A PLANNING MODEL FOR TRANSPORTATION IN URBAN ACTIVITY CENTERS

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This paper is concerned with the formulation and implementation of a planning model describing transportation in dense specialized urban activity centers, such as the central business districts of major cities. The several models developed include an activity accessibility model (AAM) to simulate the demand for trips generated in the area; an economic impact model to describe the impact of accessibility, derived from the AAM and combined with some other variables, on the area's economy; an environmental effects model to deal with air pollution and noise generated by moving and fixed sources; and a network systems costing model to derive the costs of new modes to be implanted in the AAM. This paper deals only with the AAM, a nonlinear statistical model of the generalized gravity type. The AAM is a planning model insofar as it allows testing of new policies, land uses, and technological possibilities in a quasi-equilibrium context. It is also a planning model in that the ability to predict detailed traffic patterns has been sacrificed—probably only to a slight degree—to a formulation that is explanatory and fundamental in its approach to trip-making. It should, therefore, have wide applicability. At the same time, the number of variables is held to a modest number so as to make calibration practical if not easy. Formulation, calibration, and preliminary validation in real-life situations are discussed.

•ALTHOUGH there are at least two schools of thought on whether land use shapes transportation or vice versa, there is general agreement on the importance of transportation in land-use development and economics, especially in the context of commuting between residence and work (1, 2, 3, 4, 5, 6, 7, 8).

The importance of the economically oriented, local, office-based trip, whether for business, lunch, or personal service, is less well realized outside of the business sector. Yet various urban activity centers display glaring differences from this point of view. This is indicated by contrasting the highly specialized lower Manhattan CBD with the more diffuse, all-purpose one in Milwaukee. Both have an area of less than a square mile. More than 500,000 people are employed in lower Manhattan; in Milwaukee the number is about 150,000. Both cities offer a choice of several transportation modes: five in New York—where walking is the dominant mode, and taxicabs and private vehicles are rendered almost useless because of congestion; and four in Milwaukee—where private vehicles and buses are the primary mode. There is considerable retail activity in both areas, but in New York it is largely oriented toward lunch-hour shopping and is limited in variety; Milwaukee stores cater mostly to the surrounding area and are languishing somewhat. In New York, economic activities are clustered in even more compact and specialized synergistic subregions (shipping, brokerage, financial, law, and insurance), whereas in Milwaukee a somewhat broader spectrum of sectors is geographically scattered and lacks such tight organization.

Such comparisons must not be carried too far. Certainly many of the differences can be traced to the size and specialization of the surrounding area and to past land-use

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traditions and development history. Nevertheless, it is tempting to conclude that the spatial organization of CBDs has much to do with their functional success and that ease of local trip-making may play a catalytic role therein.

The purpose of contract HUD-1067 has been to focus on the role of transportation in the economic viability of an area and to help predict whether transportation improvements, either through policy changes or investments, can improve the area's viability and evironmental quality. The program has been in existence for 1½ years. The first year was devoted to the formulation, design, and programming of a number of computer simulation models. In the present phase, these models are being applied to some real-life problems to test their usefulness and relevance. In the third phase, some model improvements and extensions will be undertaken based on the experience acquired during the present phase.

A model that simulates in adequate detail the trip-making pattern of an urban activity center is basic to the whole program. A number of transportation models were, of course, already in existence and had to be considered for adaptation. In the end, none of these were adopted outright but several were borrowed from. The discussion that follows is meant to be merely indicative of the considerations that were applied. It is not intended to be a comprehensive or critical review (1, 9, 10).

The basic Bureau of Public Roads model package (11, 12, 13) was specifically designed for predicting modal-split shifts when improvements are made in transportation or when modest population changes take place. Although the basic gravity approach was appealing, it was decided not to adopt this model directly because of the following:

1. The basic gravity approach is really not suited for a fine-grained description of an area because it produces a configuration of many small zones, each of which requires a rather large-sample and almost prohibitively expensive origin-destination survey;
2. It has forfeited considerable "explanatory" power in order to afford close calibration to an existing local situation and must therefore be used very cautiously for forecasts involving new technologies or policy changes; and
3. Its mode choice criterion, consisting of a modal split between automobile and public transit introduced following trip distribution, is too simple for our needs, and it does not consider essential behavioral factors.

Econometric models of the type proposed, for example, by Kain (14) were rejected for operational reasons. They generally contain a large number of variables in a framework of an even larger number of simultaneous equations and require a major calibration effort. Most models of any type do not spring full-blown but require numerous adjustments and changes until they are properly "tuned." This tuning is especially difficult for the econometric type of model because everything in it is coupled together. We preferred models consisting of several subcomponents that can be tested and adjusted separately.

The intervening or alternate opportunities concept (15, 16, 17) has some of the non-linear features that play an important role in trip-making decisions. On the other hand, ready-made models based on this concept are either too large in scale (18) or share many of the shortcomings of models in the BPR package but without their history of practical application.

Quandt and Baumol's Abstract Mode Model (19, 20, 21) seemed to have some of the behavioral features we were looking for in a planning model—especially regarding treatment of modal choice—and some of their concepts were borrowed and considerably extended. In any case, this model as originally formulated could not be directly adapted to a situation with hundreds of origin-destination pairs because of the enormous quantity of data required for calibration but not readily available.

