TRANSPORTATION CENTER

"A Rationale for an Alternative Mathematical Paradigm for Movement as Complex Human Behavior"

NORTHWESTERN UNIVERSITY EVANSTON • ILLINOIS

"A Rationale for an Alternative Mathematical Paradigm for Movement as Complex Human Behavior"

Pat Burnett
Department of Geography
and Transportation Center
Northwestern University
Evanston, Illinois 60201

Susan Hanson
Department of Geography
Middlebury College
Middlebury, Vermont 05753

Paper submitted for presentation and publication, Transportation Research Board Meetings, Washington, D.C., January, 1979.

August 9, 1978

ABSTRACT

This paper contains arguments and data analysis to support a new mathematical approach for the study of movement, particularly intra-urban travel. The first section criticizes current disaggregate models of movement, on the grounds of their unrealistic axioms about: the simplicity of human behavior incorporated in the conceptualization of the dependent variable, a trip; the 'constancy', 'ad hoc' differences or 'random variability' of choice sets between persons; and the complexity of decision rules in notions about how utilities are formed and maximized. Some new arguments are advanced concerning scientific and societal needs for more realistic approaches to movement, and thus for inductive data analysis to specify new explanatory-descriptive probabilistic choice models with more accurate assumptions, and thence a consistent underlying micro-economic theory of demand with more plausible axioms for the ultimate derivation of improved analytic models of travel behavior. Sections two, three and four of the paper contain data analysis to demonstrate that reconceptualizing movement as more complex, choice sets as more systematically limited, and decision strategies as simpler than currently conceived - hypotheses can be formulated which fit standard kinds of travel data as well as current models with different, less realistic assumptions. This paves the way for the further development of the alternative paradigm proposed here for studying movement as complex human behavior.

1. General Argument

1.1 Background

Since the early 1970's, one focus of work on movement in the United States and Europe has been the development of disaggregate models of intra-urban travel. (See, for example, Stopher and Meyburg, 1976; Charles River Associates, 1976; Jones, 1976; Brog et al, 1977; Fried et al, 1977; Pred, 1977; Adler and Ben-Akiva, 1978; Burnett, 1978(b); Heggie and Jones, 1978). Logit and probit models now are especially in widespread use to predict, inter alia, the choices of the route, mode, activity, destination and timing of trips by different, often 'socioeconomically homogeneous', population groups. These models, like many other models of movement (e.g. Smith, 1975), are derivable from extensions of utility theory, especially from neo-classical microeconomic approaches to consumer demand (e.g. Stopher and Meyburg, 1976). The general claim has been that a better understanding of individual and group movement has been obtained by these theoretical and modeling developments and that consequently a firm base now exists for their application, if desired, in most planning contexts.

Recently, however, some concerns have arisen which have caused this claim to be reevaluated, and more attention to be paid to defining precisely those kinds of questions for which current models might be appropriate (e.g. Heggie and Jones, 1978). A number of workers in Europe and the U.S.A. have especially criticized current utility-theory based models of movement, and have questioned their general applicability. It has been asserted that:

(1) They are far from providing a realistic description or explanation of the group movement which they attempt to predict, since they ignore decisions concerning the complete sequencing of a household member's activities over space and through time during a given decision period (perhaps a day); these decisions are clearly intimately connected with observed selections of modes, destinations, etc. (Westelius, 1973; Hensher, 1975; Hanson, 1977; Jones, 1977; Burnett, 1978(b));

(2) They assume that a limited set of designated socioeconomic characteristics of individuals (e.g. income) and the characteristics of options (e.g. the convenience of alternative modes or destinations) are the major determinants of the demand for travel; they thus underemphasize and do not explore explicitly the relative contributions of many other possibly important variables, especially those spatial and temporal variables beyond the individual's control (institutional variables), which influence the availability of travel options (e.g. the locations and hours of business of many different kinds of urban land use) (Burnett, 1978(a),(b));

(3) They generally assume each individual has very complex sets of choices (e.g. choice sets containing at least two alternatives for choices of modes, destinations, activities, trip timing, etc.), whereas there may be many instances where

individuals have limited kinds of choices and a very limited number of alternatives in their choice sets, to the extreme of no choice or missing preferred choices and alternatives, because of spatial, temporal and other constraints on movement (e.g. no bus close enough at the right time for a viable mode choice) (Brog, et al, 1976; Burnett, 1978(a), (b));

(4) Many individuals may not form, manipulate and maximize utilities in the precise and complicated ways specified by current models, at least for simple routinizable behaviors like travel (Fried et al, 1977; Burnett, 1978 (b)).

