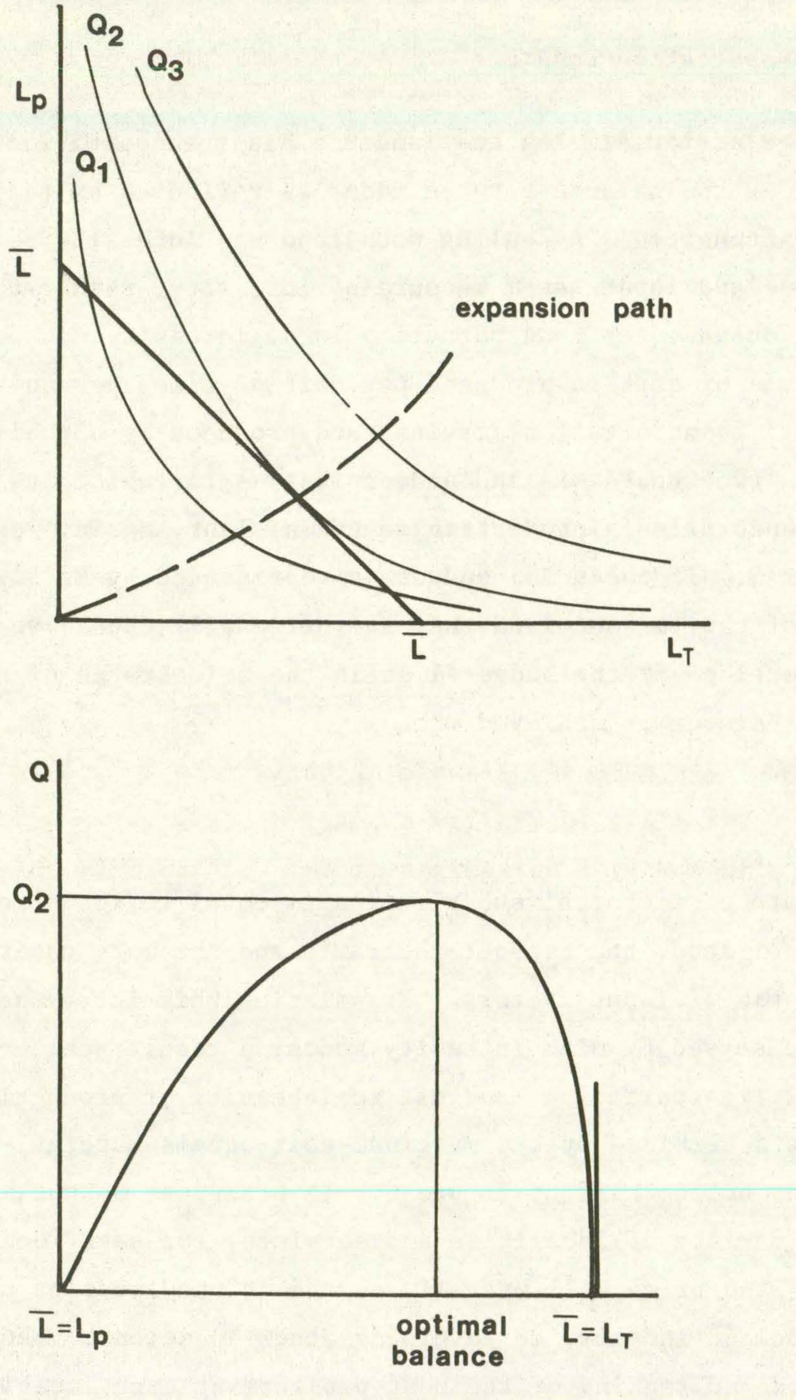

Figure 5. OPTIMAL ALLOCATION OF LAND TO TRANSPORTION VERSUS PRODUCTIVE ACTIVITY

to reach sixty percent or more in parts of some cities. Intuitively, one wonders whether this could possibly be an optimal use of urban land.