A model has been devised at Harvard for application to goods movement on a regional or larger scale (22). Although based on economic activities for generation and distribution of trips, it is too coarse-grained for our purposes and does not contain the behavioral cost component necessary to explain multipurpose trip-making.

Finally, several efforts were and have been in progress (23) to formulate micro-transportation models, but these were not far enough along to be useful to us at the inception of our program.

The task of formulating a new set of models was therefore undertaken. This was done with some trepidation because the literature abounds in models that were published but never used—usually, for lack of data with which to calibrate them. Whether the effort has been worthwhile cannot yet be determined with finality; the reader may supply an interim judgment for himself.

OVERVIEW

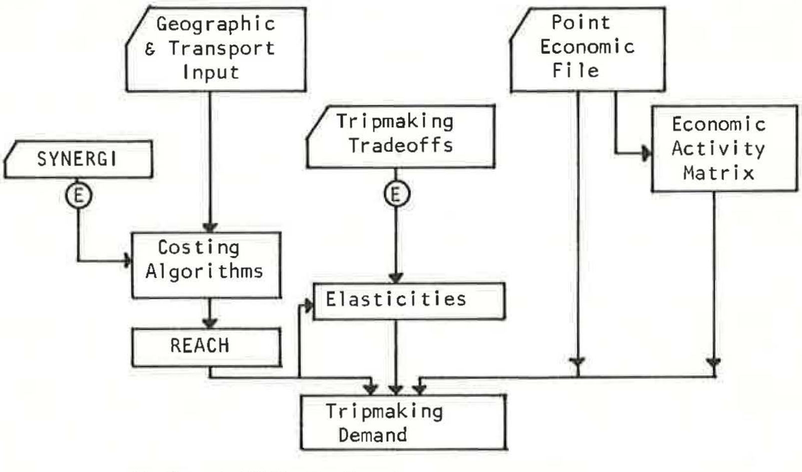
The purpose of the transportation model developed in this research program and called the activity accessibility model (AAM) is to forecast changes in trip demand or in traffic patterns due to demographic, economic, behavioral, policy-making, or technological changes, or the implantation of a new transportation system.

In formulating the model, we had to steer a course between two hazards. A model can attempt to be highly analytical; it can describe the interaction of various components in such a general way that the model can be applied to very diverse situations but at the expense of sufficient detail to represent adequately a specific situation. Or the model can, at the opposite extreme, be so phenomenological and well-calibrated for describing the status quo in a given area that it loses most of its extrapolative value. We have attempted to strike a balance between these two extremes.

The AAM uses highly detailed information about a given urban activity center (UAC) and, because of the interaction of various economic sectors within the UAC, combines this with some general but rather disaggregated information about trip-making. Forecasting in our model is accomplished by means of a generalized trip demand function, which should react sensitively to changes in the input.

The assumption is made that, within the UAC as a whole and on the average, economic activities and trip-making (other than commuting) associated with them are in a state of quasi-equilibrium at any given time. Forecasting with the model assumes that the change being examined is either localized and therefore not far-reaching enough to destroy overall equilibrium or, if not localized, is not sufficiently drastic to cause the economic description of the UAC to become invalid. Such assumptions also underlie, as far as we know, most traffic-forecasting models. Multiple iterations to determine incremental changes to the original equilibrium can, of course, be performed as long as the process converges.

Figure 1 is a schematic diagram of the AAM. The model has certain distinguishing features—some conventional, others novel—that are presented for overview.



E = Numerical Estimation Procedure

Figure 1. Schematic diagram of the activity accessibility model.

1. The distribution function has the form of a modified gravity model:

$$d_{ij} = G\ M_i\ M_j/R_{ij}$$

where

d_{ij} = number of trips generated at node i (a street intersection) that is to be allocated to trip-end node j (another street intersection);
G = a constant incorporating a weighted measure of the intensity of interaction between economic activities at the origin and destination;
M_i, M_j = measures of activity intensity at nodes i and j respectively; and
R_{ij} = an impedance or friction factor dependent on the generalized cost of trip-making between i and j.

2. The cost for a trip is treated as a multicomponent vector (rather than scalar) quantity; typically, three distinct components are included: money, time, and stress.
3. Perceptions of stress and the behavior-related cost component coefficients are quantified with the help of a stratified panel rating procedure—Systematic Numerical Evaluation and Rating by group iteration (SYNERGI).
4. Origin-destination surveys, which are ordinarily used to fix G, are replaced by an economic activity matrix (EAM) that describes trip-making intensity and propensity among economic sectors.
5. Demographic data, which are normally used to describe M_i and M_j, are replaced by employment for various sectors present at nodes i and j.
6. Each urban activity center is described in considerably more detail in the AAM than in most models, and economic, geographic, and transportation information is assembled on a block-by-block basis.
7. Trips are described in fine detail—by purpose, trip-making conditions (weather and congestion), and economic sector-to-sector interaction.
8. All modes, walking included, are described in detail; the possibilities of switching from one mode to another are also realistically represented. A route-selection algorithm (REACH) retains those "feasible" routes that are competitive with others in cost, time, and/or stress.
9. The expression d_{ij} acts as a true demand function that generates trips at the origin, allocates trip-ends to different destinations, and distributes trip-making demand among competing modal routes by means of behaviorally determined factors. It also determines how many total trips are made.
10. An accessibility index describes the relative ease with which an economic sector at a given point can interact with other sectors in the surrounding area necessary to its functions. Mathematically, this index is a ratio of the trip-making propensity of a specific activity located at a specific point to the average trip-making propensity for that particular activity in the area as a whole.

