Special Session on Human Judgment and Spatial Behavior, Great Plains/Rocky Mountains AAG Meetings, Manhattan, KS, Oct. 1976.
15. J. J. Louviere, J. M. Piccolo, R. J. Meyer, and W. Duston. Theory and Empirical Evidence in Real-World Studies of Human Judgment: Three Shopping Behavior Examples. Center for Behavioral Studies, Institute for Policy Research, Univ. of Wyoming, Laramie, Research Paper No. 1, March 1977.
16. B. J. L. Berry. Geography of Market Centers and Retail Distribution. Prentice-Hall, Englewood Cliffs, NJ, 1967.
17. Old West Commission. Construction Worker Profile. Billings, MT, 1975.
18. R. D. Luce and P. Suppes. Preference, Utility and Subjective Probability. In Handbook of Mathematical Psychology, Vol. 3 (R. D. Luce, R. R. Bush, and E. Galanter, ed.), Wiley, New York, 1965.
19. D. McFadden. Conditional Logit Analysis of Qualitative Choice Behavior. In Frontiers in Econometrics (P. Zarembka, ed.), Academic Press, New York, 1974.
20. M. G. Richards and M. E. Ben-Akiva. A Disaggregate Travel Demand Model. Saxon House, D.C. Heath Ltd., Westmead, England, 1975.
21. T. Domencich and D. McFadden. Urban Travel Demand: A Behavioral Analysis. Elsevier, New York, 1975.
22. J. Berkson. A Statistically Precise and Relatively Simple Method of Estimating the Bioassay with Quantal Response, Based on the Logistic Function. Journal of the American Statistical Association, Vol. 48, 1953, pp. 565-599.
23. H. Theil. A Multinomial Extension of the Linear Logit Model. International Economic Review, Vol. 10, 1969, pp. 251-259.

Publication of this paper sponsored by Committee on Passenger Travel Demand Characteristics and Committee on Traveler Behavior and Values.

**The work described in this paper was performed while both authors were at Cambridge Systematics, Inc.*

Effects of Employment and Residential Location Choices on Urban Structure: A Dynamic Stochastic Simulation

Timothy J. Tardiff, Tenny N. Lam, and Brian F. Odell, Department of Civil Engineering, University of California, Davis

The pattern of home-to-work linkages in urban areas is affected by household mobility decisions. This paper describes a dynamic stochastic simulation model designed to illustrate the effects of mobility decisions on urban structure. The major feature of the model is the representation of household changes in employment or residential locations or both. The sequential process of the decision to move and the search for and selection of new location is specified. The role of accessibility in this process is an important consideration in the model, which allows quick execution of simulation experiments. Experiments consist of alternative input assumptions involving factors such as city size, numbers and locations of job centers and dwelling units, initial pattern of home-to-job linkages, moving rate, and importance of accessibility in selecting new locations. Two types of experiments are presented. The first examines the dynamic properties of the model by varying the initial pattern of home-to-job linkages and the mobility rate. The major conclusion is that there appears to be an equilibrium pattern of home-to-job linkages that is independent of the initial configuration and mobility rate. The second type of experiment involves the variation of the importance of accessibility in the mobility decision process. The results show that the pattern of home-to-job linkages varies in the expected way with changes in the decision process.

The pattern of linkages between residential and employment locations in urban areas and the changes in this pattern over time are the result of many complex economic and social processes. To isolate the contribution of each by looking at the total patterns through time series or cross-sectional analyses is difficult, if not impossible. An alternate approach is to study theoretical models that deal with a small number of processes, or a small part of the problem, at a time. Data and theory must finally agree, of course. In attempting to model the effects of the processes on urban structure, one must make simplifying assumptions in order to make the problem analytically tractable. The nature of the assumptions is dictated by the purposes of a particular modeling approach.

The purpose of the present modeling effort is to examine the effects of accessibility-based household decision rules on the changing structure of prototypical urban areas. The emphasis on accessibility is consistent with numerous previous studies and also facilitates an examination of the transportation requirements for urban areas. The model is a dynamic stochastic simulation model that processes household location decisions sequentially within a given time period. Each time period represents a fraction of the population making intraurban mobility decisions, i.e., residential location changes, employment location changes, or simultaneous home-job changes. An additional objective of the modeling effort is to generate a basis for conducting controlled theoretical experiments, the purpose of which is to examine questions such as stability, statistical variabilities, and observability of urban relationships. These issues are important for linking theoretical results with empirical data.

Much simplification of the socioeconomic details such as the distributions of household and dwelling unit types over the urban areas is allowed in order to sharpen the

model's focus on the accessibility-based choice decisions. The central issue is how household decision rules affect the overall state of the hypothetical urban system. Simplification allows the model to be processed over many time periods at fairly low computational expenses and thus facilitates examination of the dynamic aspects of urban areas.

A primary concern of the modeling effort is the existence of constraints at both the household and urban system levels. In regard to the former, the dynamic aspects of the model implicitly incorporate three constraints: those on the search for new residences; those on the available choices, which are limited by the number of vacancies in a given time period; and those implicit in the competition among households for the available dwelling units. All of these constraints potentially lessen the pure effects of accessibility in the household decision rule. There appear to be dynamic equilibria at the systemwide level that are determined, in part, by the nature of the household location decision rule. This implies that planned changes in the urban structure that are inconsistent with the underlying decision rules are unstable. Therefore, effective planning policies seem to be constrained by basic household behavior.