4. Intensity of Transportation Land Use

As another slice at formalizing the land use and transportation relationship, we will consider the balance between modes as reflected by their varying levels of land use intensity. In dealing with land use intensity above, it was necessary to use non-land inputs as a measure of intensity, rather than some measure of usage or output; for transportation land, intensity can be measured directly as the volume of service produced per unit of time, per unit of land.

Suppose that all transportation services are produced by a public enterprise, which utilizes two inputs -- land and capital -- for which it pays market prices. The enterprise's production function might, again, look like those in Figures 2 or 5. If the total budget is represented by M, Figure 6 shows the input mix of capital and land the enterprise will choose so as to maximize output. The slope of the budget line is the price ratio of capital to land, so the optimal balance is achieved when

$$\frac{\partial T}{\partial K} \Big/ \frac{\partial T}{\partial L} = \frac{k}{R}$$

i.e., the marginal rate of technical substitution is equal to the price ratio. The higher the value of land, the steeper the ratio and the more capital will be emphasized in the mix of input factors. Translating this into modes, high-priced land should be served by high intensity modes, a result achieved by matching intensity of transportation land use to intensity of productive land use.

Total output is determined by the marginal-cost-equals-marginal-benefit criterion shown in the bottom half of Figure 6. In practice, output is actually the aggregation of a variety of facilities and services; for each location a different demand and land price will prevail, demand at one location being interdependent upon demand and service levels at other locations. Thus the supply curve is an ordered ranking of the best projects at each location, demand is a similarly aggregated function, and a different set of tradeoffs between land value and capital intensity exists at each location.