The central expression of the AAM is the trip-making demand between two points, i (origin) and j (destination). Because our model is of the generalized gravity type, the demand is determined by factors giving how many trips are generated at i and how many of their trip ends are ideally located to j. (We here adopt the terminology of the transportation engineer. We could, with equal validity, reverse the process by considering destinations as trip generators.) The ideal demand is then divided by a trip-making impedance R_{ij} (which must be greater than, or equal to, unity). Details are given in the Model Components section in this paper.

The trip-making impedance is determined through a set of costing algorithms and through the REACH network selection program. The costing algorithms fix the user cost on all links, defined as the mode-specific paths among communicating nodes. These include sidewalks for the walk mode, streets for the automobile, taxi, and bus modes; tunnels for the subway mode; and so on. User costs include money, time, and stress. Stress is determined by a stratified panel rating procedure. User costs may depend on trip-making conditions such as weather and congestion. Once the cost components are determined for each link, a trip between any points i and j can be described for any path by a succession of links. Costs are summed as the trip proceeds. The REACH program selects, out of all possible paths between i and j, those paths that have an advantage over others from the viewpoint of at least one of the cost components. The trip impedance is a function of these cost components. The trade-off coefficients between the components are functions of trip purpose and trip conditions and are behaviorally determined.

Trip generation and distribution are determined partly from a land-use file and partly from an EAM developed by ad hoc economic analysis of the UAC as a whole. The EAM determines the average number of trips generated between economic sectors. Information from the EAM, when suitably combined with employment at i and j obtained from the land-use file, results in a consistent generation of trips and assignment of trip ends.

DATA INPUTS

In this section, we shall deal with inputs in somewhat more detail. The inputs required are of the cross-sectional type. It is more important that they all pertain to the same point in time than that they be current. (Inputs are given in Table 1.)

Geographic File

A geographic data file is assembled, in which each street intersection is given a code name, and the streets linking two intersections are identified by name, length of the segment, width between curbs and buildings, and range of street numbers on each side of the street. These data are obtained from Sanborn maps.

Transportation File

A master transportation file is prepared and stored, in which all existing or planned transportation modes (including walking) are described. Each transportation mode is

TABLE 1

INPUTS FOR THE AAM

Input Data	Sources
Geographic links: streets and street addresses, street and sidewalk widths, directionality of flow	Sanborn maps
Routed systems and transfers: locations of bus routes and stops and transfer points	Bus route maps, subway maps, and direct field survey
Parking, signals, and turns: intersections where there are traffic lights, nearby parking, or where left turns for vehicles are restricted	Direct field survey and Sanborn maps
Transportation system characteristics: schedule, speed, capacity, fare, and operational details	Information from transportation agencies and ad hoc studies
Land-use file: economic activity (employment by 4-digit SIC code) assigned to addresses and then aggregated to nodes	Duns Market Indicator (DMI) tapes, special census tabulations (for retail trade), and direct field surveys
Economic activity matrix: trips between economic sectors, by purpose, time of day, and other conditions	Employment derived from land-use file, trip-making coefficients from ad hoc studies and direct field surveys of sample buildings, and other transportation surveys
Trip-making stress by link: derived for different trip purposes, times of day, and other conditions	SYNERGI rating panel
Elasticities of demand for cost, time, and stress: derived for different trip purposes and other conditions	Questionnaire on trip habits

specified link by link, where a link is a segment connecting two nodes, and a node is understood to be a point at which the possibility exists for choosing between alternative routes or switching from one mode to another. The geographic location of transit nodes can be slightly distorted to coincide with the coded nodes describing street intersections.

The master transportation file is thus a collection of links, and each link is mode-specific and described by the code numbers of the nodes that it joins. In addition each link has specific descriptors, such as length, schedule, speed, fare structure, and other user costs that are detailed later.

In addition to mode-specific links, the transportation file contains a list of "dummy" or switching links. Dummy links have the same coded node number at each end, but they identify a change from one mode to another. For example, a change from private car to walking involves a dummy link for the act of parking the car. Dummy links have their own costs in money, time, and stress. Waiting time and payment of fares are attributed to dummy links, for instance, where there is a delay due to schedule and where one fare is paid on boarding regardless of length of the trip. A trip is then described as a succession of links, with dummy links inserted wherever the traveler makes a change in mode.

Land-Use File

In addition, information is obtained about economic activity at each address. This information is partly available from Duns Market Indicator (DMI) tapes, which list businesses according to four-digit SIC identity at a given address and are based on special census tabulations and other sources. Because the readily available tabulations were found to be insufficient for our purposes, additional research was required to bring this task to a satisfactory state of completion.

By means of an add-matching routine, the economic activity information stored by address can be aggregated from the surrounding area onto the nearest street intersection. Each intersection or node is then characterized by a spectrum of SIC code numbers and by their associated economic activity. Code numbers can then be grouped to form specified economic sectors.