BACKGROUND

Since the emphasis of the present study differs from that of much previous work, the methodological approach also differs. Of the two major categories of previous work, the first emphasizes the description and analysis of the spatial patterns of urban areas, usually in an atemporal manner. Studies of this nature often develop and apply spatial interaction concepts such as accessibility (1, 2, 3, 4) or intervening opportunities (5, 6). Although many of these models yield fairly rich spatial detail for particular urban areas, they usually do not explicitly consider the household decision processes that generate the macrolevel patterns.

The second category of previous work focuses on explaining household spatial choice processes. Of particular interest for this study is the examination of intraurban location choices. Studies of this nature have used various methodologies and have arrived at conclusions that differ according to the disciplinary perspective of the study. Some studies, such as Lerman's (7), hypothesize an economic explanation of location choice. In these studies, home-to-work accessibility is implicit in transportation costs. Other studies focus on the search process involved in moving. In these studies the key accessibility concept is often the accessibility of potential new homes to the old home, rather than home-to-work accessibility (8, 9). A third type of study emphasizes the effects of household characteristics and/or reported reasons for moving on the actual decision to move (10, 11, 12, 13). These studies seem to indicate that accessibility is a relatively unimportant reason for moving. Household, dwelling unit, and neighborhood characteristics are cited much more frequently. However, there is evidence that actual behavior of households is consistent with an accessibility hypothesis (14, 15).

Recently there have been a few notable efforts to explicitly incorporate household choice behavior into models that explain spatial structure to create a hybrid of the two categories (16, 17). Often these efforts are consistent with economic explanations of spatial choice. Further, there is some attempt to dynamically represent the urban structure. However, such models have had fairly detailed spatial descriptions, have been specific to a particular metropolitan region, and have not been explicitly concerned with the sensitivity of spatial patterns to changes in behavioral assumptions.

In addition to the importance of accessibility, two other important issues are encountered in previous work. First, it is possible to distinguish between optimal versus nonoptimal decision processes. At the household level optimality is implicit in the conventional utility maximization assumption of economic models. In contrast to this are explanations involving a three-phase decision process: decision to move, search, and selection (18, 19). These explanations do not rely on optimality assumptions in the sense that there are usually constraints in the search phase that inhibit the selection of the optimal location. Systemwide models allocate activities based upon some optimality criterion such as welfare maximization (8, 16, 20, 21) or some other planning goal such as systemwide travel minimization (22, 23, 24). In contrast to the optimality at a systemwide level are models using an accessibility allocation rule that is not explicitly optimal (1, 4, 25, 26).

The second issue involves the role of home-to-job linkages in location choices. Consistent with monocentric spatial models (27), most economic models assume that job location selection occurs before residential location choice and that the latter depends on the former. On the other hand, job location is not explicitly considered in explanations that hypothesize search processes dependent on the old home. Both explanations ignore the possibility of changes in job location without changes in residential location. Recent empirical evidence suggests that such a location decision may also be important (28, 29).

The various possibilities are summarized in a classification scheme suggested in a review article by Senior (30). The entire population in an urban area in a given time period can be classified as nonmovers, job changers with fixed residences, residential movers with fixed job locations, and simultaneous residential and job movers. It is apparent that the usual employment-centered residential choice assumption ignores some types of moves.

SIMULATION MODEL

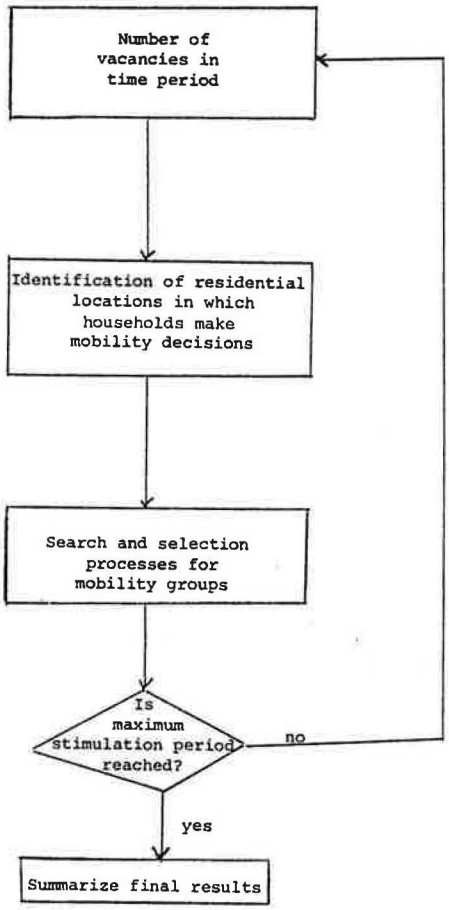
The basic model represents a highly idealized prototypical urban area. No attempt is made to classify households or dwelling units; therefore, zonal demographic and individual characteristics remain unspecified in the simulation process. The random component of the household location choice process allows potential effects of household behavioral and characteristic differences to be realized without explicit specification.

