Opportunity-Accessibility Model for Allocating Regional Growth

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•SYSTEMATIC and comprehensive transportation planning has come to depend more and more on objective techniques involving the use of high-speed computers to deal with problems of data processing, data analysis, traffic simulation, and network evaluation. The selection and design of multimillion dollar transportation plans depend on the simultaneous evaluation of many diverse factors including traffic volumes, operating costs, construction costs, land costs, accident characteristics, and travel costs of thousands of transportation links and population numbering up to and beyond the millions. Subjective evaluations and intuitive speculations have come to play a much smaller role in planning transportation systems.

This trend is also apparent in city and regional planning. Although it is clear that design and aesthetic characteristics have a tremendously important role to play in planning cities of the future, it is also equally clear that the analysis and manipulation of the massive details that make up a functioning city of a million inhabitants require computer technology. Nowhere is this more apparent than in the estimation of the land and transportation requirements for a metropolitan region at a point in time of 20 to 25 years in the future.

The development of the model described in this paper is based on an attempt to bring into an objective framework methods and concepts which have been commonplace in planning for several years, but whose applications have most often been subjective and have defied replication by other professionals. The notions of holding capacity, access, density, etc., are not new. The manual application of these concepts by small geographic areas has been too often a subjective and, at times, an irrational process.

The reader is cautioned that there are both empirical and theoretical shortcomings in the model as it now exists. The model, however, does incorporate some of the more significant factors thought to be associated with the growth and functioning of urban regions into a flexible program which produces spatial arrangements corresponding quite closely to observed patterns. To the extent that it simulates urban growth, the model is extremely useful in providing the measured statements necessary to the planning of transportation facilities.

The model has been developed and is being tested by the Subdivision of Transportation Planning and Programming group. Its purpose is to allocate future estimates of activities (expressed in this instance in the form of trip destinations) to small geographic areas (travel analysis zones). This geographic allocation, in turn, is the input to the traffic assignment model which is used in the testing, evaluation, and design of alternative systems of transportation facilities.

The model leans heavily on the work of Schneider in trip distribution. Previous work in land-use models has also been of immeasurable value in design and development. The number of sources and references is too great to allow individual acknowledgment; however, some should be mentioned. Excellent reviews of literature and current thought in land-use modeling are contained in a special issue of the Journal of the American Institute of Planners, edited by Voorhees (1) (and particularly in his introductory report) and also in an article by Chapin (2). The recent report on current land-use models prepared by the Traffic Research Corp. for the Boston Regional

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Planning Project also provides coverage of work in progress at the time of its issue. More recently, the following significant seminars pertinent to the subject have been conducted: Seminar on Models of Land Use Development at the Institute for Urban Studies, University of Pennsylvania, Oct. 22-24, 1964; the Second Annual Conference on Urban Planning Information Systems and Programs, the Institute of Local Government and the Knowledge Availability Systems Center, the University of Pittsburgh, Sept. 24-26, 1964; and the meeting of the Committee on Land Use Evaluation of HRB, Nov. 23, 1964.

Although the authors are grateful for the contributions others have made, they accept full responsibility for any of the model's theoretical and practical shortcomings.

CONCEPT OF THE MODEL

The model is an opportunity model. In essence, the spatial distribution of an activity is viewed as the successive evaluation of alternative opportunities for sites which are rank ordered in time from an urban center. Opportunities are defined as the product of available land and density of activity (units of activity per unit area of land):

$$A_j = A\left[e^{-\ell O} - e^{-\ell(O + O_j)}\right]$$

where

- A_j = amount of activity to be allocated to zone j,
- A = aggregate amount of activity to be allocated,
- ℓ = probability of a unit of activity being sited at a given opportunity,
- O = opportunities for siting a unit of activity rank ordered by access value and preceding zone j, and
- O_j = opportunities in zone j.

Clearly, the use of the negative exponential formulation following an access search across an opportunity surface presumes that the settlement rate per unit of opportunity is highest at the point of maximum access or, most usually, the center of a region. This presumption is elementary and agrees well with both empirical observations and the bulk of the theory dealing with the economics of land use.

An example of the empirical relationship was observed in the Niagara Frontier. Figures 1 and 2 illustrate the regularity of the relationship between activity and opportunities for siting that activity when arranged in access (minimum time path value) order. These curves translated to the probability statement form the basis for the model.

Notion of Opportunities

The concept of an opportunity for siting a unit of activity involves both land and a measure of the intensity of use of that land. Land-use intensity or density has been treated as an equilibrium of the price of land and transport costs.

An historical analysis of density must consider changing transportation costs, changing building costs with particular emphasis on the costs of first floor area vs multistoried floor area, and changing requirements or preferences for location among competing activities. In addition to the difficulties that these considerations impose, there is the problem of structural rigidity of the physical region in terms of buildings and transportation facilities. These represent substantial investments which change only slowly.