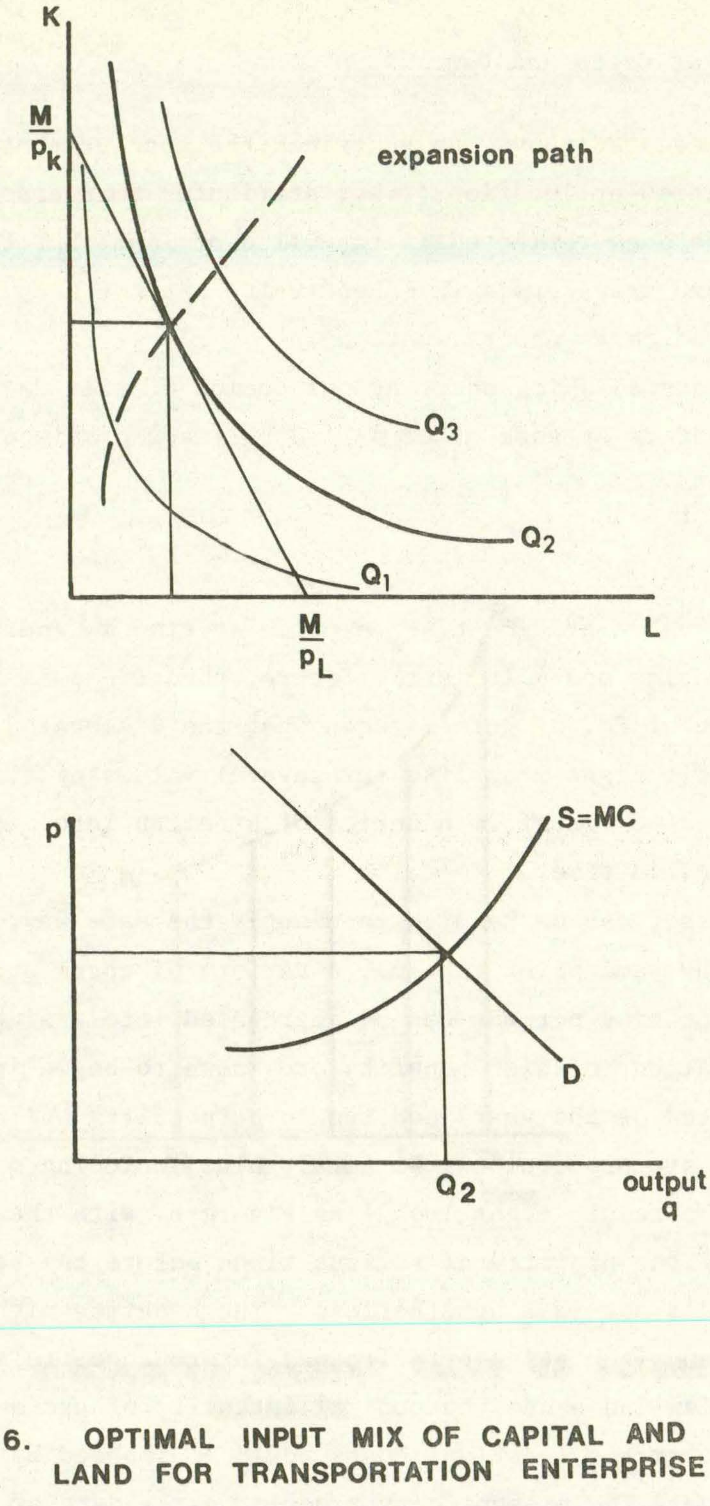

Figure 6. OPTIMAL INPUT MIX OF CAPITAL AND LAND FOR TRANSPORTATION ENTERPRISE

5. Capitalization of Costs and Benefits

The theory presented above has contained the concept that the value of attributes of a particular location (i.e., attributes that cannot be moved to another location) becomes reflected in the value of land, but the mechanism by which benefits become transformed into land value has not been illuminated. The mechanism is referred to as capitalization.

Benefits (or costs) which occur at one period of time can be transformed into equivalent benefits at some other period by means of discounting. In general,

$$P_t = P_\alpha (1 + i)^{t - \alpha}$$

where P_t = price or value at time t, P_α = price at time α, and i = discount rate. If t is the present time and α is in the future, then $t - \alpha$ is negative and P_t is the present value of P_α. Figure 7 shows what the discounted present value of a given future benefit might look like for several values of t. The same technique can be used to transform a series of benefits into a single lump sum at a particular point in time.

Costs, of course, can be handled in exactly the same way. Once transformed into lump sums at the same point in time, a variety of costs and benefits from different sources and time periods can be aggregated into a single value. Take, for example, a situation in which benefits are known to begin in future year α (paying off at the end of the year) and run in perpetuity, while costs are to begin in year t and are proportional to total value including discounted benefits. Diagrammatically, the result might look like Figure 8, with the dashed line showing the value of the property at various times before the benefits begin.

The situation is not just hypothetical. The benefits might be the consequence of a rapid transit station or a freeway interchange, raising the level of access of the location and hence the optimal intensity of use as well as the ability to pay rent for the location; costs would be imposed by an ad valorem tax on property value. The present time t would be the date at which it became known that the facility would be constructed -- the "announcement" -- and time α would be the date the facility commenced operations. Uncertainty about the size and nature of the benefits (including the possibility that the