The urban area is represented by a rectangular array containing housing and job center locations. In general, the relative spatial separation between the cells of the array may be manipulated through topological transformations to reflect actual spatial patterns and/or transportation systems. Each residential location contains a small number of identical dwelling units. The distribution of dwelling units among locations can represent any desired density, although most of the simulations accomplished to date have used uniform densities. Similarly, the size and location of job centers can be specified in any manner, although there is no differentiation by job classification.

At any given time the structure of the urban area is represented by the distribution of job locations for residents of each residential location. Using this basic information, it is possible to develop various systemwide summary statistics such as the distribution and moments of the distribution of home-to-work distance.

The dynamic properties of the model are a result of the representation of changes in employment and residential locations over time. The essentials of these processes are represented in Figure 1.

Figure 1. Major components of the simulation model.



In addition to accounts of the temporary and final states of the urban system, the dynamic model contains three major components. The first of these is the generation of the number of movers for a particular time period. This number is selected randomly from a Poisson distribution with expected value equal to a fixed proportion of the population. This proportion can be interpreted as a mobility rate for a given time period. There are two interpretations of this mobility rate. First, higher or lower rates may represent higher or lower mobility propensities for a time period of fixed length. Alternatively, increases or decreases in the mobility rate may represent decreases or increases, respectively, in the length of the basic time period. Operationally, the two interpretations are indistinguishable.

The remaining two major components capture the essentials of the hypothesized household location choice processes. These processes are consistent with previous work suggesting a sequential decision process that involves a decision to move, a search process, and a selection process rather than the individual or systemwide optimization procedure.

The representation of the decision to move is the first of these components. Consistent with some of the survey research findings on decisions to move (10, 11, 12, 13) and also with the Morrison concept of the existence of a hypermobile population (31), the decision to move is assumed to be determined by household or environmental characteristics and to be independent of home-to-work accessibility considerations. This strategy is also consistent with that used in other recent dynamic models (16, 17). Since the present model does not distinguish among these types of characteristics, the location of households making mobility decisions is identified randomly as suggested by Harsman and Snickars (20).

The identification process involves two random processes. First, the location of the household is selected randomly from all possible locations. Then, the household is classified probabilistically by the type of mobility decision: job change only, residential change only, or simultaneous job and residence change. The classification probabilities are established as input parameters. This procedure continues until the previously established households have been identified and classified. Movers are accumulated by mobility type in a regional pool to await subsequent processing.

The last major operational component represents the search and selection processes. There are two levels of sequential processing. First, individual households are randomly selected from the mover pool and randomly assigned to either available house or available job locations. The procedure is somewhat similar to that used by Mason (17), although this process is random while Mason's process prioritized households by income. Second, individual households drawn from the mobility pool and assigned to initial locations sequentially encounter housing or job opportunities. They make an acceptance or rejection decision based on a preselected choice function that usually specifies that the probability of acceptance decreases with an increase in the city block distance between the potential opportunity and the relevant home or job location. The role of accessibility in the choice function is consistent with economic explanations of location choice and with some survey research findings suggesting that, while accessibility might not be important in the decision to move, it may be an important consideration in the selection of the new location (10). By varying the importance of the random component of the choice function, it is possible to test various hypotheses that give greater or less weight to the importance of accessibility.

The search and selection processes are similar to actual or proposed strategies in other dynamic models but differ in important ways. First, the random nature of the search process has been suggested by Okabe (32) and Harsman and Snickars (20). However, both of those studies hypothesize a simultaneous deterministic choice among a prespecified number of possible vacancies rather than the sequential probabilistic choice process in the present model. The sequential processing of households contrasts with the models incorporating systemwide optimization rules (16, 32).

The details of the search and selection processes are as follows. First, a mobility type is selected probabilistically (without replacement) from the list of households generated by the previous component. The probabilities are proportional to the actual numbers of households in each mobility category at the time the particular household is processed. If the mobility type is a job change only, a residential location is selected randomly from those locations with job-changing residents. Next, a job location is selected probabilistically (without replacement). The probabilities are proportional to the number of job vacancies at each job center. The accessibility-based choice function is then used to probabilistically accept or reject the job location. Since rejected job locations are not replaced, the household must accept the last location if all others have been exhausted. As all jobs at a given location are identical, this strategy is consistent with the assumption that rejection of a job implies rejection of all job opportunities at the location for that time period.

