An Approach to the Economic Evaluation of Urban Transportation Investments

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A conceptual framework for the economic evaluation of urban transportation investments is presented. It is suggested that urban transportation planners must be concerned with both the economic efficiency and the distributional efficiency of investment alternatives. The economic efficiency characteristics of transport investments are developed in terms of demand curves for accessibility and for environmental quality. Several measures of accessibility are reviewed and it is suggested that a community demand schedule for accessibility may be derived from models of the urban land market. It is suggested that demand schedules for environmental quality will have to be derived from regression analyses of urban property prices. It is demonstrated how the economic efficiency criterion may be modified to reflect distributional efficiency requirements. An approach is presented that is developed in terms of the accessibility gains to car owners and non-car owners.

•DURING RECENT YEARS there has been a growing disenchantment with the existing horizon-year type of urban transportation planning process. Many of the difficulties have arisen because of the inadequacies of the evaluation methodology embodied in this process. Two principal types of evaluation methodology have been proposed and used. The first group includes those that are based to some extent on welfare theory. Typical examples of this group are the frameworks proposed by Winch (1), Wohl and Martin (2), Beesley and Walters (3), and Rahmann and Davidson (4). The second group consists of those that have attempted to replace the concept of a competitive market by some form of rating scheme; it includes those reported by Hill (5), Schimpeler and Grecco (6), Falk (7), and others.

The principal difficulty with those methodologies based on economic theory is the reliance on market prices, or imputed market prices, for the measurement of benefits and costs. The second group is inadequate because of the lack of any sound conceptual basis. Rating scales possess many inherent deficiencies and the author has discussed some of the problems associated with their use in another context (8).

In spite of the shortcomings of welfare theory, it does provide a sound basis on which to erect an evaluation framework. Community preferences may find expression through mechanisms other than dollar-voting in the market, or even imputed dollar-voting. It is the purpose of this paper to advance an evaluation framework for urban transportation investments that the author believes will provide a broader approach to evaluation than those advanced by other authorities (1, 2, 3, 4).

EXISTING FRAMEWORKS

Winch (1) reported on one of the first attempts to apply the economic concepts of demand and supply schedules to highway investment analysis. He developed demand and supply curves for highway travel in terms of user costs of travel and the number of

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road vehicles passing a point on a highway link. The framework advanced by Winch assumes that the elasticities of demand for movement can be estimated and that there are no system effects of project investment. Winch does not attempt to account for the externalities associated with trip-making that are particularly important in urban area travel.

Wohl and Martin (2) have adapted the type of framework proposed by Winch to the economic evaluation of urban area road investments. Their framework is restricted to mutually exclusive investment alternatives, and their concentration on user benefits and costs restricts the application of their framework. In addition, their exclusion of consumer surplus from the benefits of road investments is not supported by the main body of economic thought.

Beesley and Walters (3) have also used an approach similar to that described by Winch. They have proposed that the objective of urban transportation system investment should be the maximization of the users' consumer surplus subject to constraints on those nonuser objectives that are influenced by the transportation system. Beesley and Walters emphasize the substitution and complementarity effects of road projects and attempt to incorporate these characteristics into their evaluation framework. They have also discussed the problems of urban amenity and the accommodation of various interest groups but have not provided a formal treatment of these two attributes of the problem.

The major features of these evaluation frameworks may be illustrated as shown in Figure 1. Hypothetical demand, DD, and supply SS, curves are shown in the diagram for two roads. The area WXYZ identifies the user benefits that may be assigned to the proposed road project. Also shown in Figure 1 is the users' marginal cost curve for increasing traffic volumes on the existing road. A number of investigators (9, 10) have noted the need for some form of congestion levy, in addition to the normal user taxes, in order to yield an efficient traffic volume on a roadway link. The magnitude of this congestion levy is given by AB.

A rather different approach has been proposed by Rahmann and Davidson (4). The principal difference in their evaluation framework from those mentioned previously is in their attempt to rationalize the modal investment problem. The previously mentioned frameworks are all restricted to the evaluation of road investments. The essence of the approach suggested by Rahmann and Davidson (4) is shown in Figure 2. In this diagram,

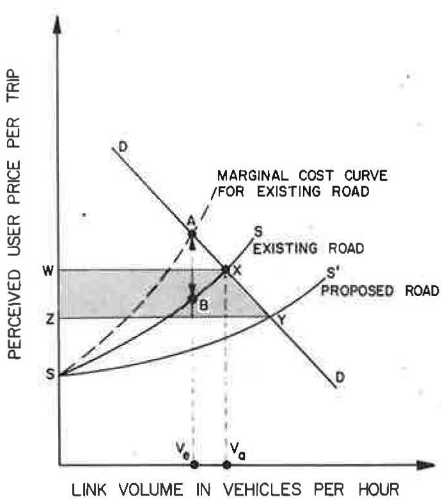

Figure 1. Basic structure of existing approaches to the economic evaluation of road investments.