The criticism of these unrealistic assumptions of current mathematical models of movement, and incidentally of parallel assumptions in their underlying theory base in micro-economics, seems well-founded from several points of view. First, there is the general, well-accepted, though perhaps somewhat purist argument, that no matter how well any theory or model predicts or forecasts, a better alternative will always be one which predicts or forecasts as well and which incorporates 'more realistic' assumptions. This argument of course guides research in any field towards the development of increasingly more realistic theory containing increasingly more information about the realm with which it deals, although in the developmental stages the predictive/forecasting power of any new 'more realistic' theory might be low.

A second and more pragmatic argument stems from present differences in application of theories and models in the social sciences as distinct from theories and models in other fields, especially the physical sciences. This important point can be elaborated as follows. It is a truism that social systems, including cities and their movement patterns as systems, are dynamic. Major decisions in both public and private sectors can therefore be, and now often are, in an age of social and economic problems and crises, directed towards altering current system trends through changing the behaviors of component populations. A trite but not trivial example is energy conservation and other policies directed toward the alteration of urban mode-choice behavior. For these increasingly common and important kinds of action of the late seventies, directed not so much towards accommodating but towards modifying collective human behaviors in cities, it seems imperative to identify correctly the causes of, and the decision mechanisms behind, individual behaviors. For example, in order to alter the way preferences are formed for busses vs. cars for energy policy, such as through transit-marketing or gas-pricing strategies, it is well-accepted that we need to know exactly what attributes of busses and cars govern preference and choice and how. Since social science theories and models are often now to be used to impact and alter the behavioral process of the individual and through this the collective actions of human population groups, there is a growing requirement that the axioms or assumptions of such models be 'accurate' or 'realistic', and that such axioms or assumptions be 'correctly' related causally to behaviors. The requirements of many theories or models in the social sciences, including models of movement, then, are now diverging from the requirements for theories and models in other sciences. In the physical sciences, whose approach to methodology was at first borrowed by social sciences, more often than not, the realism of assumptions has not been a major issue (if it is an issue at all) since accommodation to, rather than radical modification of, the behavioral principles of the system under study is implicity assumed appropriate. Thus the major and often the only requirement of a model or theory is that it predicts the aggregate behavior of the system well over some forecasting period, assuming that it is to continue operating in current ways. Such an instrumentalist approach, of course always but one of many to scientific procedure, is, as we have argued, no longer suitable for much social scientific research, including research on movement.

Both the preceding kinds of argument for necessarily having more realistic assumptions in theories and models for movement are different from the standard argument originally advanced for developing models with behavioral assumptions in the late sixties and early seventies. The original rationale for disaggregate models of movement seems to have been that by incorporating accurate assumptions about individual behavior, theories and models would predict better. Though this argument still holds, of course, both the preceding ones which we have advanced seem now to make the strongest case for still more realistic approaches to the study of movement to meet either scientific or political requirements or both. Consequently, the demand for new models of movement without any of the key unrealistic assumptions of present ones is well-founded.

A number of approaches to develop such new models seem possible at this point. First, there is the possibility of exploring successive modifications to existing models, such as those of the logit and probit variety, with the goal of improving the predictive accuracy of them by modifying one or another unrealistic assumption (e.g. Adler and Ben-Akiva, 1978; Williams and Thrift, 1978; Wermuth, 1978). Since such models are basically used for forecasting urban travel flows in the aggregate, on the assumption that - once identified through, say, a set of coefficients linking travel to significant independent variables - current patterns of behavior and decision processes will continue at least in the immediate future, this approach can be used to furnish 'better numbers' for ongoing highway and transit investment decisions which must be taken now. Second, there is the possibility of developing models or similar devices which will explore realistically individual and group responses to some specific policies at the local level, designed to impact on specific types of behavior (e.g. to explore the effects of staggering work hours or changing school hours on travel and congestion in a suburban city). The Household Activity-Travel Simulator developed at TSU Oxford is one such device for opening this avenue of research (Dix, 1977; Jones, 1977; Heggie, 1977). This kind of work meets immediate policy needs, especially planning agency needs, for investigating how to modify behavior and to examine and evaluate the outcome of such modifications, without necessarily estimating 'numbers' of persons making different kinds of changes, at least in the short term. Such research appears better oriented towards some of the new requirements of models of movement than simpler and earlier macro-scale forecasting approaches.