For the residential change only, a job location is selected probabilistically in proportion to the number of

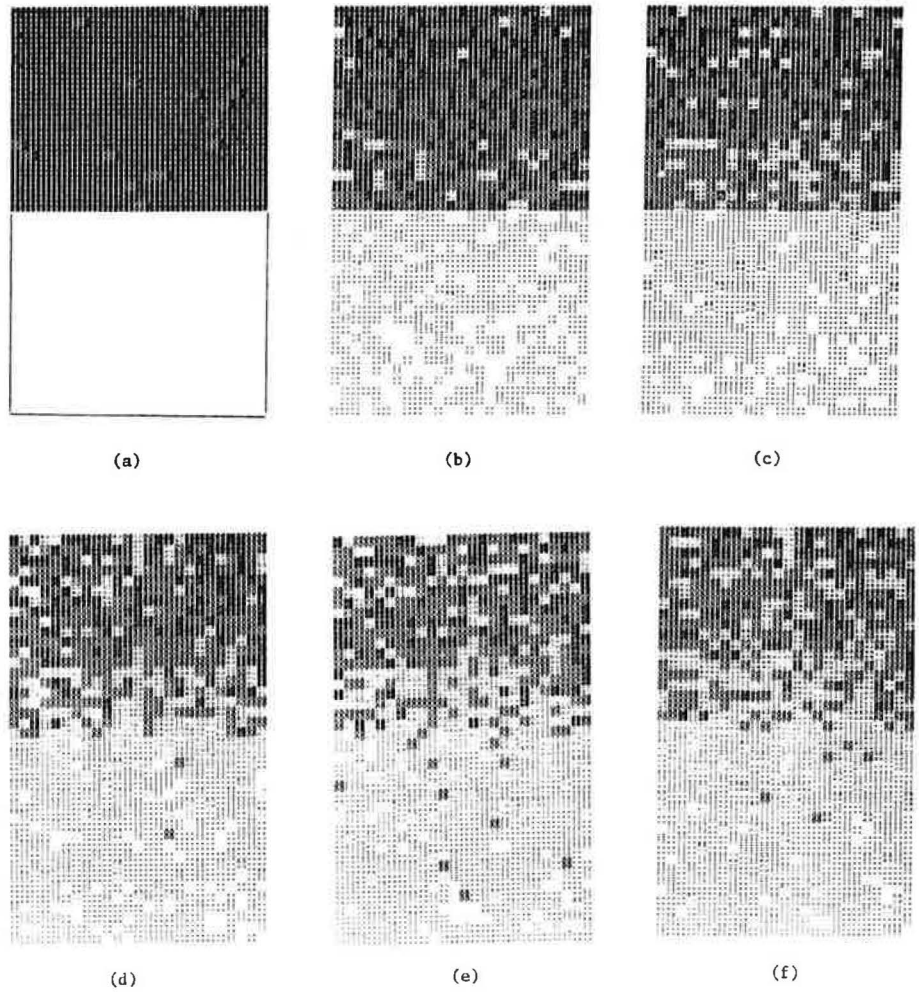


Figure 2. Pattern of home-to-work linkages over time (initial pattern concentrated at time periods 0, 10, 20, 30, 40, and 50).

residence-changing job holders at each location at the time the household is processed. A residential location is then selected randomly (with replacement) from those locations with housing vacancies. The accessibility-based decision rule is then used to accept or reject the residential location. The process continues sequentially until a residential location is selected or until a prespecified maximum search length is encountered, in which case the last location is selected.

Households simultaneously changing jobs and residences are first probabilistically classified into two groups: those who select the residence first and those who select the job first. The classification probabilities are prespecified. Households subclassified into the first category are then processed in the same way as job changers and those in the second subclassification are processed as residential changers.

The complete processing of all moving households marks the end of the time period. Iterative processing through subsequent time periods, or moving cycles, continues until a terminal period is encountered.

ILLUSTRATIVE RESULTS

The purpose of the simulation is to study the effects of household mobility processes and various physical characteristics of urban systems on the home-to-work transportation requirements. By sacrificing detail, a wide range of simulation experiments can be examined.

Each simulation experiment involves variation of one or more of the following inputs: (a) the dimensions of the rectangular array; (b) the number, sizes, and location of job centers; (c) the distribution of dwelling units within the array; (d) the probabilistic accessibility-based location choice rule; (e) the expected proportions of mobility types; (f) the mobility rates; (g) the initial pattern of home-to-job linkages; and (h) the level of service on transportation links.

The experiments performed to date can be classified by the essential purpose of the experiment. All experiments have used the same expected proportions for mobility types: one-third job changers, one-third residence changers, and one-third simultaneous changers. In the last category, half are expected to select the residence first. Almost all the experiments have used a uniform distribution of ten dwelling units per location and have assumed uniform level of service on transportation links, although some preliminary results modifying these assumptions are available.

Four major categories of experiments have been performed. First, the dynamic properties of urban systems have been examined by varying the initial pattern of home-to-job linkages and the mobility rates. Second, the effects of the accessibility-based decision rule on home-job patterns have been examined by varying the choice function. Third, the effects of urban structure on transportation requirements have been examined by varying the dimensions of the array and the number, size, and location of job centers. Finally, the effects of variations in transportation level of service and the density distribution of dwelling units were examined.

Over 40 simulation experiments have been run. Because the purpose of this paper is to illustrate methodology, an exhaustive description of the results will not

be given. Rather, general findings from the first two categories of experiments will be described. These categories contain the most easily interpretable results and the most definitive conclusions at this time.

Some results involving dynamic properties have been described elsewhere (33) and will only be summarized here. The major conclusion is that there appears to be an equilibrium pattern in home-to-job linkages aggregated over distance that is independent of the initial configuration and the mobility rate. However, the time required to reach equilibrium varies with the initial configuration and the mobility rates.