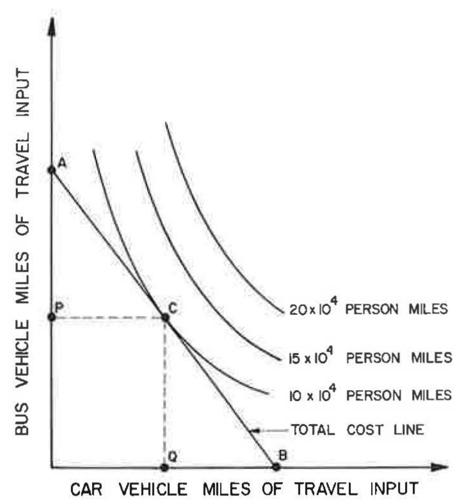

Figure 2. The Rahmann and Davidson approach to urban transportation investment analysis.

isoquants of transportation system output (person miles) are shown in terms of the combinations of car and bus mileage that would be required to yield these output levels. The line AB represents the total cost line and C yields the most efficient condition. That is, the community selects the combination of public and private transport at which the marginal rate of substitution of public for private transport equals the cost ratio as viewed by the community.

The framework proposed by Rahmann and Davidson provides a distinct improvement over those proposed previously. However, it is the author's opinion that this framework still fails to treat the nonuser dimensions of urban transportation investments adequately. Most of the issues associated with urban transportation investment in many urban areas involve conflicts between the provision of accessibility and the quality of the urban environment. None of the evaluation frameworks proposed to date provides a satisfactory mechanism for resolving these issues.

ELEMENTS OF AN EVALUATION FRAMEWORK

The principles of welfare economics and the methodology of systems engineering (11) indicate that the following sequence of activities must be performed in order to erect an economic evaluation framework:

1. Establish the community objectives (or preferences),
2. Identify the transportation system outputs that relate to each of these objectives,
3. Identify the strengths of the community objectives in the form of community willingness to pay for outputs, and
4. Identify a decision criterion for ranking alternative investment proposals and for establishing the optimal level of investment.

Each of these elements is explored in the following sections of this paper.

OBJECTIVES OF URBAN TRANSPORTATION INVESTMENT

It is appropriate to begin this discussion of the objectives of urban transportation investment by quoting from an essay by Marglin (12) on the objectives of water resource system investment.

> The prime objective of public water resource development is often stated as the maximization of national welfare. That this is a goal to be desired few would question; that it cannot be translated directly into operational criteria for system design, few would deny. Translation would require not only agreement on a definition for the deceptively simple phase "national welfare" but also some assurance that the defined concept is measurable.
>
> One possibility is to define national welfare as national income. The objective of system design then becomes maximization of the contribution of the system to national income. This definition is measurable, but it has implications for the meaning of national welfare that make us unwilling to accept it as a complete expression of the broad objective. Identifying national welfare with the size of the national income not only excludes non-economic dimensions of welfare but also implies either that society is totally indifferent as to the recipient of the income generated by river-development systems, or that a desirable distribution of gains will be made by measures unrelated to the way in which the system is designed.
>
> Social indifference to the distribution of income generated by the system suggests that the marginal social significance of income is the same regardless of who received it.

The broad goals of urban transportation investment might be identified as (a) maximizing the aggregate consumption of the community, and (b) assisting in the realization of an equitable real income distribution among members of the community. These broad goals reflect Marglin's statement that planners of public systems must be concerned with both economic or allocational efficiency and with distributional efficiency.

The concept of economic efficiency is usually defined in the following way. An allocation of resources to a system is said to be economically efficient if there is no other allocation of resources that would make anyone better off without making someone else worse off. The conditions that must be fulfilled to yield allocational efficiency within a system will be discussed later in this paper.

An allocation of resources to a system may be said to be efficient in the distributional sense if the distribution of real income corresponds to the distribution desired by the community. The question as to whether a particular urban-wide distribution of travel opportunities is efficient in the distributional sense is a value judgment that must find expression through the political process

The concept of distributional efficiency is illustrated by the following statement made by Thompson (13) in discussing socioeconomic segregation in cities in the United States:

> Simultaneously with the decline of mass transit, manufacturing, retailing, and other activities have been suburbanizing. With suburban densities far too low to support the extension of the lines of even a healthy mass transit system, the elderly, those financially unable to own a car, those unable to drive, and others, find that dependence on the central city mass transit system has narrowed their employment opportunities very appreciably. Clearly, growing affluence has led to greater mobility for most, but less mobility for a significant group, both in their roles as consumers and producers. A wide range of choice, the great virtue of the large city, is more the prerogative of some than others.

The goal of maximization of aggregate consumption may be divided into three groups of subgoals of objectives; they are (a) to maximize the aggregate accessibility provided by the system, (b) to maximize the aggregate environmental quality (as defined in 20) of the urban area that is related to transportation system outputs, and (c) to maximize the achievement of desirable long-term urban development patterns. These objectives suggest that a central problem of urban transportation investment analysis is to determine what kinds of urban development meet the aesthetic preferences of urban residents as well as their accessibility requirements. The orientation of investment implied by these objectives is quite different from the previous approaches to evaluation that have been concerned primarily with the evaluation of changes in movement impedance.

Experience with urban transportation investment in North American cities has demonstrated that, to a large extent, the objectives of accessibility and environmental quality are competitive. Much of the transportation investment has been concentrated in road facilities. These road facilities have allowed an increased penetration of urban land uses by motor vehicles that, in many instances, has decreased the environmental quality of these land uses.