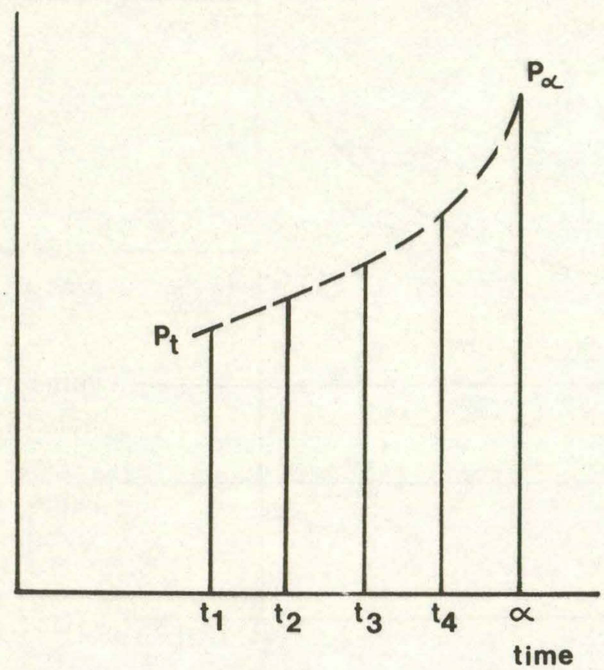

Figure 7. DISCOUNTED PRESENT VALUE OF FUTURE BENEFITS

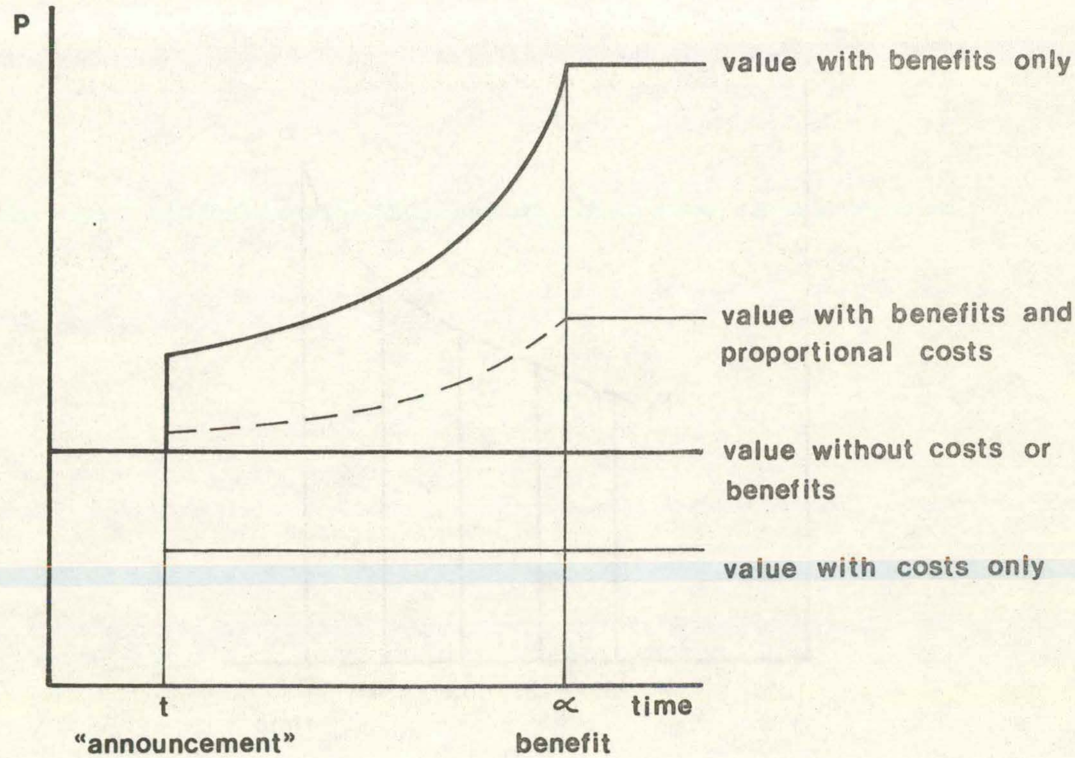

Figure 8. CAPITALIZED COST AND BENEFIT STREAMS

decision to construct the facility might be overturned) and their timing would tend to have the effect of increasing the discount rate used by potential buyers of affected property.

Capitalization, then, is the process by which the future costs and benefits associated with a piece of property become incorporated into the price of the property; when the property is purchased, it is the stream of costs and benefits that is bought. At the instant a change in the future net benefit stream becomes known, the real property market capitalizes (however imperfectly) that change into the price of the property. This one-shot windfall (it may be negative as well as positive) can never be recovered, once conferred--subsequent attempts to use the property tax to get back windfalls only compound the inequity. Suppose, for example, that cost and benefit streams which would leave property values unchanged are announced, but costs (e.g., taxes) are announced a year after the benefits. Assuming the costs were unexpected at the time of the benefits announcement, property owners could sell their land and liquidate the benefits stream. Subsequent owners would then reap a negative windfall when costs were announced, and both announcements will have created income transfers without any particular efficiency or equity purpose.