Largely because of the difficulties involved in simulating the intensity of land use, we have chosen to utilize the present density as an appropriate measure which is independently introduced into the model. This independence allows the use of alternative densities whether analytically derived, guessed, or planned. We would naturally prefer to have these values generated with the model utilizing an algorithm which

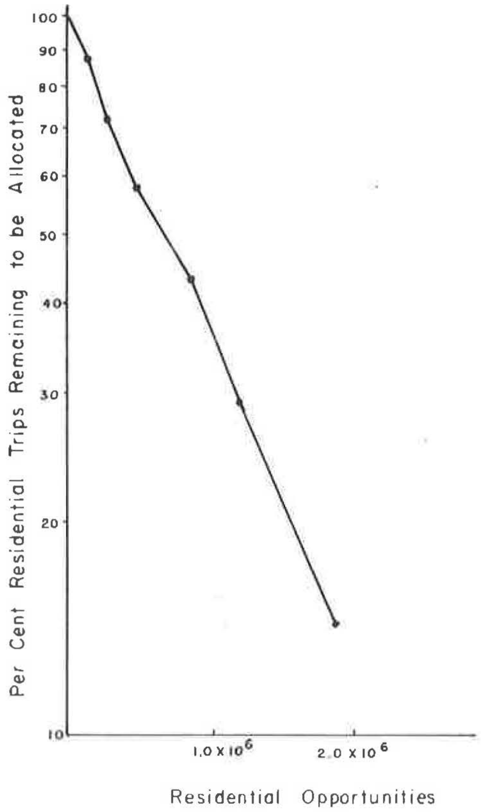

Figure 1.

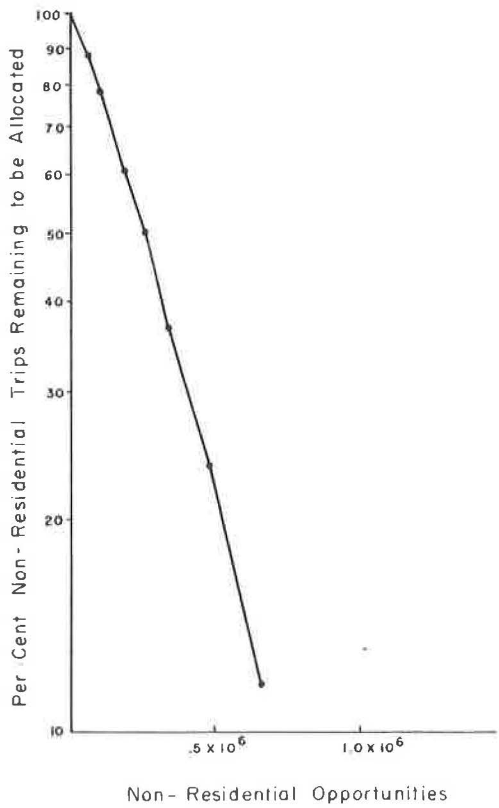

Figure 2.

would simulate the competitive processes that establish land-use intensity. This remains as an area to be resolved in future work on the model.

Notion of Probability of Siting

The parameter ℓ is the probability that a unit of activity will settle or be sited at a unit opportunity. For a given surface of opportunities, the larger this value, the more tightly packed the region will be. The smaller the value of ℓ, the more scattered or sprawling the settlement pattern will be. Thus, it is a measure which describes, within the constraint of the density-land opportunity surface, the relative importance of central positioning within the region.

The model distributes growth increments across an opportunity surface which has been rank ordered by time path value to the center. After each increment of growth is allocated, the available land is reduced by the land required to site the increment of activity, the opportunity surface is decreased, and the activity inventory by zone is updated. Ignoring for the moment competing activities, the use of an ℓ with large values would tend to settle each unit of activity at the first opportunity encountered. Thus, growth would simply be a process of completely using land in ever-increasing bands of access from the center. Very small values of ℓ, on the other hand, would tend to scatter activity across the region. Although the center would still dominate and act as a center, the pattern of settlement would be very sparse. As ℓ approaches zero, the notion of a region simply disappears.

There appears to be some general historical correspondence to a decreasing ℓ, presumably as a result of changes in the transportation technology (especially the