This conclusion is based on five experiments involving a 40 x 25 array with ten dwelling units per location. Two job centers located in the middle of the array in the short dimension and one-quarter of the length of the array from the edge in the long direction both contained 5000 jobs. Three percent of the dwelling units were vacant. The accessibility function was linear with a maximum probability of 95 percent at the minimum distance (1 block) and 5 percent at the maximum distance (42 blocks).

Three initial patterns and three mobility rates were used. The three patterns combined into a uniform pattern (roughly equal distribution of home-to-job linkages for each residential location), a concentrated pattern (every resident working at the closest job center), and the equilibrium pattern. The last pattern resulted from starting with all residences and jobs vacant and assigning the entire population in one time period. By necessity, all movers were simultaneous job and residential changers with probability of subclassifications equal to one-half. The three mobility rates were 0.5, 1, and 4 percent.

The apparent equilibrium is that obtained with the equilibrium initial pattern. The dynamic aspects of the path to equilibrium are illustrated in Figure 2. This figure depicts the distribution of households working in one job center for each residential location. Darker areas represent higher concentrations of workers. The initial configuration is the concentrated one, and the mobility rate is 4 percent. The pattern changes from one in which everyone in one-half of the city and no one in the other half is working at the job center to the equilibrium position in which the split is roughly two-thirds and one-third.

There are two major implications. First, for experiments concerned with equilibrium rather than dynamic properties, the equilibrium initial pattern can be generated directly, with substantial savings in computation costs. Second, the existence of equilibria seems to indicate that initial patterns inconsistent with the choice behavior resulting in the equilibria are unstable. For example, the situation involving the concentrated pattern may represent the outcome of the frequently advo-

Figure 3. Alternative accessibility-based location choice functions.

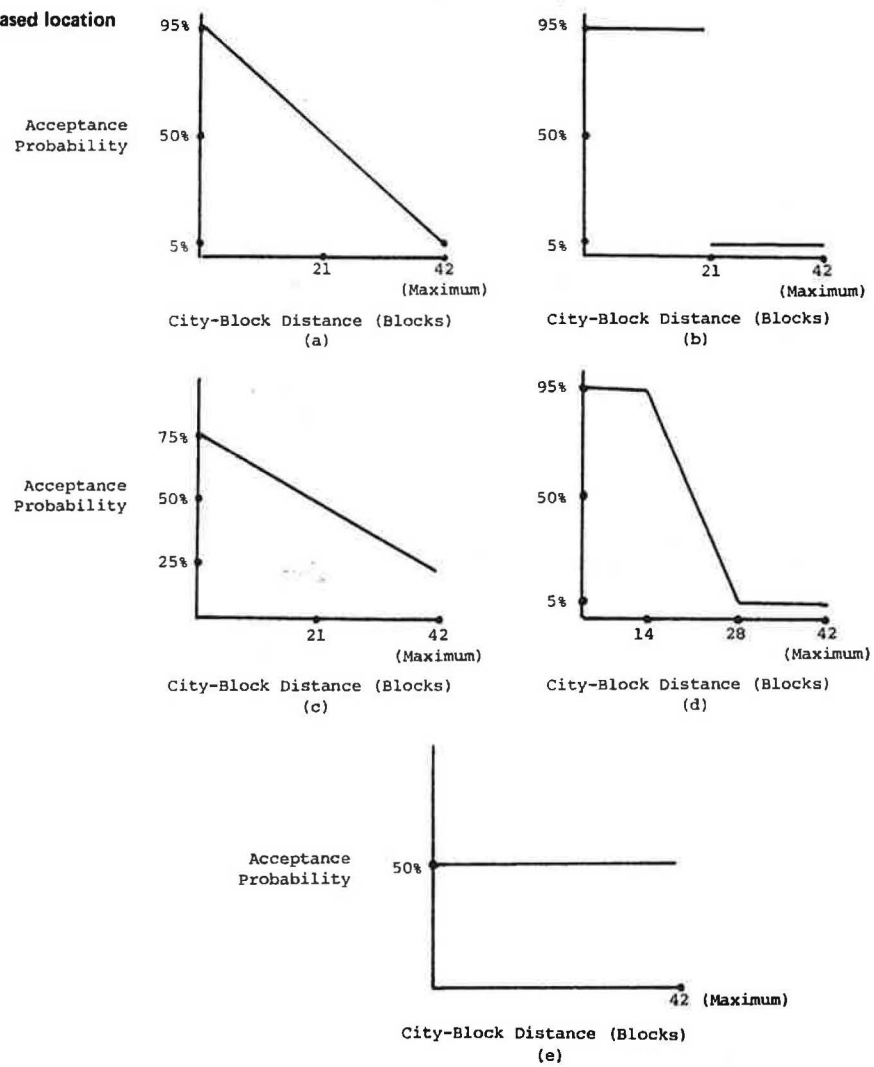


Table 1. Means and variances of home-to-work distance distribution for various location choice functions.