COMPARATIVE STATIC ANALYSIS

An important attribute of good theory (useful for policy analysis) is the property of being able to change one variable of interest and deduce the impacts of that change. If, for example, we combine the first two models and ask about the consequences of underpricing transportation to users, the results are shown in Figure 9. From the positive aspects of the theory, it can be seen that a decrease in transportation costs shifts the supply curve outward and flattens the rent gradient, extending the area under production but reducing rents and intensity of use at the center. Normatively, this result can be viewed as a market distortion with negative welfare consequences unless there are offsetting external benefits created by the distortion.

Another topic of interest is the impact of a major increase in access at a particular location, cuased by a freeway interchange or a rail rapid transit

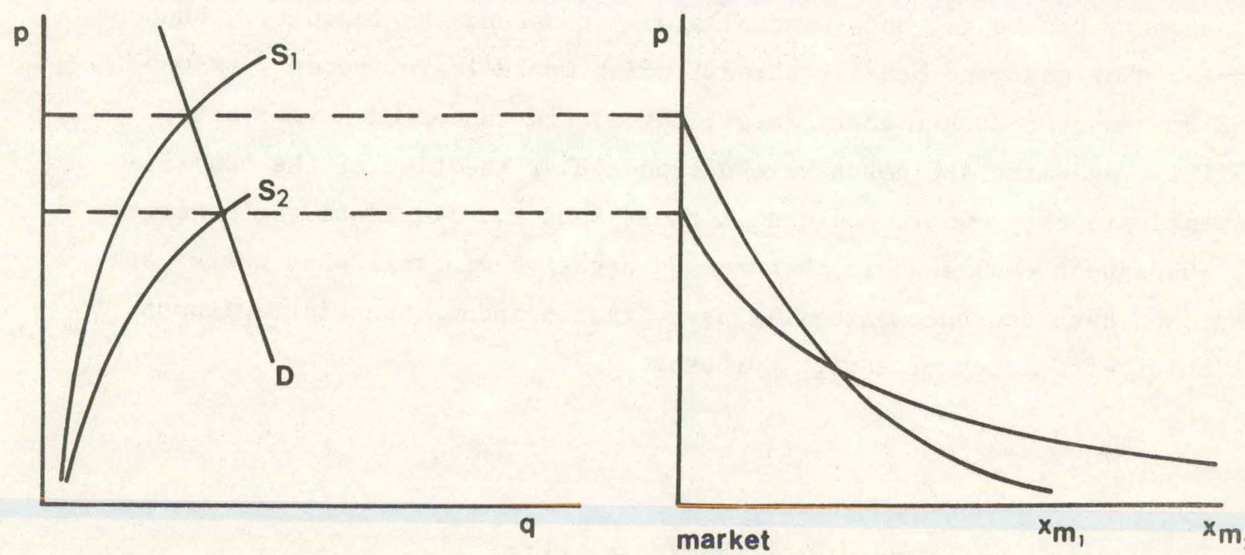

Figure 9. IMPACTS OF UNDERPRICING TRANSPORTATION

station. Suppose such a change occurred at x_1 in Figure 10, providing a level of access there previously enjoyed by land at distance x_0. Then the effect is to shift the rent-and-intensity gradient outward from the market; land values will increase at all locations outside x_1, but the largest increases will take place in the vicinity of the access point x_1.