Economic Activity Matrix

Trip-making between different economic sectors is quantified in the EAM. A given element in this matrix gives the daily trips for the entire UAC between the origin sector specified on the ordinate of the matrix and the destination sector specified on the abscissa, corresponding to a certain trip type or purpose (24). Because six trip types k are distinguished, there may be six different matrices. For example, each matrix for the lower Manhattan UAC has 18 sectors, 4 outside the study area (but within commuting distance) and 14 within the area itself. Thus, each matrix has 18 × 18 = 323 elements, some of which generally are negligibly small or zero. The matrix tends to be symmetrical about the diagonal, although this is not rigorously true in principle. The 14 UAC sectors in lower Manhattan are as follows:

Activity	Sector
Business and professional services	5
Goods and supplies (wholesale)	6
General office	7
Government	8
Warehousing and on-site manufacturing	9
Restaurants, bars, eating places	10
Retail	11
Parks and plazas	12
Miscellaneous (schools and museums)	13
Brokers	14
Exchanges	15
Miscellaneous financial	16
Insurance	17
Banks	18

TABLE 2

TRIP TYPES AND CONDITIONS

Trip Type k	Description	Good Weather		Bad Weather	
		{C}	$[v^k(C)]^{-1}$	{C}	$[v^k(C)]^{-1}$
1	Trip to work	{01100}	1.000	{11100}	$1.0[1 + \epsilon_1]$
2	Office-based business trip (non-lunch)	{00100}	0.900	{10100}	$0.9[1 + \epsilon_2]$
		{00001}	0.100	{10001}	
3	Office-based business trip (lunch)	{01100}	1.000	{11100}	$1.0[1 + \epsilon_3]$
4	Office-based personal service trip (lunch and non-lunch)	{00000}	0.150	{10000}	$0.15[1 + \epsilon_4]$
		{01100}	0.834	{11100}	$0.834[1 + \epsilon_4]$
		{00001}	0.016	{10001}	$0.016[1 + \epsilon_4]$
5	Home-based personal service trip	{00000}	0.800	{10000}	$0.80[1 + \epsilon_5]$
		{00001}	0.200	{10001}	$0.20[1 + \epsilon_5]$
6	Goods delivery trip	—	N. A.	—	N. A.

There would be different sector choices for a different UAC. The six trip types k = 1 to 6 are given in Table 2.

Cost Vector

The most important information associated with each link is the user cost. User costs will be regarded as a vector having several components, typically three: money, time, and stress.

Although we are aware that nonquantitative costs such as stress are difficult or impossible to evaluate explicitly in terms of dollars, our approach assumes that it is possible to assign to them a cardinal number that specifies the quality in question unambiguously, in the sense that greater stress is always described by a bigger number than is smaller stress. The trade-off among stress, time, and fare is obtained by determining how people make modal choices for various trip types under different weather conditions. Because individuals differ in their personal utility functions, and even the same individual may rate stress differently relative to time or dollar cost depending on circumstances, there are no simple "once-for-all" relationships among the three variables.

Out-of-pocket costs and time for various link types are primarily obtained from information (fares and average speed) that is readily available. Some variable parameters can be included to render qualitatively the effects of congestion and other trip-making conditions.

Stress, like the weather (and partly due to it), is a cost item whose importance in trip-making has been realized for a long time but about which relatively little has been done (25, 26).

In our case, the quantification of stress is accomplished as follows: trip-making in an abstract (i.e., mode-independent) generalized sense has been analyzed in terms of sequential actions and situations. These actions and situations are then numerically rated by a carefully chosen stratified panel with regard to the importance of reducing the stress associated with them. The survey format is called SYNERGI (27).

The results of the survey are suitably processed to yield a stress "cost" for each link with its associated travel mode under a variety of selected environmental travel conditions. Up to now the travel conditions are specified in "black-and-white," yes-no binary variables and are listed as follows:

Condition	Component
Is the weather bad?	C_1
Are traffic conditions congested?	C_2
Is the traveler's personal schedule rigid?	C_3
Is it nighttime?	C_4
Does the traveler have baggage?	C_5

(The components take the value of 1 when the answer to the question is "yes" and 0 when it is "no.") In real life, intermediate situations (e.g., ordinary weather or moderate congestion) occur that fall between the sharply defined extremes noted. The model treats these—for the moment—by using (ad hoc) interpolation, under the assumption that trip-making demand is a monotonic function of each variable. Thus, the demand for trips via a given mode on a day of moderate congestion would presumably fall between the demands corresponding to high and low congestion.

To conclude this brief discussion of stress, we admit that our treatment of this variable is, at present, still quite primitive. Our underlying assumptions are as follows:

1. All user-perceived qualitative variables can be subsumed under the heading of stress and dealt with as a single variable that is definable for a given link and additive from link to link;
2. Stress is intrinsically quantifiable in terms of cardinal measures that obey the usual rules (transitivity, reflexivity, or commutativity); and
3. Transportation users are able to provide adequate estimates of these measures if given an appropriately structured situation.

We are, of course, aware that stress components are of different natures, are not necessarily additive or even commensurate, and may exhibit such nonlinear phenomena as thresholds and saturation. Our justification for disregarding these drawbacks is that the addition of even this primitively quantified variable succeeds in making the model significantly more realistic—and capable of describing actual trip-making behavior—than other models.