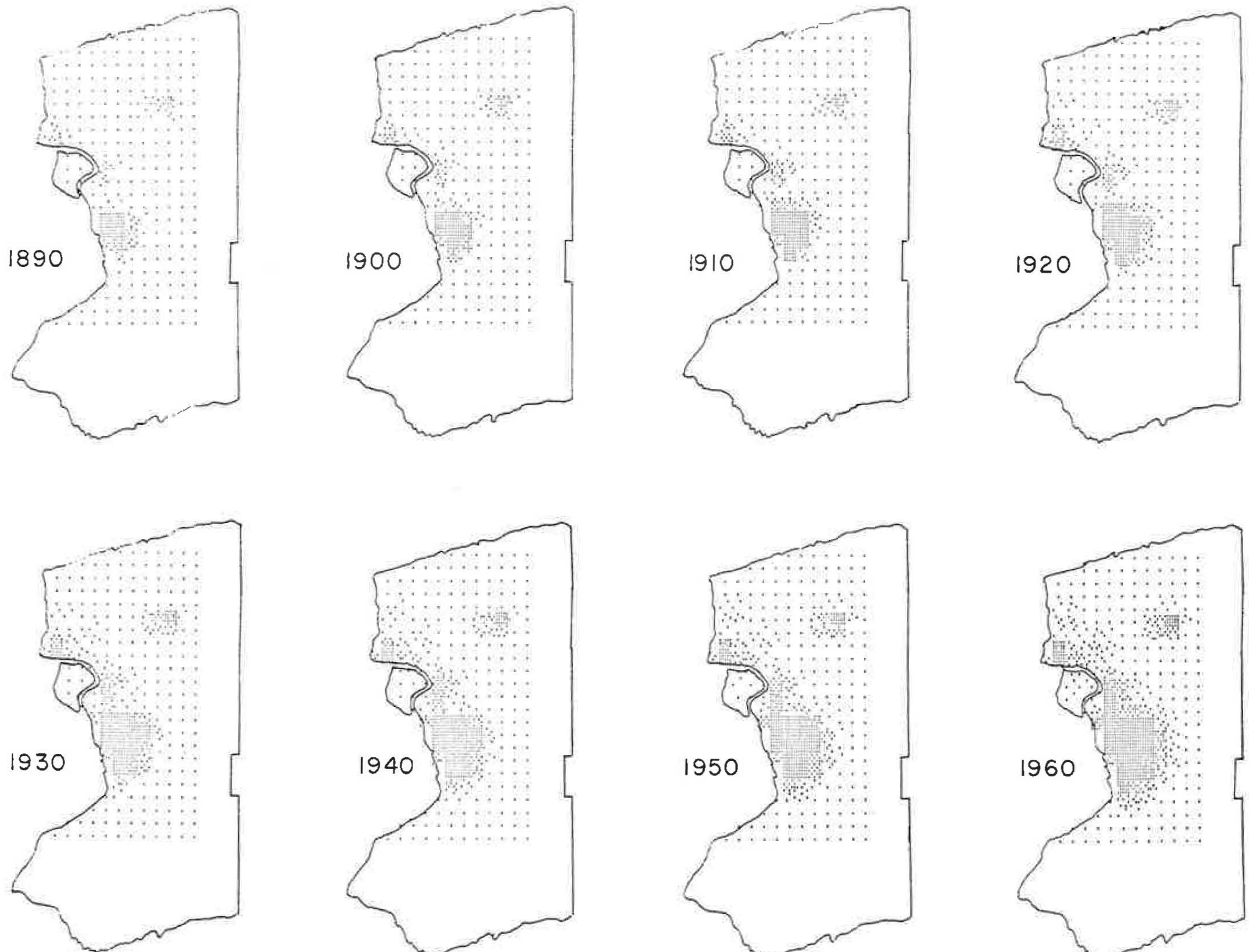

Figure 3. Niagara Frontier population growth simulation with prototype of land-use model.

widespread use of the automobile. Thus, the transition from rural to urban was more abrupt in earlier cities. Land in a given time ring tended to be substantially used up before successive time rings would be settled. Currently, the demarcation is typically in a broad band which may be several miles in width.

An analysis of the Chicago population settlement pattern reveals a lessening of the slope of land saturation at increasing distances from the Loop through time.