The increment in land value shown implicitly assumes elastic demand in the spatial equilibrium giving rise to the initial land values. A contrasting assumption would be that total income or product in the region was unchanged by the transportation investment, i.e., net benefits were neither positive nor negative, just distributed differently. Consider, for example, a new rail rapid transit system for a region. If the system is financed from uniform property taxes, there will be a redistribution of land values. Land receiving the benefits of greatly increased access would increase in value, while land not so benefited would lose in relative terms and also in absolute terms under the zero-sum (no net benefits) assumption.

CONCLUSIONS

The partial equilibrium models presented above are too general to be solved in any form other than as conceptual abstractions. Nonetheless, besides providing a rigorous analytic understanding of the structural interrelationships between transportation and land use, these models yield a number of useful general guidelines:

(1) Rent per unit of land decreases at a decreasing rate as distance from the market increases.

(2) The more accessible the location, the more intensively the land will be used (more capital inputs relative to land) and the higher the value of land.

(3) Land use intensity follows the shape of the rent gradient, decreasing at a decreasing rate with increasing distance or decreasing access. In fact, the ratio between intensity (capital investment) and rent (land value) is approximately constant.

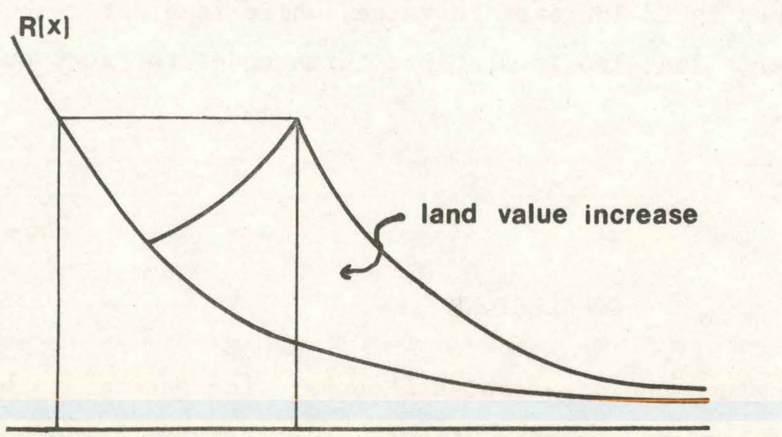

Figure 10. CHANGE IN LAND VALUE NEAR POINT OF MAJOR ACCESS CHANGE

(4) Other things being equal, urban land values are determined by the access (effective location) of the site to other sites of interest.

(5) If net social benefits are maximized, the higher the land value of a given location the higher the intensity of use, whether the use is transportation or other land use.

(6) The same factors of social cost (supply) and social benefit (demand) determine whether the best use of a site is for transportation or for some other use, at all locations. In this sense, there is no difference between land used for transportation and land used for other purposes.

(7) Whatever the type of land use, all costs (including opportunity costs) should be passed on to the direct consumers of the services provided by the land use; direct consumers will then pass on costs to indirect consumers through normal market mechanisms. No public goods aspects of transportation appear in these models.

(8) The above conclusions assume an absence of general taxation. If land is taxed as a source of general revenue, the objective of applying a non-distorting revenue instrument requires that <u>all</u> land uses be treated alike, i.e., land used for transportation should be taxed at the same rate as land used for other purposes.

(9) The above conclusions assume an absence of externalities. To the maximum extent feasible, public policy should seek to internalize significant externalities, and compensate for any residuals. (Negative externalities of transportation may occur in the form of noise, air and water pollution, and physical danger.)

(10) <u>Indirect</u> benefits of transportation are not <u>external</u> benefits, i.e., the benefits of transportation services are internal to normal market processes. Any subsidization to transportation land use from general tax sources distorts the allocation of resources away from the social optimum.

These results, of course, are a consequence of nothing more than the assumptions that we started with, including the particular form of the production function. While these assumptions are, of necessity, highly abstract, they are entirely plausible at the aggregate level and the results are consistent with empirical observation, most notably rent and density gradients for metropolitan areas. The world is much more complicated that it has been portrayed here, but it is a complexity built upon the underlying structure contained in these models.

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