Elasticities

Elasticity coefficients α_p^{kc} giving the importance of the three user-cost components ($p = 1, 2, 3$) relative to each other must be specified as an input. It is expected that the coefficients differ for different trip types and conditions (and probably other variables, such as city size, region, and climate), so that at least six sets of three may have to be determined in a given locale.

The elasticity coefficients are determined from responses of population strata as to how they would choose to make a specified trip between fixed end points under different trip-making conditions $\{C\} = \{C_1 \ldots, C_5\}$. Because different trip purposes $k = 1, \ldots, 6$ are undertaken under different conditions $\{C\}$ and by different population strata, it is possible to derive modal choices for different trip purposes.

With the help of an exponential impedance function defined in the following section, it is then possible to estimate the α_p^{kc} ($p = 1, 2, 3$) for several k and C by using a linear estimation program.

MODEL COMPONENTS

REACH Algorithm

The urban activity center (UAC) has been described in terms of a large number of nodes, typically several hundred of them, superimposed on which is a grid of links for reaching each node. There is thus a multiplicity of ways for reaching each node from any starting point. Not only can one take an indirect rather than a more direct route from i to j, one can also switch from one mode to another in a number of different ways. Moreover, innumerable routes can be devised that no one would ordinarily take, such as roundabout routes that loop back on themselves one or more times. In order to determine traffic patterns and modal choices, a criterion will be needed to determine the one (or several competing) most practical route(s) between origin and destination.

Such a criterion is given by a route selection algorithm (REACH) that eliminates all paths except those that have at least one competitive cost component and labels the surviving "feasible" paths. Distribution among these is then determined by means of the demand function, the description of which follows.

The algorithm actually computes, in one operation, the cumulative cost of traveling from a given origin to all possible destinations in the UAC. As it reaches out for these destinations, it compares user costs for various routes to a node and eliminates all those paths for which cost components are individually greater than the components of a competing path. In other words, the algorithm eliminates, as it goes along, any path whose user appeal is "dominated" by that of other paths and retains only the dominant ones. It proceeds until it has reached and labeled all destinations. In this manner, the algorithm determines all feasible routes from an origin to all destinations in the UAC. The elimination of dominated routes is behaviorally justified if the three cost components are independent of each other and form a complete set of decision-making variables for choice of routes.

In most instances, one wishes to determine the demand for a given destination from origins in the UAC. From economic analysis one can learn something about the effective budget for the type of trip involved. We assume that there is no trip-making from regions of the UAC for which the trip costs exceed the specified budget. Thus a budget vector can be introduced as a constraint in the algorithm; in which case the algorithm computes all paths throughout a "possible region" around the given destination, which is generally considerably smaller than the UAC. In this way the computing time is much reduced, whereas the neglect of trips from areas excluded by the budget should have no appreciable effect.

By applying the REACH procedure to a given node for all types of trips beginning and ending there, coupled with information on distribution of trips in time, one can develop the flow of traffic to and from this particular node. By superposing such flows from a sufficient number of adjacent nodes (following an explicit sampling procedure), one can synthesize a traffic pattern for an area. The size of the possible region centered on a specified node is an important indicator of the adequacy of the transportation system around the node for this particular trip type.

Impedance

Gravity models are characterized by the concept, borrowed from physics, that, other things being equal, trip-making is inversely proportional to the cost, distance, or time, or a function of these, between an origin and a destination. There is another way of looking at it: Trip-making is accompanied by friction (out-of-pocket cost, time loss, and stress) that causes demand for trips between any two points to be less than some ideal value; the greater the friction is, the lower the demand is, and, as friction becomes very large, the demand should go to zero. As friction vanishes, the demand should approach a maximum value that is probably finite rather than infinite; economically motivated trip-making is not an end in itself but an exogenously stimulated activity.

In the AAM, the REACH algorithm derives the cost components for any feasible route from an origin to a destination. The friction is taken as a function of these cost components. Each cost component in this function is weighted by a numerical coefficient α^{kc} (the elasticity coefficient described previously), which has behavioral significance that is determined by how important dollar cost is in relation to time and stress for a given trip type. Because this index of importance varies from person to person, the α's are taken to represent suitable "average" values.

We then define an impedance function that has the following properties: It becomes smaller as the friction becomes smaller, but tends to a finite value (such as unity) as the friction approaches the limiting value of zero; it becomes ever larger as the friction increases; it has the right curvature to exhibit the property of diminishing returns; and it satisfies the requirement that the impedances of N links in series must combine multiplicatively to give the total impedance for the N-link sequence as a whole.

For these reasons, as well as that of mathematical convenience, we have chosen an exponential form for the impedance R_{ij} between points i and j:

$$R_{ij}^{kC} = \exp\left[\sum_{p=1}^{3} \alpha_p^{kC} X_{ij}^{pC}\right] \qquad (1)$$

where

k, C = trip purpose and trip condition respectively;
X^p = user costs (money, time, and stress);
α_p = weights or "elasticity coefficients" determining the relative importance of the cost components for various k and C.

Because $(R_{ij}^{kC})^{-1}$ is a factor in the demand function, it is the $\alpha_p X^p$ that play the role of elasticities. It is also clear from Eq. 1 that the problem of estimating the α's is a linear one for this form of impedance.