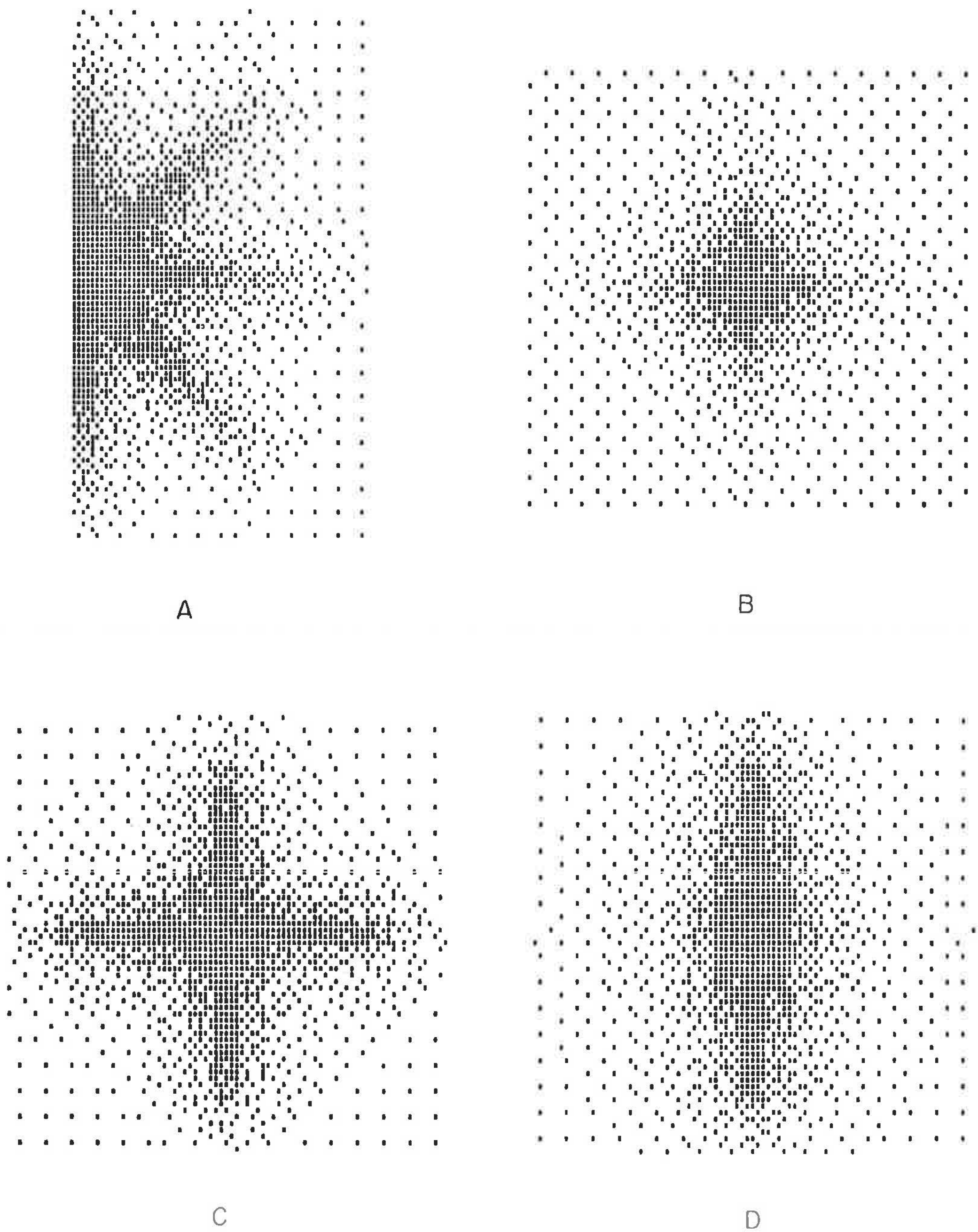

Figure 4. Allocations resulting from use of abstract networks.

Figure 3 shows a simulation of the growth of the Niagara Frontier region produced with a prototype of the present model. The decreasing concentration of activity is apparent in these allocations which are quite similar to the growth which actually occurred in the region.

Notion of Access

The obvious impact of transport costs on the development of a region has long been recognized. The inclusion of some measure of accessibility into any model proposed to simulate present growth or estimate future growth is imperative. However, the form and weight that access should have in the model are not so obvious; in fact, this is the major area which requires clarification.

We have started from a simplified notion that growth begins at a center and proceeds outward. The supply or surface of opportunities for growth will be examined in order of the travel time required to reach any location on that surface. This concept is neither new nor especially unique.

In experimenting with our model prototype, we found that the settlement pattern was very sensitive to the transportation facilities. Figure 4A shows a settlement pattern which might hypothetically have resulted with a transportation system composed of five high-speed facilities radiating out from the center. This pattern has been noted in real cities and is especially conspicuous in the stellate pattern of Chicago which is superimposed on the radial commuter lines.

We have tried other hypothetical networks and found reassuring patterns. For example, a simple grid of facilities with equal speeds gives a square settlement pattern rotated 45° with respect to the grid (Fig. 4B). If the central X and Y dimension facilities have a speed advantage over the other facilities, the sides of the square are pulled in, and the settlement pattern approaches the shape of a four-pronged starfish (Fig. 4C). Some of our midwestern plains cites do, in fact, correspond to just this pattern or are first cousins thereof.

If only a single facility has the high-speed characteristic, the linear form of the city emerges. This is common to cities which fall in a valley with the main street running parallel to the ridges. Here, of course, the topography itself (in the form of the opportunity surface) tends to reinforce the linear form of this settlement pattern (Fig. 4D).

The notion of access, developed here, should not be confused with the accessibility notion wherein a given location is related to all other locations by the sum of the quotients formed by each location's activity divided by its time or distance to the given zone raised to some power. This gravity or propensity for interaction notion of access is a distinctly different measure. We have included an option for calculating this measure within our model. To date, we have not compared the results of using this alternative measure of access.

The major point we wish to make here is that by borrowing the minimum path capabilities of the existing assignment packages, we can order the opportunity surface by a much more refined measure than air line distance to the CBD. Thus, within the limitations of our allocation algorithm, we can incorporate the effects which specific transportation improvements would have on the settlement pattern. We are then in a much better position to handle the knotty question of feedback between land use and the transportation system.

MODEL AS AN AID IN EVALUATING LAND-USE POLICY

The foregoing description of the model illustrates its utility as a basis for forecasting the future distribution of people and trip-making. It is not necessary, however, to so limit its use. The model can be used to examine the regional growth that might occur given certain policies with respect to land development. Two examples will be given, although many more are possible.