Item	Choice Function a	b	c	d	e	Concentrated Initial Assignment	Uniform Initial Assignment
Mean	15.89	12.86	17.26	13.33	18.92	11.25	19.00
Variance	74.18	35.79	85.86	42.99	94.14	21.49	93.68

Table 2. Frequency distribution of the number of residential locations containing N workers at the first job center for various location choice functions.

N	Choice Function a	b	c	d	e	Concentrated Initial Assignment	Uniform Initial Assignment
10	16	187	2	109	2	381	0
9	38	109	28	116	4	100	0
8	88	54	48	78	37	17	0
7	129	46	109	77	102	2	0
6	137	72	183	73	195	0	0
5	145	65	200	77	242	0	854
4	129	44	183	72	229	0	134
3	130	44	125	65	122	0	12
2	108	26	103	68	49	0	0
1	63	120	14	112	13	0	0
0	17	233	5	153	5	500	0

cated new town planning strategy of minimizing home-to-work distance.

The effects of alternative assumptions about the importance of accessibility in the location choice process can be examined by changing the accessibility-based location choice function. Five alternative functions, which are represented graphically in Figure 3, were examined. The dimensions of the array, the density distribution of dwelling units, and the number, size, and location of job centers were the same as in the previous sets of experiments. All experiments were the result of generating the equilibrium initial pattern.

The mean probability of acceptance, unweighted by the number of opportunities at each distance, is one-half for all alternative functions. However, the unweighted variances differ substantially. Conceptually, the alternative functions allow accessibility and other factors represented by the probabilistic nature of the functions to have varying importance. For example, function (e) in Figure 3 is consistent with the hypothesis that accessibility is of no importance. On the other hand, function (b) represents a situation where accessibility is crucial, i.e., close locations are accepted with near certainty and further locations are rejected, also with near certainty. Function (b) also represents the case in which decisions are made with respect to a maximum accessibility threshold.

Tables 1 and 2 present data that summarize the results of the experiments according to the choice functions a-e in Figure 3. The first table presents the first and second moments of the home-to-work distance distribution for the urban area, while the second table lists the frequency distributions of the concentration of workers at the first job center over the 1000 residential locations. In addition, both tables contain the corresponding information for the concentrated and uniform initial patterns used in the previous set of experiments. These latter results delimit the range of possibilities; i.e., the concentrated pattern has accessibility as totally deterministic, while the uniform pattern is essentially independent of accessibility considerations.

Qualitatively, the results in the tables are not surprising. The most important accessibility is in the location choice function, the shorter the average home-to-work distance. Further, great importance assigned to accessibility appears to result in small variations around the average distance and, consequently, more homogeneity within individual residential locations. That is, Table 2 shows that the functions that correspond to greater emphasis on accessibility (b, d, concentrated) lead to situations where a large majority of residential locations have most of their workers at a single job center. Conversely, the remaining functions (a, c, e, uniform) yield more heterogeneous results. That is, the majority of residential locations have a fairly even distribution of workers at the two job centers.

Preliminary investigation using the results of these and other experiments indicates that these qualitative findings can be strengthened by relating input parameters to model outputs. For example, there appears to be a strong linear relationship between the unweighted second moment of the location choice function and the second moment of the home-to-work distance distribution. Verification of this relationship and further attempts to relate other inputs and outputs in a rigorous fashion are an important component of future work and will be instrumental in demonstrating the ultimate potential of the methodological approach.

SUMMARY AND CONCLUSIONS

The simulation methodology just described has the potential for yielding insights into the manner in which household choice processes and the locations of spatial opportunities result in patterns of home-to-work linkages. Current results are preliminary and await further research that will define relationships between model inputs and outputs more rigorously.

The modeling system is intentionally abstract. Consequently, it is not appropriate for examining the effects of a wide range of urban policies, such as policies involving housing and/or particular subgroups of the population. In addition, since the model does not necessarily represent any particular urban area, the conclusions that do emerge from particular types of experiments are likely to be general in nature.

These limitations contribute to the particular strength of the methodology, however. Rather than applying to only one particular urban area, as do most more detailed models, the current methodology allows the quick examination of conditions for a wide range of actual or potential urban systems. Consequently, any general findings are more likely to describe the class of urban systems rather than a particular urban area. In this way, the approach lies between the two major approaches used in previous studies of location choice. That is, rather than attempting to study particular location choice behavioral processes on the one hand or attempting to describe spatial regularity at an aggregate level on the other, this methodology has the potential for examining, in detail, the consequences of location behavior on the nature of urban systems in general.

Despite the abstract nature of the methodology, the existing model has been developed with careful attention to existing knowledge. This is reflected in the dynamic capabilities of the model, in the separation of the location choice process into the decision to move and search and select components, in the division of mobility decisions into job change and residence change and simultaneous change components, and in the fact that the loca-

tion choice function contains both accessibility and other factors subsumed under the random component of the function.

These four features allow a wide range of tests of competing hypotheses. In addition, the existing model can easily be changed to incorporate other hypotheses. For example, the dimensions of the urban area may expand over time, representing growth. Experiments of this nature have already been performed. Similarly, a simultaneous decision process among a number of alternative locations instead of the sequential binary process of acceptance or rejection in the current model can be easily represented within the simulation structure.