Finally, however, there remains a need for research to explore the development of new mathematical models of movement, and a consistent, revised, underlying general economic theory of consumer demand, without any of the unrealistic assumptions noted earlier. Here the emphasis at the moment should be not on the predictive/forecasting accuracy of the models or theory produced, or on immediate policy application at local levels, but rather on the rewriting of basic theory and related models in a rigorous mathematical fashion. The aim is to provide, for the long term, the basis for more accurately specifying and predicting the effects of any political actions about movement-related social problems (congestion, land use, energy, pollution, unequal access to urban resources by minorities, women, the elderly and the poor) directed towards modifying the processes behind patterns of human behavior in urban environments. By rewriting more realistically the underlying micro-economic theory used to derive models of human responses to any transportation-related political action, the generic basis of many kinds of policy can be identified and their interrelations explored. This will supplement 'piecemeal' or ' 'problem-by-problem' approaches to urban systems, where interdependency of components and problems seem likely. The rewritten theory base to cope with the dynamics of urban areas should also provide for political and social action designed for the longer run welfare of society, rather than being simply confined to meeting the immediate demands of policymakers. All this does not, of course, deny the urgency also of developing present or other models of movement to meet immediate urban transportation needs. This paper, however, outlines how new, considerably more realistic models of movement and a consistent underlying micro-economic theory base might be developed, and presents some data analysis to substantiate the main thrust of the argument.

1.2 Identification of Key Assumptions in an Inductive Approach to Model and Theory Revision

Since any new models of movement are primarily to incorporate realistic assumptions or axioms, it seems appropriate to replace the standard deductive-analytic approach with an inductive-explanatory approach to modeling now, despite all the well-known limitations of inductive data-analytic work. Data analysis will be used throughout future research, first to investigate how current models of movement may be misspecified through the use of unrealistic assumptions, and then to specify how a more realistic explanatory-descriptive model of travel behavior for individuals and population groups may be developed in mathematical terms. At a later point an attempt will be made to use the insights gained through reformulating models of movement in this way to rewrite the deductive analytic micro-economic theory base of current models of movement, through incorporating more realistic axioms about behavior. From this rewritten theory base in turn, it is eventually hoped that most rigorous and accurate deductive analytic models of travel may again be derived. This process of development assures not only that the axioms of any new models will be realistic, but also that they will be consistent with a new general micro-economic theory of demand.

The general goal of rewriting the underlying theory base guides the choice of specific axioms for revision in future research. Such axioms are not only those which a synthesis of current work in the literature on movement suggests as the most urgent in need of revision, but also comprise important general axioms of micro-economic theory. Since a detailed review of the travel literature concerning these axioms and a critical discussion and evaluation of them is already available elsewhere (Burnett, 1978(b)) only a summary statement of the axioms selected is provided here.

The three principal assumptions on which attention is focussed are:

(1) The assumption that the individual and collective behavior to be explained or predicted by any theory or model is simple, not complex; for example, in models of movement, the behavior to be explained/predicted has generally been assumed to be a trip, where a trip is a single movement by an individual from one stop (base, place) to another;

(2) The assumption that the individual behaves by making a choice from a set of alternatives, where the set always contains at the very least two (and usually 'many') alternatives for each individual, and where the set is either constant between individuals or varies in some arbitrary 'ad hoc' or in some random fashion between them; this assumption clearly is incorporated in both the standard strict and random utility versions of the multinomial logit model, (for example Stopher and Meyburg, 1976) (We call this the 'constant choice set axiom');

(3) The assumption that the individual's decision-making is extremely complex and that all individuals in a population make decisions in an identical way in all situations; this assumption is incorporated into travel demand models through utility-maximizing decision rules for all kinds of travel choices; these rules describe the ways utilities are formed and combined and alternatives are evaluated in a choice set by an individual (it will be noted that the utility manipulations by individuals in sequential and simultaneous travel choice models (Ben-Akiva, 1978; McFadden, 1978) assume almost heroic mental dexterity).

Our ongoing research therefore has three major goals, which it is the task of this paper to justify. The first goal is to investigate behavior as a complex phenomenon in reality, and, in particular, here, to explore the mathematical reconceptualization and measurement of the individual's movement as a complex not simple phenomenon. The second goal is to develop a causal model of the choice set for the individual, assigning probabilities to any alternative being included in the individual's set. The importance of this will be further discussed in a moment. The third goal is to identify the alternative, simpler, decision strategies which different individuals might use to select alternatives in different situations, and to attempt to develop mathematical choice models for them; this follows from recent advances in choice theory in psychology which emphasize the variability of decision strategies between individuals and between different situations (Slovic, Fischoff and Lichtenstein, 1977).