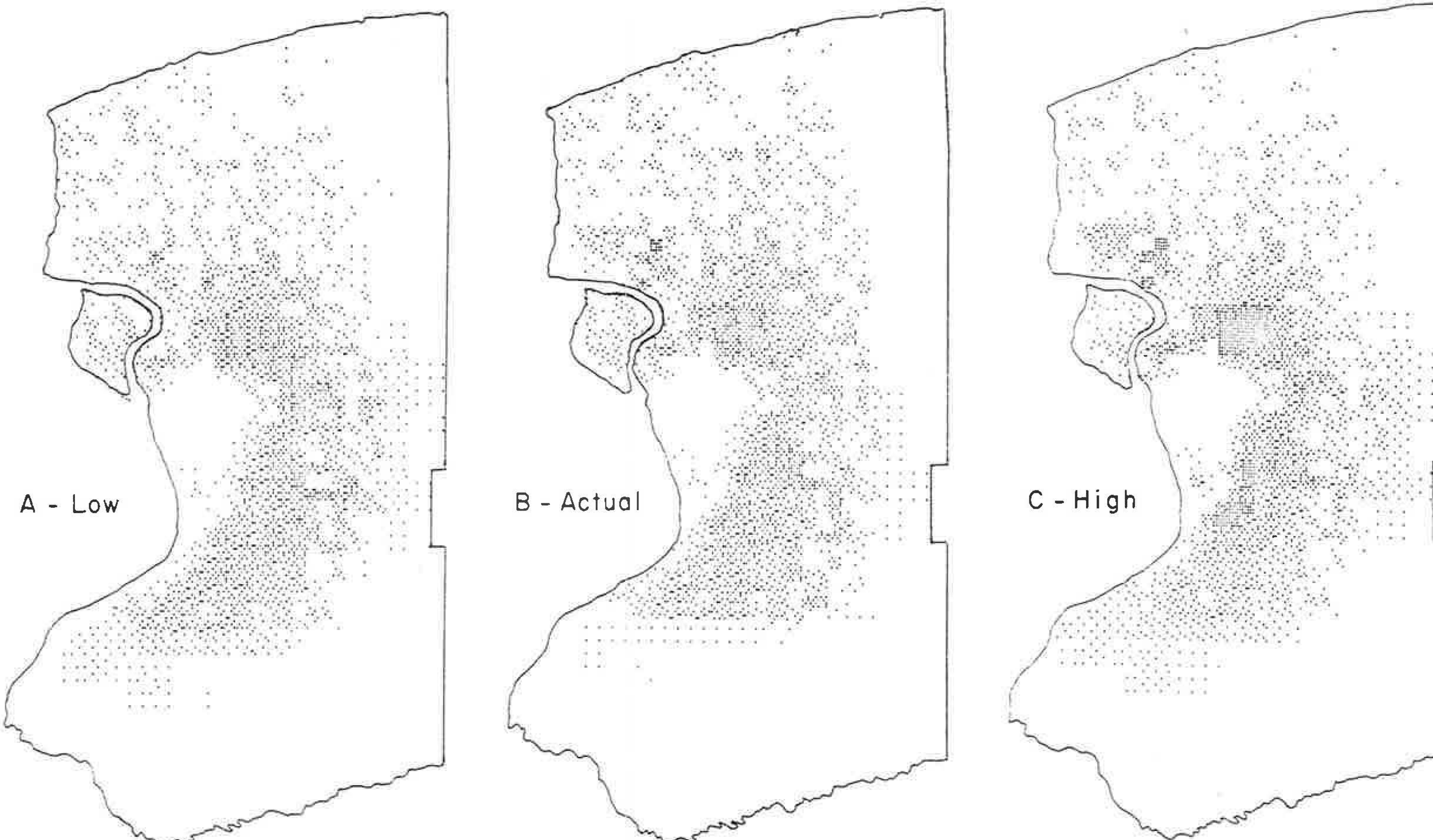

Figure 5. Effect of vehicle trip densities-residential.

Density Controls

The density or intensity of the use of land is fundamental to the structure of urban regions. The contrast between New York City and Los Angeles is the usual example of density extremes that have arisen historically in different regions. This range of densities, though not as extreme, can be found even without leaving a given urban region. The density of population in the center of Buffalo is 93, 250 persons/sq mi of net residential land in contrast to the 10, 000 persons/sq mi of net residential land found in the suburbs.

Sidestepping the issue of whether high densities are good or bad (and we find city planners on both sides of this question) and also avoiding the question of the extent to which planners can effectively control densities, we can use the model to examine the development which might occur with a prescribed density surface as opposed to an extrapolation of present densities.

The two most significant effects that the imposition of these controls might have would be in the shape or pattern of urban settlement and the amount of land which would be required to accommodate new growth. Figure 5A shows the settlement pattern resulting from a hypothetical density surface which is significantly lower than the present pattern of densities in the central cities of Buffalo and Niagara Falls. This spread pattern should be contrasted with Figure 5C which represents a model run with all parameters equal to those used to obtain Figure 5A, except that the density surface imposed is one of relatively high densities (about double present densities) in the central cities of Buffalo and Niagara Falls. Figure 5B shows the resultant pattern obtained by extrapolating present densities. Obviously, a much more compact development occurs with the higher than with the lower densities. Whether such density modifications are good or even possible will depend on many factors peculiar to a given region. The model, however, does give a visual representation of the potential settlement representative of these alternatives. Also, densities might be varied in other systematic ways to test or represent specific policies.