A great deal of evidence is available (14) to demonstrate that the changes in the physical organization of urban areas have been a consequence of the changes in the costs of urban movement. Public investment in urban transportation facilities tends to reduce the costs of movement and thereby the costs of interaction between various activity centers of the urban area. However, urban land development is influenced by many other factors, and the third objective identified previously cannot be related exclusively to the accessibility objective. With the present state of knowledge regarding land development processes the formal characteristics of an evaluation framework must be restricted to a short-run equilibrium analysis. This assertion in no way minimizes the importance of this third objective. The overriding importance of this third objective has been stated very competently by Harris (15):

> The bland assumption of the economists that a competitive optimal allocation of resources coincides with a social optimum may lead to serious pitfalls. In part, these can be avoided by a consideration of externalities, but this will lead to a consideration of policies. This will happen because it will be discovered that the externalities of locational decisions are not covered in a system of economic rents, and consequently do not adequately influence the behavior of decision makers. There is also a deeper question of the same nature having to do with the development patterns and optimization over time. Even if present externalities are accounted for in the behavioral system and the related objective functions, the effects of current decisions are frozen in capital works. As time passes and conditions change, these decisions not only may be no longer optimal but they may generate new externalities as their effects are propagated through the system. It is almost certain that the institutional arrangements which might equate individual and social optimization at one point in time, would require drastic modifications to equate current individual optimization with long run social optimization.
>
> As capital is not instantaneously convertible from one use to another, dynamic development patterns depend not only on instantaneous pressures but upon the whole history of the system.

The position taken for the purposes of this paper is that formal evaluation of transportation investment proposals must be restricted to the objectives of environmental quality and accessibility. The third objective must be realized through other types of policy decision.

URBAN TRANSPORTATION SYSTEM OUTPUTS

The models of urban development that have been developed to date have illustrated that, at least for North American conditions, location or accessibility is the dominant factor in determining the uses of land and the intensities of uses. One definition of accessibility is that derived from the gravity model, given by

$$ACC_i = \sum_{j=1}^{n} A_j \cdot f(d_{ij}) \qquad (1)$$

where

ACC_i = the accessibility of zone i relative to the n other zones of the urban region,
A_j = a measure of the attractiveness of these other zones, and
$f(d_{ij})$ = a measure of the travel impedence between zones i and j.

Equation 1 demonstrates that accessibility is a relative quality that accrues to a parcel of land by virtue of its relationship to other parcels of land and the quality, or level of service, provided by the transportation system. It must be recognized that the accessibility measure defined in Eq. 1 is only one possible measure. Little direct systematic evidence has been assembled to demonstrate that this accessibility characteristic is truly the fundamental characteristic of a transportation network that the community is willing to pay for.

Schneider (16) has proposed a formulation of accessibility that may prove to be a more realistic measure of this quality of an urban zone. He has developed the following expression for travel:

$$\frac{dV}{dR} = cI \qquad (2)$$

where

V = number of trips to and from a zone,
R = an undefined characteristic of a zone that attracts trips to it,
I = $\int FdR$, called the access integral of a point,
F = a function of the separation between zones,
c = constant of proportionality = $V_T/\int IdR$, and
V_T = total trips in the region.

Equation 2 indicates that the trip density at a point per unit of attractiveness is proportional to the accessibility of the point.

Schneider then goes on to develop the following expression for change in the development of a zone:

$$R_f = R_F \cdot R_a I/(J - R_F I) \qquad (3)$$

where

R = $R_a + R_f$,
R_a = some trip-attracting characteristic of a zone that is proportional to its land area,
R_f = some trip-attracting characteristic of a zone that is proportional to its development,
R_F = some characteristic that is proportional to the total floor area in the region, and
J = $\int IdR$.

TABLE 1

PEDESTRIAN DELAY AND NOISE LEVELS CAUSED BY VARIOUS TRAFFIC FLOWS

Traffic Flow (vehicles per hour)		Pedestrians Delayed (percent)	Average Delay to All Pedestrians (second)	Approximate Noise Level, dBa[a]	
All Vehicles	Heavy Vehicles			Mean	Climate[b]
50	5-10	6-7	<1	51	49-60
100	10-20	11-13	<1	53	49-62
150	15-30	15-19	<1	55	51-64
200	20-40	20-24	<1	56	51-65
250	25-50	24-29	<1	58	52-67
300	30-60	28-34	0.8-1.2	59	53-69
400	40-80	35-42	1.0-1.7	61	55-71
500	50-100	43-50	1.3-2.2	63	57-73
750	75-150	56-65	2.2-3.8	67	61-75
1,000	100-200	67-75	3.3-5.9	69	64-77

[a]dBa = decibels above reference noise, adjusted. [b]10 to 90 percent of whole time.

Equation 3 may provide the required link between the output of the transportation system and the willingness to pay for this output.

Another interesting approach to the characterization of the accessibility of points in an urban region is that developed by Rassam and Ellis (17). They have shown that the travel impedances between points in an urban region can be estimated analytically, given certain assumptions about the geographic distribution of speed within an urban area. This approach may also provide an important link between the transportation system output and the willingness to pay for this output. The average speed on the links of a highway network has been used in several studies (18, 19) to impute the user willingness to pay for output.