Since the model is abstract, it will ultimately be necessary to determine the extent to which it offers insights into real urban systems. At one extreme it may be only the mathematical system represented by the computer code, and at the other extreme it may be adapted to offer insights into particular urban areas. Preliminary evidence indicates that the model does, indeed, result in a reasonable representation of particular areas as indicated by a comparison of empirical and model home-to-work distance distributions (34).

In conclusion, a methodology has been developed that has the potential for yielding insights into the equilibrium and dynamic properties of urban systems. Such insights will be useful in identifying the extent to which the outcomes of planning decisions, such as the location of employment centers and transportation facilities, are constrained by household choice behavior and also by the reciprocal constraints of the existing urban opportunity structure on household choice.

ACKNOWLEDGMENTS

Research for this paper was supported in part by a National Science Foundation grant on research initiation and urban structure and transportation requirements. Additional support was received from the Rockefeller Fund in Environmental Studies at the University of California, Davis.

REFERENCES

1. W. Goldner. The Lowry Model Heritage. American Institute of Planners Journal, Vol. 37, 1971, pp. 100-110.
2. W. G. Hansen. How Accessibility Shapes Land Use. American Institute of Planners Journal, Vol. 25, 1959, pp. 73-76.
3. T. R. Lakshmanan and W. G. Hansen. A Retail Potential Model. American Institute of Planners Journal, Vol. 31, 1965, pp. 134-143.
4. I. S. Lowry. Seven Models of Urban Development: A Structural Comparison. HRB, Special Rept. 97, 1967, pp. 121-146.
5. G. T. Lathrop and J. R. Hamburg. An Opportunity-Accessibility Model for Allocating Regional Growth. American Institute of Planners Journal, Vol. 31, 1965, pp. 95-102.
6. S. A. Stouffer. Intervening Opportunities and Competing Migrants. Journal of Regional Science, Vol. 2, 1960, pp. 1-26.
7. S. R. Lerman. Location, Housing, Automobile Ownership, and Mode to Work: A Joint Choice Model. TRB, Transportation Research Record 610, 1976, pp. 6-11.
8. L. A. Brown, F. E. Horton, and R. I. Wittick. On Place Utility and the Normative Allocation of Intraurban Migrants. Demography, Vol. 7, 1970, pp. 173-183.
9. W. A. V. Clark. Measurement and Explanation in Intraurban Residential Mobility. Tijdschrift voor Economiste en Sociale Geografie, Vol. 61, 1970, pp. 49-57.
10. E. W. Butler, F. S. Chapin, Jr., G. C. Hemmens, E. J. Kaiser, M. A. Stegman, and S. F. Weiss. Moving Behavior and Residential Choice. NCHRP, Rept. 81, 1969.
11. G. Duncan and S. Newman. People as Planners: The Fulfillment of Residential Mobility Expectations. In Five Thousand American Families - Patterns of Economic Progress (G. J. Duncan and J. N. Morgan, eds.), Institute for Social Research, Ann Arbor, Vol. 3, 1975.
12. J. B. Lansing, E. Mueller, and N. Barth. Residential Location and Urban Mobility. Survey Research Center, Univ. of Michigan, 1964.
13. E. Roistacher. Residential Mobility: Planners, Movers, and Multiple Movers. In Five Thousand American Families - Patterns of Economic Progress (G. J. Duncan and J. N. Morgan, eds.), Institute for Social Research, Ann Arbor, 1975.
14. H. J. Brown. Changes in Workplace and Residential Location. American Institute of Planners Journal, Vol. 41, 1975, pp. 32-39.
15. O. Hochma, G. Fishelson, and D. Pines. Intraurban Spatial Association Between Places of Work and Places of Residence. Environment and Planning, Vol. 7, 1975, pp. 273-278.
16. G. K. Ingram, J. F. Kain, and J. R. Ginn. The Detroit Prototype of the NBER Urban Simulation Model. National Bureau of Economic Research, New York, 1972.
17. R. P. Mason. ASMUG—Simulation Model of Urban Growth. ASCE, Journal of the Urban Planning and Development Division, Vol. 103, 1977, pp. 13-25.
18. L. A. Brown and E. G. Moore. The Intraurban Migration Process: A Perspective. Geografiska Annaler, Vol. 52, Series B, 1970, pp. 1-13.
19. J. Wolpert. Behavioral Aspects of the Decision to Migrate. Papers of the Regional Science Association, Vol. 15, 1965, pp. 159-169.
20. B. Harsman and F. Snickars. Disaggregated Housing Demand Models: Some Theoretical Approaches. Papers of the Regional Science Association, Vol. 34, 1975, pp. 121-143.
21. J. D. Herbert and B. H. Stevens. A Model for the Distribution of Residential Activities in Urban Areas. Journal of Regional Science, Vol. 2, 1960, pp. 21-36.
22. J. Berechman. A Design Model for Optional Land Use Activity Allocation. Paper presented at the Meetings of the Operations Research Society of America, Las Vegas, Nov. 1975.
23. P. Gordon and W. K. MacReynolds. Optimal Urban Forms. Journal of Regional Science, Vol. 14, 1974, pp. 217-231.
24. G. C. Hemmens. Experiments in Urban Form and Structure. HRB, Highway Research Record 207, 1967, pp. 32-42.
25. J. L. Edwards and J. L. Schofer. Relationships Between Transportation Energy Consumption and Urban Structure: Results of Simulation Studies. TRB, Transportation Research Record 599, 1976, pp. 52-59.
26. A. G. Wilson. The Use of Entropy Maximizing Models. Journal of Transport Economics and Policy, Vol. 3, 1969, pp. 108-126.
27. W. Alonso. Location and Land Use. Harvard Univ. Press, Cambridge, MA, 1964.
28. M. E. Beeseley and M. Q. Dalvi. Spatial Equilibrium and Journey to Work. Journal of Transport Economics and Policy, Vol. 8, 1974, pp. 197-222.