In addition, and perhaps of equal importance, we can obtain a measure of the impact of densities on land use from these alternatives. The total land going into urban use as a result of growth at the lower density scale is 186 sq mi, or 28. 6 sq mi of developed land per 100, 000 people.

The higher density surface required 163 sq mi of land to accommodate the same population growth. This means that 25. 1 sq mi of urban land are required for each additional 100, 000 population added to the area. This compares with land requirements of about 21 sq mi per 100, 000 population that have been required or expected in regions such as Chicago and Pittsburgh.

Open Space Controls

Another policy often considered in the shaping of the urban settlement pattern is the use of controlled open space. Without entering the discussion of feasibility, we can enter an open space plan into the model as a separate input, zone by zone. We can then see our resultant hypothetical settlement pattern. This may be used in conjunction with density controls or completely independent of them. Again, however, we are able to obtain a rapid, visual picture of the region just as though we had done a broad stroke sketch plan. The difference, however, is that we also provide a measured statement of how many people and trips will be located in each zone of the region. Thus quantified, the settlement can be converted into loads on the transportation network which is proposed, and the resulting transportation costs, including transportation facility construction as well as travel, can be used to evaluate the transportation plan. Eventually, of course, one would wish to cost out land development as well as transportation to evaluate alternative plans.

Incorporation of Plans Into Model

It should be clear that the use of the model is not restricted to forecasts alone. Specific plans for redevelopment, shopping centers, the central business district,

TABLE 1

PERCENT OF TOTAL REGIONAL POPULATION ALLOCATED OVER ALTERNATIVE NETWORKS

District	Network A Minimal	Network B Extensive	District	Network A Minimal	Network B Extensive
00	0.61	0.61	50	0.87	1.44
10	8.84	8.84	51	4.41	4.77
20	2.05	2.05	52	2.72	2.23
21	2.24	2.24	53	3.15	3.21
22	4.13	4.13	54	1.63	1.01
23	2.11	2.12	55	1.94	1.71
24	2.58	2.57	60	6.65	7.01
25	0.57	0.57	61	3.03	3.60
30	1.88	1.88	62	2.25	1.30
31	4.46	4.45	63	1.85	1.92
32	4.34	4.34	64	1.68	2.36
33	1.57	1.55	65	2.17	1.85
34	2.57	2.58	66	0.95	0.78
35	1.69	1.65	70	1.81	1.71
40	1.20	1.38	71	5.85	5.72
41	3.59	3.87	72	1.44	1.18
42	2.89	2.80	73	1.37	1.50
43	1.09	1.07	74	0.42	0.77
44	1.83	1.79	75	1.81	1.71
45	1.38	1.30	76	2.18	1.53

open space, density controls, and highways can be entered into the model. Such plans are considered as givens, and the model then estimates the population and travel distributions which would accompany these plans. As an example of the variation in allocations which result from different network plans, Table 1 gives percentage of population by analysis district following allocation over two alternative networks. The access levels of the two networks are shown by the travel time contours in Figure 4. Network A represents a minimal network with about 120 mi of expressways, whereas Network B has more than 400 mi.

CRITERIA FOR MODEL DESIGN

During the actual design and development of the model, an explicit list of criteria evolved from considerations implicit in the day-to-day work of assembling the model:

1. The model should be based on some theoretical statement of the mechanisms of land development. Although it need not simulate individual decisions within the land market, it should give results which correspond to the real world.
2. The model should be incremental and recursive. Ideally, data on past land use and transportation systems should be used to simulate the present development pattern. Lacking this ability, increments of growth should be layered on the present structure.
3. The model should be relatively simple. A finite number of land uses and a minimum number of subsets of households should be required to minimize data acquisition and handling difficulties.
4. Ideally, the calculation of activity density should be endogenous to the model. Failing this, the model should readily accept exogenous densities.