The definition and measurement of environmental quality has not received as much attention as accessibility. The Buchanan report (20) and other studies in Great Britain (21) provide the major sources of information. Pendakur and Brown (22) have explored the environmental quality of a suburban shopping street in Vancouver using some of the concepts developed in the earlier studies.

It is generally agreed that the two major factors influencing the environmental quality of an urban zone are (a) the volume of vehicles using a transportation network link (either transit vehicles on separate rights-of-way on the street or motor vehicles), and (b) the visual intrusion of parked transport vehicles and their rights-of-way. The characterization of the environmental impacts of motor vehicles is discussed first.

Motor vehicles affect the environmental quality through their emission of noise, exhaust fumes, and vibration and through their interference with pedestrian circulation and safety. Table 1 gives certain information obtained in Great Britain for the delays to pedestrians and the noise levels caused by various vehicle volumes. Figure 3 shows a relationship developed by the Wilson Committee (23) in Great Britain that relates the mean noise level to traffic volume. In the absence of additional information on environmental quality, the average vehicle volume on a road link would seem to provide the transport system output that relates most directly to environmental quality.

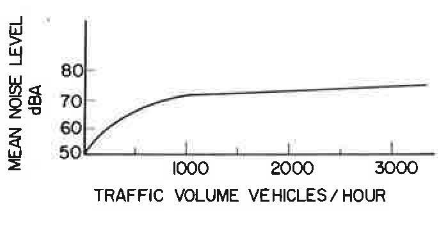

Figure 3. Mean noise level versus traffic volume.

Parked vehicles are considered to detract from environmental quality through their visual intrusion and their influence on pedestrian safety. The provision of parking facilities for motor vehicles that provide adequate standards of civic design usually involves significant expenditures and represents an important dimension of the costs of providing environmental quality.

A comprehensive measure of environmental quality would require a rationale for weighting each of the dimensions of environmental quality to yield a single index. However, insufficient evidence is available to allow such an index to be derived. The following discussion proceeds on the assumption that a unique measure of environmental quality will be derived in the short run.

The environmental impacts of transportation technologies other than motor vehicles also include noise and visual intrusion. These characteristics vary greatly with the type of technology and cannot be summarized easily. Figure 4 is an example of the type of information that is available for other modes of transport (24).

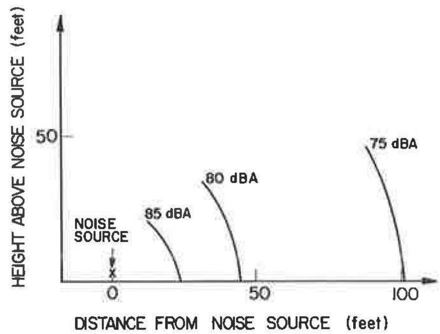

Figure 4. Noise intensity generated by a typical steel-wheeled rapid transit system.

COMMUNITY WILLINGNESS TO PAY FOR OUTPUTS

The community demand schedule is the economic concept that is available for expressing the community willingness to pay for various levels of system output. Figure 5 shows the demand curves that are of interest to the evaluation framework developed in this paper. These demand curves indicate that willingness to pay consists of a market value plus the triangle called the consumer surplus. The consumer surplus is usually defined as the difference between the maximum amount consumers are willing to pay for a specified quantity of a good rather than go without it and the value of the given quantity of the good at its competitive market price.

If the urban land market were perfectly competitive, and if accessibility and environmental quality were the major characteristics of a parcel of land that buyers were willing to pay for, then community demand curves for accessibility and environmental quality could be derived directly. These demand curves must be derived by indirect means, and it is the purpose of this section of the paper to explore possible ways of deriving community demand curves.

A number of studies have been made of urban land values, but none of these studies have related land values to reasonable measures of accessibility. Kain (25) has assumed a linear relation between land values and straight-line distance from the CBD, whereas Berry, Simmons, and Tennant (26) have observed a negative exponential relationship between land values and distance from the CBD. These broad relationships do not reflect adequately the many local peaks in land values that occur in major urban regions and provide a poor basis for the derivation of community demand curves. Theoretical frameworks of the type developed by Wingo (27) and Alonso (28) appear to provide the most promising approach to the derivation of a demand curve. The basic structure of the framework proposed by Wingo is reviewed briefly in the following to demonstrate one possible approach.

Wingo (27) has isolated the transportation function shown in Figure 6a as the key feature of an urban transportation system that influences the distribution of households in an urban region. Wingo has then shown how this transportation function may be used to derive a spatial structure of position

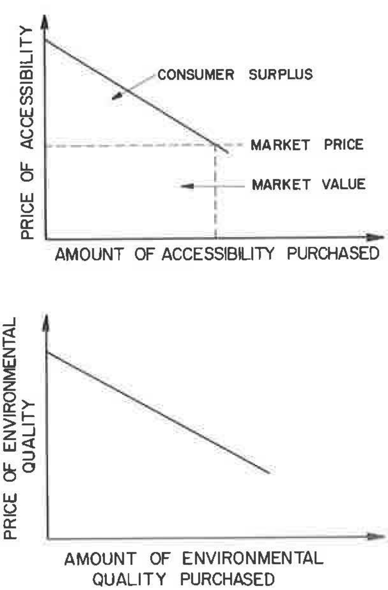

Figure 5. Community demand curves required by the evaluation framework.