Demand Function

Once we select a given origin and destination, say nodes i and j respectively, the land-use file can tell us what economic activities are present at i and j and what fraction of total economic activity in each sector for the whole UAC is carried on at these points. With the help of the EAM, we can identify the types of trips that will take place between i and j and work out the expected volume (in a statistical sense) of trips of each type generated at i and ending at j. Because the EAM is derived from total figures for the UAC, this volume would be that obtained if the friction between i and j were equal to the average friction prevailing over the entire UAC.

To obtain a better representation of trip-making between i and j, we must multiply this volume by the trip-making impedance between i and j. This is obtained by running REACH, identifying feasible routes between i and j, costing each out, deriving partial impedances if there are several routes, and thus obtaining a single combined impedance. The resulting number is the trip-making demand function between points i and j, in units of trips per day. It can be multiplied by a suitable function of time of day, dependent on trip type, to give an hourly trip distribution.

The demand function takes into account the economic activities at the two end points of the trip and the trip-making impedance between them. Intervening opportunities and peculiarities of local activities departing from the norm are not modeled in detail. Nevertheless, the same α's that represent people's evaluation of the relative importance of the user cost components, when coupled with a rough determination of travel intensity under "ideal" conditions, lead to the value of trip-making impedance in response to which economic activities have arranged themselves in an UAC, given enough time for equilibrium. Thus, although the demand function cannot model the unusual attraction presented by an outstanding restaurant, it does model the characteristic spacing of more or less equivalent restaurants, which occurs, at least partly, in response to people's unwillingness to travel very far for lunch.

By using the EAM we obtain the total number of trips from one economic sector to others with which it interacts, given the trip type. By using the land-use file, we can derive the total number of employees for the UAC in the originating sector; therefore, we can derive the average number of trips generated by one employee in that sector to all interacting sectors.

We can now implant one such employee at origin i and ask for the number of trips generated by him to the interacting sectors at j, given the spectrum of activities at j and the trip-making characteristics between the two points. By summing over all destinations j, we then obtain the number of trips generated by the one employee in the given sector at i. If we divide this number by the average number of trips generated by one such employee, we obtain the accessibility index for that sector.

The accessibility index gives an indication of how favorable a location is for the pursuit of economic activity in a given sector, given the actual location of activities with which it interacts and the ease of reaching the interacting activities from i. It plays a central role in the economic impact model.

Mathematically, the demand function is given by

$$d_{ij}^{\eta\mu,kc}(t) \equiv A^{\eta\mu,k} f^{k}(t) B_{i}^{\eta} m_{\eta\mu}^{k} B_{j}^{\mu} (\bar{R}_{ij}^{kc})^{-1} [v^{k}(C)]^{-1} \tag{2}$$

where

$d_{ij}^{\eta\mu,kc}(t)$ = demand (trips per hour) for trips of type (or purpose) k under conditions $\{C\}$ from activity η at point i to activity μ at point j;
$f^{k}(t)$ = fraction of daily trips of type k taken in a given hourly interval;
B_{i}^{η} = fraction of activity η at point i relative to that throughout the UAC, in terms of employment;
$m_{\eta\mu}^{k}$ = number of daily trips of type k between η (origin) and μ (destination) throughout the UAC;
B_{j}^{μ} = fraction of activity μ at point j relative to that throughout the UAC;
$[v^{k}(c)]^{-1}$ = fraction of trips of type k carried out under conditions $\{C\}$;
$\bar{R}_{ij}^{kc}$ = trip-making impedance (defined later); and
$A^{\eta\mu,k}$ = normalization factor (defined later).

$f^{k}(t)$ is one of a small set (6) of simple step-function distribution functions stored and called into play when k is specified exogenously; B_{i}^{η} is derived from the land-use file; similarly, for B^{μ}, $m_{\mu\eta}^{k}$ is one ($\eta\mu$) element of a small set (6 or less) of EAMs stored as tables. R_{ij}^{kc} is given, for the case of only a single feasible route between i and j, by Eq. 1.

If there are several competing routes, $\ell = 1, \ldots, r$, between i and j, the REACH algorithm gives us

$$R_{ij\ell}^{kc} = \exp\left[\sum_{p=1}^{3} \alpha_{p}^{k} X_{ij\ell}^{pc}\right] \tag{3}$$

for each. These we call the partial impedances. In that case, we might be tempted to put $R_{ij\ell}^{kc}$ into Eq. 2 in lieu of $\bar{R}_{ij}^{kc}$ and call the resulting expression $d_{ij\ell}^{\eta\mu,kc}(t)$, the partial demand for previously defined trips on route ℓ.

However, such a treatment cannot lead to qualitatively correct results because it combines the separate impedances as if they were resistances in parallel across a constant-voltage power supply to give the total demand. In actuality, the demand resembles neither a constant-voltage nor a constant-current supply precisely but is generally closer to the latter; i.e., trip-making on the total of several parallel paths is usually greater than it would be on any one of them alone (i.e., if it were the only one present) but far less than would be obtained by summing over all paths considered as though each one were treated in isolation. The reason is that, if one adds an alternative route to one already present, most of the trip-makers on the new route are people who formerly traveled on the old one but perceive the alternative as offering less friction; the only new trip-makers are those who considered the old route too abrasive for making the trip at all but find the new one (or the old one after it has been decongested) more acceptable.