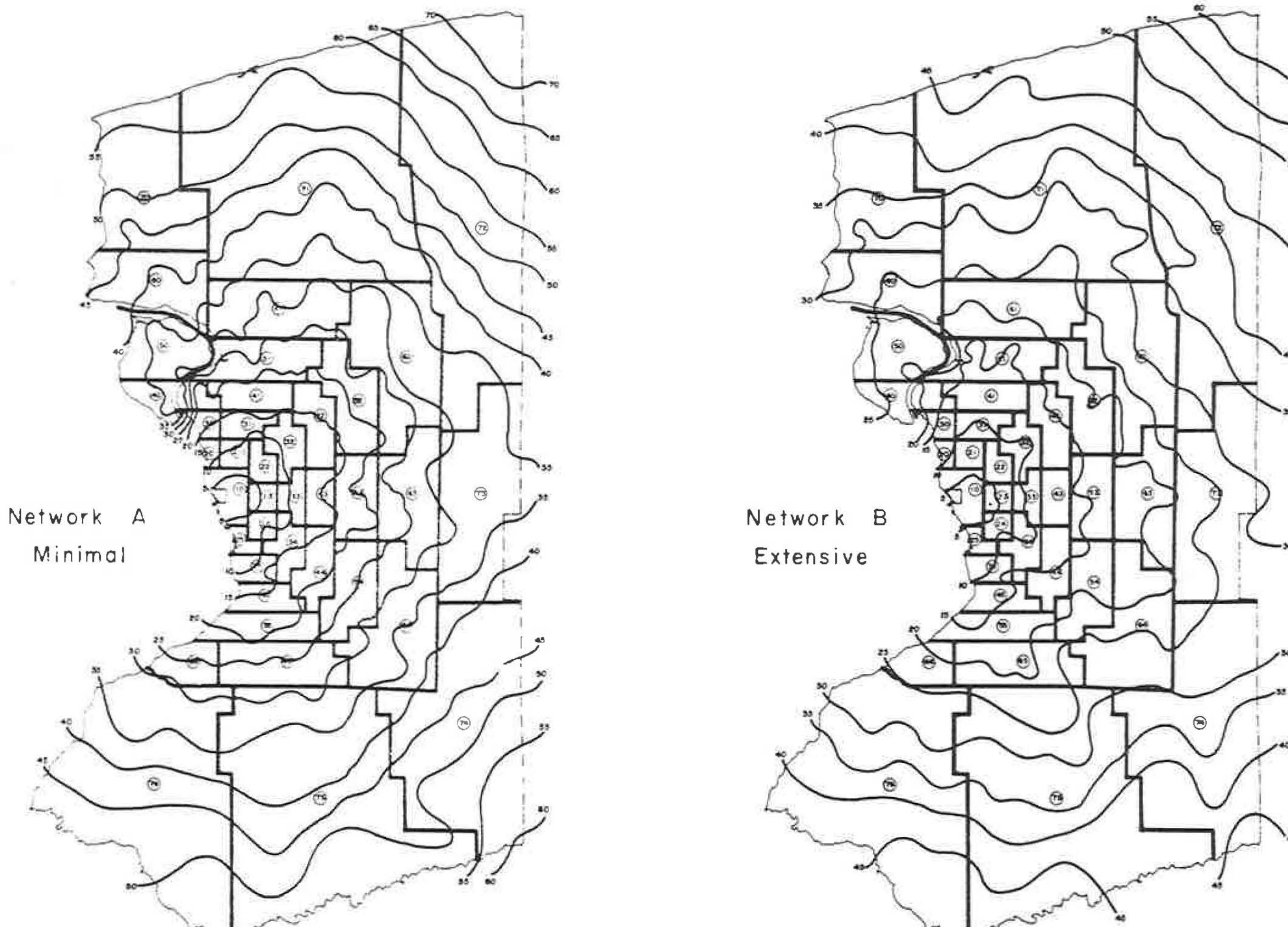

Figure 6. Travel time contours generated from two networks.

5. The model should accept alternative measures or indices of access. This provides the required flexibility should one measure be particularly appropriate to a given activity type and a different measure of access be best suited to other activity types.

6. The model should be able to accept data from redevelopment, urban renewal, or new-town plans. This might be done as a preliminary updating (internal to the model) of the land use and activity base or within the main frame of the model.

7. The model should be capable of being calibrated. For example, it should be possible to simulate past growth, or at least calibrate the model parameters using the present structure.

8. Provision for sensitivity analysis should be considered in the design of the model. It is vital to be able to evaluate the effect of unit changes in a given parameter on all facets of the allocation produced by the model.

9. The output of the model should permit easy and rapid comprehension of allocation results with particular emphasis on a simple graphic description of settlement patterns. This graphic output is particularly important to the comprehension and evaluation of alternative model inputs. Tabular outputs which can be used in calibration, sensitivity analysis, and allocation evaluation are also an obvious requirement.

10. Output from the model should be directly usable in existing traffic assignment procedures to minimize the difficulty and time involved in applying the results of the operation of the model.

Operation Description

A simplified flow diagram illustrating the inputs and operation sequence is shown in Figure 7. Actual operation of the model is initiated by providing seven sets of data describing the conditions in each zone at the beginning point in time. These are vacant land, nonresidential land, residential land, nontrip-generating land, nonresidential trips, residential trips, and population.

Vacant land is partitioned into two categories: available for development, and permanently withheld (the latter considered to be an irreducible minimum on the order of 10 percent). The opportunities for an increase in activity in each zone are then calculated by applying internally calculated (or previously supplied) activity densities to the vacant available land. The estimate of growth in the activity is then allocated across the opportunity surface from one or more regional centers. Opportunities are considered in the order established by the particular accessibility measure being used. The opportunity surface is updated, summary tables are revised, and the decreased opportunity surface is reconverted to vacant available land. Allocation of a second activity follows in a similar manner.