In sum, our research is directed towards using data analysis to specify an explanatory-descriptive model for the individual and thence for appropriate population groups of the general form:

$$P_j = (P_j \varepsilon A) \cdot (P_j | j \varepsilon A) \quad \ldots . \quad I$$

where

j = the individual's complex travel behavior (to be defined);

A = the choice set of alternatives from within which j is selected, for the individual;

$P(j \in A)$ = a causal model assigning alternatives to the choice set, for the individual;

$P(j \mid j \in A)$ = the appropriate decision strategy for the selection of the behavior, assuming there is more than one alternative possible behavior in the choice set for the individual. (At the moment, of course, as a first pass, Equation I ignores possible complex interdependencies between its different terms)

The second goal of the research and the related development of the model for the individual's choice set in Equation I is regarded as the most important. Inquiring into the determinants of the individual's choice set now has a relatively long though spasmodic history; however, as yet, no satisfactory model of choice set formation has been developed. Over a decade ago, North American geographers investigated the relations between the individual's opportunity set for spatial choice (all his/her spatial alternatives in a city), his/her cognitive opportunity set (known alternatives), and his/her choice set (all those alternatives ever used) (Marble and Bowlby, 1968; Hanson, 1973). So-called 'choice set generation' problems were also further discussed in the mid seventies in U.S.A. in connection with spatial choice modeling by both geographers and engineers

(Burnett, 1973, 1976; Lerman and Adler, 1976) and latterly also in connection with mode choice (Tardiff, 1976; Recker and Stevens, 1977). Independently, workers in Europe (Westelius, 1973; Lenntorp, 1976; Brog et al, 1976; Jones, 1976; Heggie, 1977; Dix, 1977; Wermuth, 1978) began inquiring into the ways in which many possible variables (constraints) limited the number of alternatives which individuals have for any decisions, in many cases reducing them to one. At the moment, not much is known concerning the nature, the number and especially the relative importance of the many variables now postulated to form the choice sets for different individuals making different decisions in different situations.

Recent European work emphasizes the relative significance of institutional constraints, that is, constraints on the content of the individual choice set placed as a result of organizational or collective decisions operating through the institutions of any advanced urban industrial society (government, corporate enterprise, even the social expectations of economic classes concerning roles); such constraints are often expressed and encountered by the individual in the form of the detailed spatial distributions of activities (residences, work places, shops) and their scheduling within the city (urban space-time constraints). Such constraints need detailed definition and measurement for large population groups for all kinds of travel decision, and their relative significance vis-a-vis variables more under the individual's control in forming choice sets (e.g. time and money budgets) needs to be assessed for different kinds of individual and population groups. The development of a causal model of the individual's choice set using comparable sociodemographic, travel diary and geocoded land use data sets for a number of European and American cities will entail answering this question.

The development of a causal model of the individual's choice set will not only help answer some basic scientific questions but also, if desired, have some immediate policy implications. The investigation of the relative importance of institutional versus personal constraints in a causal choice set formation model and their relation to movement will indicate those individuals and population groups whose behaviors are determined largely by institutional constraints on choices and are hence better impacted through government intervention aimed at changing urban spatial and temporal organization (e.g. mode-switch changes engendered through controls on residential densities and proximities to transit lines). Alternatively, the development of a choice set formation model in the fashion indicated could also suggest for which individuals and population groups behavior could perhaps be better modified through strategies relying on alterations by the individual of his/her behavior through changes in time or money budgets (personal constraints).

Finally, from the perspective not of policy but of the long term development of theory, exploration of causal choice set formation models for the individual, as outlined here, could permit the explicit incorporation in micro-economy theory of precise statements about the connections between institutional behaviors (social decision-making at the macro level) and observable individual behavior, like travel, at the micro level, through intervening variables defining the space-time structure of the modern metropolis. In the present admittedly simple view, institutions create the distributions of activities in space and time which form the tangible day-to-day environment of the human being; these distributions help form choice sets for individuals, which in turn circumscribe the possibilities for their behavior and help explain and predict it. Although, of course, this may not be the only way in which institutions affect individual behavior, and although the operation of institutions through urban space-time constraints may not be relevant for all individuals in all decision situations, current research has indicated that these might be fruitful relations to explore. A revised micro-economic theory base could draw on descriptive choice set formation models like the one proposed here to provide, hopefully, for a more rigorous treatment of the impacts on individuals and groups of political and other collective actions primarily directed towards changing institutions (e.g. changing the housing market; changing the hiring practices of different kinds of firms in different kinds of location; changing social roles reflected in changing life-styles).