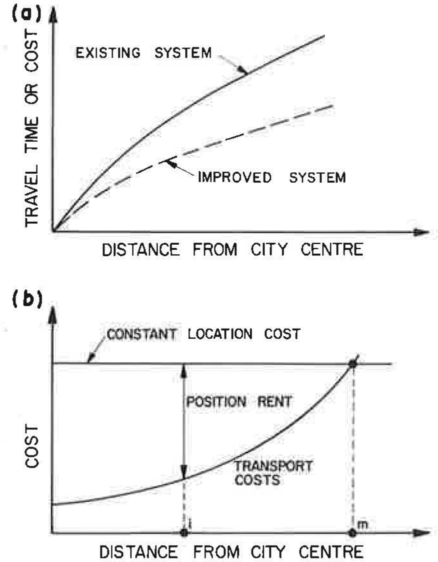

Figure 6. Curves showing (a) the transportation function and (b) the spatial structure of position rents.

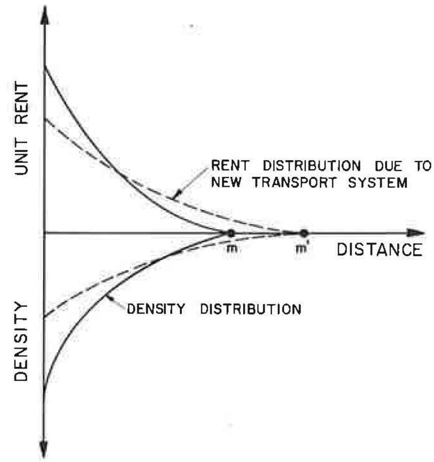

Figure 7. Unit rent and density profiles with distance.

rents, as shown in Figure 6b. The notion embodied in Figure 6b is that the householder located at i enjoys a premium in transportation costs with respect to a household located at the margin. This locational premium invites competition from all households located at a greater distance than i, because a household at the margin can offer a position rent for i equal to the difference in transportation costs, R_i. In this way, a locational equilibrium is established where each household's locational costs are constant. Wingo has then demonstrated how density and unit rent profiles of the type shown in Figure 7 may be derived from certain assumptions about space consumption and the position rent relation of Figure 6b. Changes in the density and unit rent profiles resulting from changes in the transportation function are shown by the broken lines in Figure 7 and 6a respectively.

Little empirical evidence is available to allow the rent surfaces to be defined. However, this theoretical approach or the present attempts at modeling the housing market (29, 30) should provide a means for deriving a community demand function for accessibility.

With the present state of knowledge regarding the measurement and evaluation of environmental quality, it would appear that a community demand curve will have to be derived by a regression analysis of property values. However, it has already been noted that the urban property market is influenced by a large number of factors other than accessibility and environmental quality.

A DECISION CRITERION FOR HORIZON-YEAR SYSTEMS

A decision criterion is required that will allow the most efficient system to be identified. The criterion presented in this section has been developed by Marglin (12, 31) for water resource systems. The decision criterion proposed by Marglin represents a modification of the Pareto optimality condition and is defined in the following paragraphs.

A proposed horizon-year urban transportation system A1 is economically more efficient than a system A2 if those affected by A1 are willing to pay those affected by A2 a sum sufficient to persuade them to agree to the construction of A1. Willingness to pay for a system may be subdivided into those who are made better off and those who are made worse off by a system A as expressed by the following equation:

$$W(A) = E(A) - C(A) \qquad (4)$$

where
W(A) = aggregate willingness to pay for system A,
E(A) = willingness to pay of those who benefit from system A rather than have no system at all, and
C(A) = willingness to pay of those who disbenefit from system A not to have the system at all.

Marglin (12) has pointed out that the decision criterion of Eq. 4 will provide a transitive ordering of systems only if the amount that the beneficiaries of one system are willing to accept as compensation to do without their project is equal to the amount that they are willing to offer as compensation to the beneficiaries of other systems to persuade them to do without their projects.

A production function may be defined as

$$f(x_1, x_2, \ldots, x_i, \ldots, x_m, y_1, y_2, \ldots, y_j, \ldots, y_n) = 0 \tag{5}$$

where

x_i = the quantities of factors used in production, i = 1, ..., m; and
y_j = the quantities of goods produced, j = 1, ..., n.

Equation 4 may be rewritten to incorporate the production function terminology of Eq. 5 as follows:

$$W(\vec{x}, \vec{y}) = E(\vec{y}) - C(\vec{x}) \tag{6}$$

where

$\vec{x}$ = the vector of input variables, and

$\vec{y}$ = the vector of output variables.

The decision criterion becomes the selection of the system with the maximum value of $W(\vec{x}, \vec{y})$ subject to the constraint that it is a member of the production function. If Eqs. 5 and 6 are differentiable, then the following Lagrangian function may be defined:

$$L(\vec{x}, \vec{y}) = W(\vec{x}, \vec{y}) + \lambda f(\vec{x}, \vec{y}) \tag{7}$$

where λ = the undetermined Lagrangian multiplier.