Thus we must find a way of more correctly combining impedances of connecting routes. This will yield a mean impedance $\bar{R}_{ij}^{kc}$,,which "explains" total trip-making between i and j. The flow on a given route ℓ (among several competing ones) is then given by a function of $\bar{R}_{ij}^{kc}$ and of $R_{ij\ell}^{kc}$, which distributes the flow among the competitors. To a first approximation one may be able to use the functions $R_{ij\ell}^{-1}$, raised to some power, as a measure of relative flow.

A sophisticated way of deriving the combined impedance $\bar{R}_{ij}^{kc}$ will have to take into account a probability distribution for each of the coefficients α_{p}^{kc} and carry out the corresponding probability integrals, as done by Quandt (20). We have used a simpler, more approximate procedure, but even so the equations are complex enough to require separate treatment elsewhere (28).

The normalization factor $\overline{A}^{\eta\mu,k}$ is most simply defined and evaluated by

$$(A^{\eta\mu,k})^{-1} \equiv \overline{{}_{j}B_{j}^{\mu}/R_{ij}^{kC_0}}^{\,i} \equiv \overline{{}_{i}B_{i}^{\eta}/R_{ij}^{kC_0}}^{\,j} \equiv (A^{\mu\eta,k})^{-1} \tag{4}$$

where the overhead bars denote weighted averages over all points i with activity η, or all points j with activity μ, as the case may be, the weights being the B_i^{η} or B_j^{μ} respectively. C_0 is the standard condition for which the EAM is derived. In practice, a sampling of points may suffice to form the averages, and $A^{\eta\mu,k}$ may be quite insensitive to k and yield only a narrow range of values for different $\eta\mu$ pairs.

The trip-condition coefficient $v^k(C)$ is exogenously obtained and indicates what percentage of trips is taken under nonstandard conditions (e.g., what percentage of people taking trip type k carry baggage). For bad-weather conditions, $v^k(C)$ also contains factors $(1 + \epsilon_k)$ that adjust total trip-making relative to good-weather conditions for a given k if this additional degree of freedom is found to be necessary. The definitions of six trip types, the conditions $\{C\}$ appropriate for each trip type k, the reciprocals of $v^k(C)$, and the factors $(1 + \epsilon_k)$ are given in Table 2. The values of $v^k(C)$ are crude estimates and are for illustration only.

The demand function (Eq. 2) serves as a point of departure for the prediction of flow on links and the calculation of accessibilities for input to the economic impact model. We can define a sector-specific accessibility index in terms of Eq. 2 by calculating the number of trips generated by a single average employee in a given sector at a given point to all the surrounding activities and by dividing this quantity by the number of such trips made by such an employee on the average throughout the UAC. The expression for a simple form of the accessibility index is

$$\Delta_i^{\eta} \equiv \left[\sum_{\mu,k} m_{\eta\mu}^{k}/v^k(C)\right]^{-1} \sum_{\mu,k} A^{\eta\mu,k}\, m_{\eta\mu}^{k} \sum_{j} B_j^{\mu}\left[\overline{R}_{ij}^{kC} \cdot v^k(C)\right]^{-1} \tag{5}$$

Accessibility, rent, and environmental quality in turn serve to determine the demand for adapted space that forms the point of departure for the economic impact model.

APPLICATIONS AND EXTENSIONS

Present Work

Our present effort consists of making some improvements and changes to the models while at the same time applying them in their present form to some "real problems."

The changes consist of some minor program cleanup and streamlining but are mainly aimed at reducing the running time of the REACH algorithm, which currently takes from 1 to 2 min for all the modes and nodes in lower Manhattan from Fulton Street southward. The REACH algorithm is, by far, the most time-consuming and core-storage demanding component of the model. Any reduction in these requirements will make more computers accessible and will allow us to generate more collective information such as traffic on links as opposed to sampling information such as accessibility indexes at selected points.

The reasons for applying the models to actual problems at this stage are to determine whether planners like working with the models; whether their input data base is manageable; whether the planning process using the models produces new insights and more rational approaches and advances the state of the art in planning; and whether the forecasting ability of the models can be tested in some "before-after" situations.

In lower Manhattan, we are working with the Planning Commission and the Office of lower Manhattan Development to examine possible effects of selected closings of lower

Manhattan streets to private vehicular traffic. Effects on goods movement and delivery, cab traffic, pedestrian traffic, and shopping patterns will be examined. In Milwaukee, we are working with the City Development Commission on the effects of a major new office building complex, to be built in the CBD, on transportation and pedestrian circulation and demand for retail and office space. Other, longer range projects are under way in several cities, including one or more with the Port of New York Authority.

Extensions

For the models to achieve maximum usefulness and flexibility in application, certain extensions and modifications should be undertaken, only the most important of which are mentioned in this paper. These extensions are in addition to the very necessary tasks of making the models operational and validating them by sensitivity analysis and application to one or more real situations.

Data Methodology

The economic activity matrix is one of the unique features of the AAM. Data gathering for the EAM will always remain somewhat ad hoc, but the process can be formalized by providing a system for gathering, collating, and referencing the data, estimating their reliability, and designing a program that will generate the best fitting matrix.