After all activities for a given time increment have been allocated, the model repeats the entire procedure beginning with the first activity for the next increment. A simultaneous allocation of population is made, independent of the allocation of other activities, to help to maintain perspective and to provide a population growth allocation for subareas of the region.

The population allocation is made in a similar manner with an opportunity surface described as a function of (a) the proportion of used and vacant land, (b) the population density, and (c) externally provided limiting values for these proportions and densities. Accounts of the change in the number of opportunities available are again maintained along with estimates of the used land and vacant available land.

Currently the output of the model consists of a series of tables reporting the input values, the opportunity surfaces and the allocation for each activity and each center, the final totals for each activity, and the remaining opportunities. In the present application, an estimate of future trip ends directly useful in the current version of the Chicago or Schneider assignment and trip distribution model is produced, as well as an input to a mapping program used to produce graphic output for analysis and display.

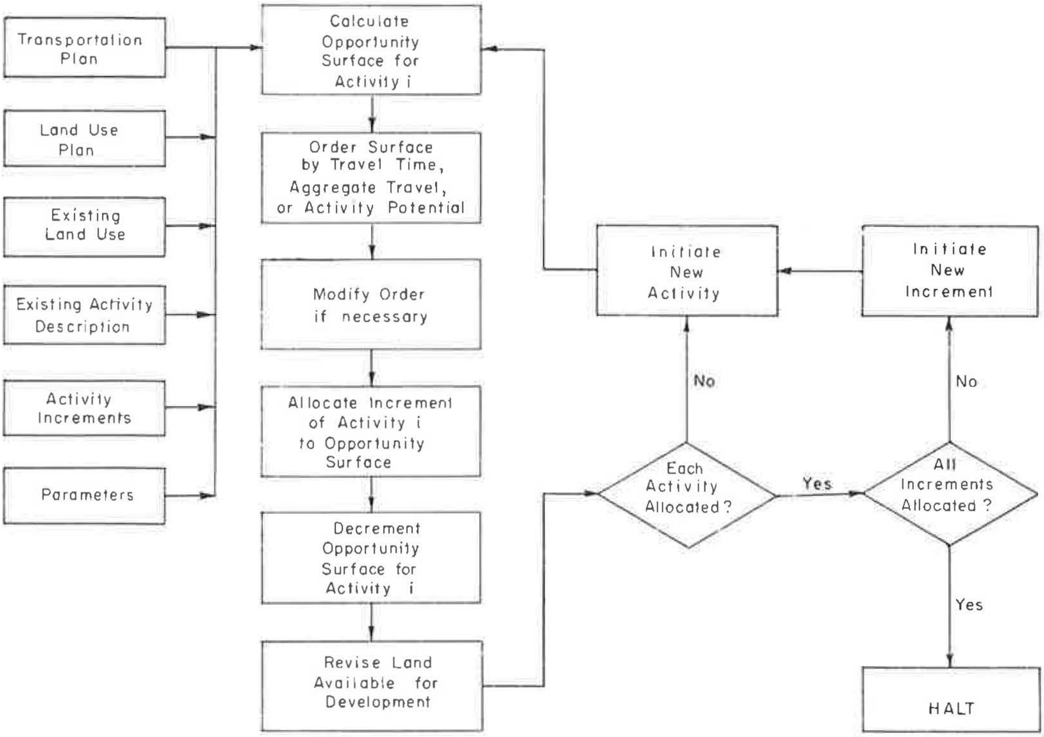

Figure 7. Sequence of operations within model.

Preliminary allocations for the Niagara Frontier region have been made in about 6 min using a minimum time path value tree to measure accessibility, three regional subcenters, and two increments of growth.

Alternatives Available in Model

The model has several intentional points of flexibility within the basic operation sequence. Input data may be varied to simulate almost any situation of land use and activity density. Plans for both land use and transportation networks may be incorporated by stating amounts of different classes of land at the outset, by establishing trip density values to meet some predetermined level, and by providing minimum travel time trees from various networks. Alternative base data may also be substituted at the start of any increment.

The order of consideration of the zones may be altered by factoring any accessibility measure by an exogenously provided multiplier. The model also will consider the region as completely undeveloped, permitting allocation from a zero condition rather than incrementing the existing trips or population.

SUMMARY

In this brief paper we have given a general description of an allocation model which is largely based on access to a regional center or set of regional subcenters. Currently, variables other than access can be introduced by modifying the rank order of opportunities.

Qualitative examination of hypothetical results provides persuasive evidence that the settlement pattern has historically responded to access as we have measured it. Quantitative verification and calibration is difficult because of the lack of historical data on land use and transportation networks. We are attempting, however, to measure the extent to which population growth since 1940 can be explained by use of the model. This requires the assumption that net activity densities have remained fairly constant in this period.

We are not satisfied with the use of external independent estimates of activity density. Eventually, these densities must be made endogenous to the model.

The operating speed and output flexibility of the model are a great advantage in research. We are quite interested in evaluating the extent of variation in growth attributable to other variables or to different statements of access. In this sense, we consider the model an experimental technique which will allow us to measure further and, hopefully, come to a better understanding of the urban growth process.