The maximum conditions for Eq. 7 are given by

$$\frac{\partial w}{\partial x_i} = -\lambda \cdot \partial f/\partial x_i \text{ for } i = 1, \ldots, m \tag{8a}$$

and

$$\frac{\partial w}{\partial y_j} = -\lambda \cdot \partial f/\partial y_j \text{ for } j = 1, \ldots, n \tag{8b}$$

If Eq. 8a is divided by Eq. 8b, the following expressions may be obtained:

$$\frac{\partial w}{\partial x_i} \Big/ \frac{\partial w}{\partial y_j} = \frac{\partial f}{\partial x_i} \Big/ \frac{\partial f}{\partial y_j} \tag{9a}$$

$$\frac{\partial w}{\partial x_i} \Big/ \frac{\partial w}{\partial x_h} = \frac{\partial f}{\partial x_i} \Big/ \frac{\partial f}{\partial x_h} \tag{9b}$$

$$\frac{\partial w}{\partial y_j} \Big/ \frac{\partial w}{\partial y_k} = \frac{\partial f}{\partial y_j} \Big/ \frac{\partial f}{\partial y_k} \tag{9c}$$

The production function constraint is $f(\vec{x}, \vec{y}) = 0$ and this yields

$$\frac{\partial f}{\partial x_i} \bigg/ \frac{\partial f}{\partial y_j} = -\partial y_j/\partial x_i \tag{10a}$$

$$\frac{\partial f}{\partial x_i} \bigg/ \frac{\partial f}{\partial x_h} = -\partial x_h/\partial x_i \tag{10b}$$

$$\frac{\partial f}{\partial y_j} \bigg/ \frac{\partial f}{\partial y_k} = -\partial y_k/\partial y_i \tag{10c}$$

Equation sets 9 and 10 yield the necessary conditions for an input/output vector that maximizes Eq. 8; these conditions are

$$\frac{\partial w}{\partial x_i} \bigg/ \frac{\partial w}{\partial y_j} = -\partial y_j/\partial x_i \tag{11a}$$

$$\frac{\partial w}{\partial x_i} \bigg/ \frac{\partial w}{\partial x_h} = -\partial x_h/\partial x_i \tag{11b}$$

$$\frac{\partial w}{\partial y_j} \bigg/ \frac{\partial w}{\partial y_k} = -\partial y_k/\partial y_j \tag{11c}$$

The three conditions described may be interpreted in several ways. Equation 11a identifies the condition that the ratio of the marginal cost of the ith input to the marginal benefit of the jth output must be equal to the marginal productivity of the ith input when devoted to the jth output. Equation 11b states that the ratio of the marginal cost of the ith input to the marginal cost of the hth input should be equal to the marginal rate of substitution of the hth input for the ith input. The condition identified in Eq. 11c states that the ratio of the marginal benefit of the jth output to the marginal benefit of the kth output should be equal to the marginal rate of transformation of output k for output j. Equation 11a also implies that the marginal benefits equal marginal costs.

If the community demand curve is represented as a function $y_j(p)$ of the price p, willingness to pay is given by

$$E(y_j) = \int_o^{y_j} D(\eta)d\eta \tag{12}$$

where

η = a dummy variable of integration, and
$D(\eta)$ = the inverse of the function $y_j(p)$.

The benefit of each output y_j is the willingness to pay for that output, and the aggregate benefits are given by the sum of the benefits of each output:

$$E(y) = \sum_{j=1}^{n} \int_o^{y_j} D(\eta)d\eta \tag{13}$$

providing that the willingness to pay for each output is independent of the quantities of other outputs provided by the system.

When construction expenditures and benefits are spread over many time periods, the following decision criterion may be defined:

$$W(A) = \sum_{q=1}^{Q} v_q \left[E_q(y_{jq}) - M_q(x_{iq}) - k_q(x_{iq})\right] \tag{14}$$

where v_q = the present value factor applicable to the demand period q, which is given by

$$v_q = \left[1 - (1+i)^{-T/Q}\right] \Big/ \left[i(1+i)^{(q-1)T/Q}\right] \tag{15}$$

and where

q = 1, 2, ..., Q, and is the particular time period,
i = discount rate,
T = the economic life of the system in years,
$E_q(y_{jq})$ = the annual benefits in period q as a function of the outputs in period q,
$M_q(x_{iq})$ = the continuing (maintenance, etc.) costs during period q, and
$K_q(x_{iq})$ = the capital cost during period q.

The marginal conditions for the maximization of Eq. 14 have been identified in Eq. 11a, which yields from Eq. 14 the following:

$$\sum_{q=1}^{Q} v_q D_{jq}(y_{jq}) \partial y_{jq}/\partial x_i = \sum_{q=1}^{Q} v_q (\partial M_q/\partial x_i + \partial K_q/\partial x_i) \tag{16}$$

Equation 16 states that the marginal willingness to pay for output in period q rather than go without $[D_{jq}(y_{jq})]$ times the marginal productivity in period q of the i th input when devoted to the j th output $(\partial y_{jq}/\partial x_i)$ is equal to the sum of the present value of continuing and capital marginal costs.