A quantitative rating scheme will have to be used in every location where the AAM is to be applied in order to yield the numerical behavioral data required in the trip-making demand function. The SYNERGI scheme, as formulated under the present contract, provides a suitable starting point; however, it needs further development.

A very desirable improvement would be to undertake the exercise in a teaching-machine format, which permits instantaneous feedback. Following the initial preference rating, a participant's results would be processed through a remote terminal linked to a time-sharing computer to yield a prediction concerning modal preferences. If these are at variance with the participant's stated preferences, he receives suggestions on alternative ways of modifying his ratings to achieve self-consistency. This improvement requires fairly extensive experimentation and testing, including some software development.

AAM Model Improvements

One of the obvious ways of validating the model in a given area is to enable it to calculate traffic flows. To this end, economical algorithms should be devised for approximating vehicular traffic on a link—short of the brute-force method of doing REACHs for all nodes in a region. This will then also make it possible to calculate congestion effects.

Congestion greatly affects an area's accessibility, which in turn plays a crucial role in describing the economic impact of transportation. Congestion can affect the three user-cost components of trip-making as well as having undesirable externalities. Up to now, congestion effects in the model are crudely simulated by additional costs that can be switched in exogenously regardless of calculated traffic flow.

The alterations that we propose would involve coupling the initial traffic flow calculated as shown earlier to the user costs on a link through a typical flow-velocity relationship using information about the capacity of the link. The traffic calculation is then iterated until convergence is obtained. Once experience is obtained with this procedure, the iterative link can then be closed internally.

The model is, at present, able to include residential accessibility only crudely in terms of UAC entrance turnstile counts as inputs. Modifications should be formulated and implemented that allow the AAM to describe movements from residential areas to business districts and institutions for purposes of employment, personal service, and educational and cultural pursuits.

The AAM requires some adaptation to be suitable for the description of goods movement, goods movement accessibility, and the interaction between goods movement and trip-making traffic. The objective will be to give the model the ability to describe the effects of an implanted goods movement system on the area.

The AAM demand function is impedance-sensitive; i.e., it aims to predict how tripmaking for a given purpose changes when external conditions change (such as the weather or the transportation system). This concept remains to be validated.

In addition, various improvements and major additions should be made to the economic impact model that would allow one to handle time-dependent problems, investment constraints due to policy measures or the state of the economy, and to devise, by using network selection techniques, optimal spatial arrangements for economic activities. Although we have not discussed the economic impact model in detail in this paper, mention of these items will make what follows more intelligible.

Future Applications

Here we discuss some applications of the transportation and economic models. We indicate what special data base (if any) would be needed beyond that discussed previously and what additions to the models would be required. The reader may be able to think of numerous additional possibilities.

1. The effects of possible operational decisions can be examined and evaluated. Among these might be street closings to vehicular traffic, changes in schedules, and new fare structures (including parking fees).
2. Costs and benefits, to both users and nonusers and by economic sector, of major investment decisions can be evaluated. Among such decisions one might mention the implantation of entire new transportation systems (such as moving sidewalks) or smaller changes (such as new routes, tunnels, stations, or equipment) or zoning and policy changes.
3. The effects of major investment decisions or zoning changes on land values can be used to form the rationale for formation of an assessment district. There has been much discussion recently on whether the public can, in this fashion, recoup some of the "windfall" gains accruing to the private sector favorably affected by these public investments or zoning changes.

The following applications require the type of data base that was acquired for lower Manhattan on the present contract; no additional major model development is needed.

1. The economic impact resulting from congestion can be investigated. The relative effectiveness of possible relief measures can be examined by means of the models. The effect of public investment decisions or zoning changes on relieving or creating congestion can also be evaluated. This application would require the addition of a vehicular congestion submodel and the development of algorithms permitting the computation of traffic flows without excessive computer running times.
2. The models could be of major help in airport location and surrounding land-use and transportation planning. The economic impact model is well-suited to develop criteria for viable mixes of economic sectors, subject to restrictive constraints such as immunity to noise. The AAM would derive transportation demand and could compare various transportation systems from the point of view of costs, benefits, and externalities.
3. The models would provide a suitable tool for planning of new towns where there are few improvements at the beginning. The model would be developed in terms of the complete horizon plan (or several plans to be compared), and various staging alternatives for reaching the horizon would be compared to evaluate problems of cash flow, land values, capital improvements and investments, and growth rate. If the problem were to develop a horizon plan, branch and boundary methods would have to be developed to allocate land optimally to various economic activities. The most suitable transportation systems for the horizon year, and alternate transportation investment policies during the intervening period, would of course be selected by application of the AAM.

SUMMARY

In applications so far, the model has been useful in helping local decision-makers to weigh policy alternatives. Future applications, some requiring addition of certain features to the model, may include the following:

1. Comparison of various "implanted" transportation systems, such as people movers, to assess the demand created, capacity required, fare policies, reduced load on existing facilities, effect on accessibilities and land values, and other externalities, in order to make more comprehensive cost-benefit estimates;
2. Formation of assessment districts to defray part of the public investment in a new transportation facility, the assessment being based on the windfall land value gains accruing to owners along or near the right-of-way; and
3. Evaluation of the effect of various zoning policies (such as floor-area ratios) on the demand for transportation, the creation of congestion, and a more comprehensive approach to quantifying the costs of congestion, including many of the externalities.

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