29. J. Siegal. Intermetropolitan Migration: A Simultaneous Model of Employment and Residential Location of White and Black Households. Journal of Urban Economics, Vol. 2, 1975, pp. 29-47.
30. M. L. Senior. Approaches to Residential Location Modeling 1: Urban Ecological and Spatial Interaction Models (A Review). Environment and Planning, Vol. 5, 1973, pp. 165-197.
31. P. A. Morrison. Movers and Stayers: An Analysis Based on Two Longitudinal Data Files. Rand Corp. Paper P-4409, 1970.
32. A. Okabe. Formulation of the Intervening Opportunities Model for Housing Location Choice Behavior. Journal of Regional Science, Vol. 17, 1977, pp. 31-40.
33. T. Lam, B. Odell, and T. Tardiff. A Stochastic Model of Residential Mobility and Urban Structure. Proc., 1975 ICS Winter Simulation Conference, 1976, pp. 631-637.
34. T. N. Lam and T. J. Tardiff. Urban Structure and Transportation Requirements. Proc., 1978 ICS Summer Simulation Conference, 1978, in press.

Publication of this paper sponsored by Committee on Passenger Travel Demand Forecasting and Committee on Traveler Behavior and Values.

Spatial Aggregation of Disaggregate Choice Models: Areawide Urban Travel Demand Sketch-Planning Model

Thawat Watanatada, International Bank for Reconstruction and Development, Washington, D.C.
Moshe E. Ben-Akiva, Center for Transportation Studies, Massachusetts Institute of Technology, Cambridge

This paper describes an aggregate urban travel demand model designed for areawide transportation policy evaluation with limited preparation of input data and fast response times. It does not include supply models but it can be used by itself for travel demand predictions with exogenously specified transportation level-of-service changes or it can be incorporated in the framework of the TRANS model. The methodology is generally applicable to urban transportation sketch-planning situations in which large geographic units are used. Aggregation is performed over spatial travel alternatives and spatially distributed individuals to produce required aggregate travel demand forecasts. An efficient solution method for spatial aggregation was developed that employs mathematical functions, expressed in terms of coordinates in the urban space, to describe the spatial choice process and to represent the geographic distribution of behavioral units, spatial alternatives, level-of-service characteristics, and locational attributes. This allows the spatial aggregation problem to be solved efficiently, by integrating the travel demand models over the urbanized area. Monte Carlo simulation techniques are employed and the procedure entails (a) generation of a sample of representative households distributed over the urban area using available census data, (b) generation of a sample of destinations for each trip purpose for each household, (c) computation of travel demand forecasts for each household based on the sampled destinations using a system of disaggregate travel demand models, and (d) accumulation and expansion of disaggregate predictions to produce aggregate forecasts.

This paper describes the methodology and application of an aggregate model of urban travel behavior. The model is designed to be applied at a high level of geographic aggregation—the entire urban area—for quick assessment of urban transportation policies. The underlying methodology is applicable to a wider range of sketch-planning analyses that are characterized by the use of readily available input data (for example, from the U.S. Census) and fast response times. These features are essential for a successful integration of technical analysis and transportation decision-making processes.

Typically, the travel demand models employed in existing sketch-planning packages offer little policy sensitivity and require separate calibration for different levels of spatial aggregation or zone sizes.

The basic premise of this study is that the use of disaggregate travel behavior models (1, 2, 3, 4) in sketch-planning applications with appropriate aggregation procedures would remove these shortcomings. Although disaggregate choice models have many advantages over conventional aggregate travel demand models in general, their distinct advantages from the sketch-planning standpoint are that once estimated they can be applied to any desired level of geographic aggregation and that they have the potential of being transferred from one urban area to another.

The aggregate demand model developed in this study represents an extreme level of spatial aggregation since it treats an entire urban area as a single analysis unit. It is suited to metropolitan transportation planning studies in which impacts on specific areas are not required. When incorporated into a complete supply-and-demand analysis system, it can be used to determine scale and composition of transportation investments on an areawide basis, involving approximate funding allocations to modes and facility types, to construction and maintenance expenditures, etc. It can also be used to analyze aggregate impacts of pricing and operating policies such as fuel price change, parking cost surcharge, and areawide transit improvements.

The model can be used in the framework of the multimodal national urban transportation policy planning model