Equation 16 may be written in the simple notation of the following equation:

$$\sum_{q=1}^{Q} v_q MVP_q(x_i) = \sum_{q=1}^{Q} v_q\left[MM_q(x_i) + MK_q(x_i)\right] \tag{17}$$

where

$MVP_q(x_i)$ = the marginal value (revenue) product (i.e., marginal annual benefit) in period q from an extra unit of input x_i,
= the partial derivative $D_{jq}(y_{jq})\partial y_{jq}/\partial x_i$,
$MM_q(x_i)$ = the marginal annual continuing costs, and
$MK_q(x_i)$ = the marginal capital cost.

If the time horizon notation is suppressed and Eq. 16 is divided by $\partial y_j/\partial x_i$, the following expression is obtained:

$$D_j(y_j) = \frac{\partial M}{\partial x_i} \cdot \frac{\partial x_i}{\partial t_j} + \frac{\partial K}{\partial x_i} \cdot \frac{\partial x_i}{\partial y_j} \tag{18}$$

which may be restated as

$$ME(y_j) = MM(y_j) + MK(y_j) \tag{19}$$

This equation states that the marginal willingness to pay for the output y_j is the rate at which the recipient of outputs is willing to substitute money for the output, which is equal to the sum of the marginal continuing and maintenance costs representing the rate at which money can be transformed into output by the construction and operation of the system.

If it is assumed that the community demand schedules for accessibility and environmental quality have been defined, and if it is further assumed that the financial inputs to the transportation system are the continuing and capital expenditures throughout the

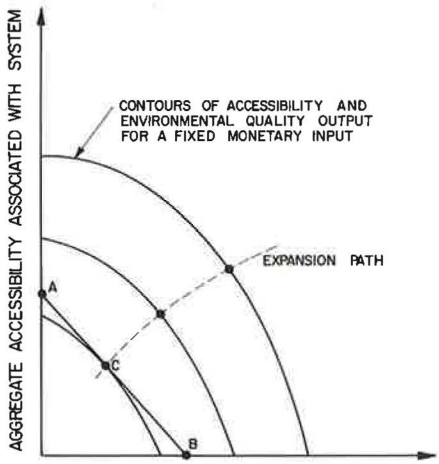

Figure 8. Input-output relations and the expansion path.

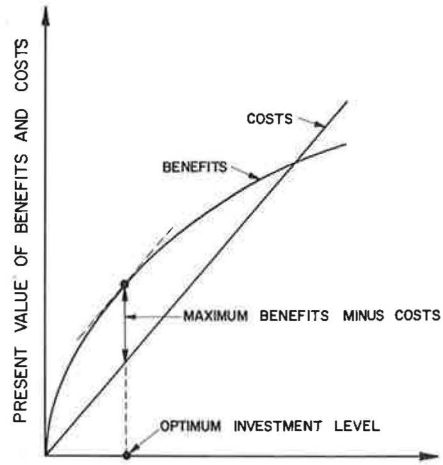

Figure 9. Determination of the optimum investment level.

period T, then the pertinent economic characteristics of alternative systems may be expressed as shown in Figure 8. This diagram shows the combinations of accessibility and environmental quality that can be achieved for a fixed monetary input. That is, each transformation function represents a contour of output for a fixed monetary input. A price line AB can also be shown in Figure 8, at least conceptually, that represents the combinations of accessibility and environmental quality that are of constant value.

The equilibrium or efficiency condition is given by the point of tangency between the price line and the transformation function contour. That is, point C shows the best combination of outputs that can be achieved for a fixed input. In fact, the locus of the points of tangency may be established for increasing monetary inputs as shown in Figure 8. Figure 9 may be constructed from Figure 8 to show the net present value of benefits for each input level. The optimum investment level may be determined from Figure 9 at the point at which the benefit and cost curves are parallel. This is the condition specified in Eq. 11a. An alternate approach to this same problem is shown in Figure 10, in which the community indifference curve is used to establish the equilibrium condition at C.

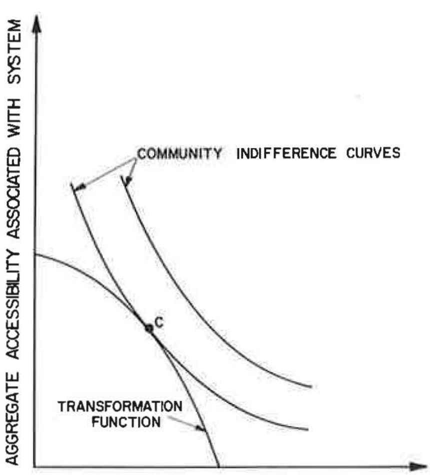

Figure 10. Identification of equilibrium condition using the community indifference curve.

In practice it may be difficult to establish the price line of Figure 8 or the community indifference curve of Figure 10. This problem may be resolved by using one of the following criteria:

1. Maximize the aggregate accessibility of the system subject to a constraint on the aggregate level of environmental quality, or
2. Maximize the aggregate environmental quality of the system subject to a constraint on the aggregate level of accessibility.

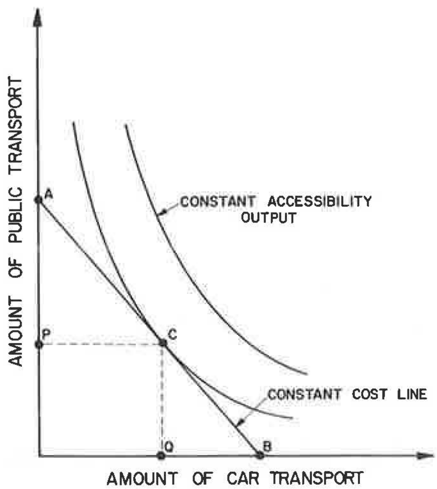

Figure 11. Accessibility isoquants for various input combinations and input combinations yielding a constant cost.

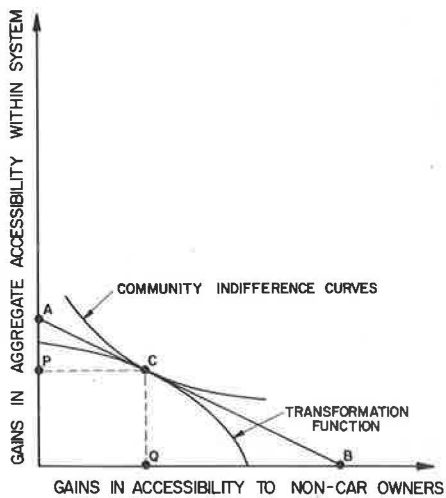

Figure 12. The analysis of distributional efficiency.

An alternative view of the problem may be developed if it is assumed that the inputs to the system are limited to public transport facilities and private-car-oriented facilities. A relationship of the type shown in Figure 11 may be developed that shows isoquants of accessibility output for various combinations of public transport and road facilities. A similar diagram for isoquants of environmental quality output could be prepared as well. If the costs of the public transport and road facilities are specified, then the constant cost line AB may be established and used to identify the optimum mix of facilities at C, which is similar to the approach suggested by Rahmann and Davidson (4).

Modification of the Allocational Efficiency Criterion

The decision criteria examined have been concerned with identifying the conditions that would yield economically efficient transportation investments. The allocational efficiency criterion must be modified to reflect the second goal of urban transportation investment, which is concerned with distributional efficiency.

It is useful to recall that a fundamental assumption of welfare theory is that the marginal utility of income is constant and equal for all members of the community. It was pointed out earlier that distributional efficiency must be appraised relative to a disaggregated view of an urban region which recognizes the irrational nature of the given assumption. For the purposes of this paper, it is assumed that urban households may be classified into car-owning (CO) and non-car-owning (NCO) households. It is further assumed that NCO households tend to be segregated geographically and that these households lack adequate urban travel opportunities. The distributional efficiency of alternative urban transportation investment proposals may be examined in terms of Figure 12.

In Figure 12 the gains in aggregate accessibility of an urban region are plotted along the ordinate and the gains in NCO zones accessibility are plotted along the abscissa. Community indifference curves may be plotted in Figure 12 showing the relative weights that the community places on these two objectives. The indifference curves shown in Figure 12 suggest that a premium is placed on the gains in accessibility to NCO zones relative to aggregate accessibility. A transformation function may also be plotted in Figure 12 illustrating the boundary of feasible transportation investments with respect to their relative contributions to aggregate accessibility and to the accessibility of NCO zones. The equilibrium condition is given by point C, which is the point of tangency between the transformation function and an indifference curve. At point C the slope of both curves is equal to the slope of AB, which implies that the marginal rate of transformation between aggregate and NCO accessibility and the marginal premium on NCO accessibility relative to aggregate accessibility are equal. The program of investment represented by point C will contribute OP to aggregate accessibility in the region and OQ to the accessibility of NCO zones. A similar approach could be identified for the treatment of environmental quality.

A decision criterion may also be subjected to constraints on the minimum levels of accessibility and environmental quality that should exist within individual zones. The decision criterion then becomes the maximization of the weighted contributions to aggregate consumption subject to constraints on zonal accessibility and environmental quality.

SUMMARY AND CONCLUSIONS

Existing approaches to the economic evaluation of urban transportation investment proposals assume that the principal output of a transportation system that gives rise to benefits is the volume of vehicles passing along links of a network. This paper outlines an evaluation framework in terms of two broader outputs: accessibility and environmental quality.

The paper suggests that urban transportation planners must be concerned with both the economic efficiency and the distributional efficiency of investment alternatives. The goal of economic efficiency is developed in terms of the following objectives: (a) the maximization of aggregate accessibility, and (b) the maximization of aggregate environmental quality.

Several measures of accessibility are reviewed, but insufficient evidence is available to support the choice of one of these measures. The few studies of environmental quality that have been performed to date suggest that link traffic volumes are the best system outputs to relate to the environmental quality objective.

The paper suggests that the derivation of a community demand schedule for accessibility will have to be derived from models of the urban land market that have been calibrated for a given region. Community demand schedules for environmental quality will have to be derived from regression analyses of urban property prices.

A decision criterion for allocational efficiency is presented that is derived from welfare theory principles. The paper demonstrates how this efficiency criterion may be modified to reflect distributional efficiency.

The framework outlined provides a conceptual basis for the economic evaluation of urban transportation investment proposals. Empirical evidence must now be assembled to make this framework operational.

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