Current micro-economic theory assumes unchanging institutions with unidentifiable links to individual choice sets, which especially is revealed in the 'constant choice set axiom' of the models of movement derived from it and outlined above. It thus permits neither a satisfactory realistic explanation of behavior, including travel behavior; nor precise statements of the differential impacts of institutional changes on individuals and groups in deductive models like the logit; nor the possibility of planning for the radical social, economic and environmental transformations which urban systems will and should still undergo.

Against this grand perspective, the tasks of the remainder of this paper appear somewhat limited. We conduct some preliminary data analysis to substantiate some key alternative assumptions for future model and theory development, namely, that the individual's behavior is complex, that choice sets are highly restrictive and vary in a systematic way between persons, and that decision strategies are simpler than commonly conceived. The data analysis hopefully paves the way for developing an explanatory-descriptive elaboration of Equation I in mathematical terms, and thus for rewriting the economic theory base for more rigorous and insightful models of movement in the ways described above.

The following sections of the paper are therefore devoted firstly, to demonstrating that a sample of daily travel dairies for individuals from six homogeneous socioeconomic groups are well described by a mathematical reconceptualization of the individual's travel as a path in n-dimensional space; and secondly, that the same travel data is also well explained by some hypotheses, implied by the reconceptualization, which assume far more restrictive choice sets for the individual than hitherto considered and also assume much simpler decision rules. The degree of systematic variation between different groups of individuals in behaviors, choice sets and decision rules is also explored. The objective of this is to indicate that models based on the new axioms about individual decision mechanisms and choice sets might be used to provide accurate statements about group behaviors using segmentation and aggregation approaches already familiar in disaggregate modeling. The paper concludes with a discussion of possible procedures whereby the complex movement of the individual, as reconceptualized here, may be statistically measured and classified. Some of the procedures mentioned are far less complex than classification procedures already familiar in the disaggregate behavioral modeling literature (e.g. Dobson and Kehoe, 1975). Since some research indicative of the usefulness of these procedures has already been carried out in previous work by one of the authors of this paper (Hanson and Marble, 1968), this final section draws on existing expertise in the area to counteract the immediately apparent and major objection to our approach, namely, its vulnerability to the charge that redefining the principal variable of models of movement, the dependent variable, travel itself, in a very much more complex fashion, will at once lead to intractable modeling problems. The thrust of the thinking in the remainder of this paper is that, since alternative mathematical formulations, such as the nested logit, are also fitted acceptably to the same kinds of data used here, and these models can be argued to rest on less realistic key assumptions, preliminary evidence is provided by our analysis for extending new modeling and theoretical research in the directions outlined above.

2. A MATHEMATICAL RECONCEPTUALIZATION OF MOVEMENT AS COMPLEX HUMAN BEHAVIOR

2.1 Travel as a Path in n-Dimensional Space

The dominant tendency in both aggregative and disaggregative approaches to modeling movement has been to consider "the trip" as a link between two stops (bases or destinations), and then to consider purpose, frequency, mode, time of day and destination to be the principal "choices" which the individual confronts for the conduct of each trip. The trip is therefore theoretically the unit of (derived) demand, though there are many varieties of trips from which to choose (by auto or bus for example, or for shopping or work). One of the conceptual problems of treating movement as a complex rather than a simple phenomenon, that is, with departing from the simple notion of a trip as the unit of demand, is thus to reconsider what it is that individuals demand (admittedly indirectly) when they travel. In this section, we briefly review the literature on travellers' complex behaviors and then use data to document how individuals conduct their travel in reality as a much more complex phenomenon than hitherto conceived; in Section 3 we consider, in addition to the larger questions raised earlier in this paper, some of the implications of considering behavior in this way for defining the entities which individuals demand in movement. This clearly assists with the appropriate redefinition of the L.H.S. term of Equation I and with rewriting the underlying micro-economic theory base of models of movement.

Geographers early conceptualized travel as home-to-home circuits (e.g. Marble, 1959), and divided movement by individuals into single-purpose (simple trip) and multiple-purpose (complex trip) travel (Nystuen, 1959; Curry, 1962). They then attempted to study the linkages (chaining) of stops which occurred on multiple-purpose travel. Considerable emphasis was put on the statistical analysis of longitudinal travel data for individuals, in order to define as rigorously and as objectively as possible the kinds of multiple-purpose trip which persons in cities tend to make (Nystuen, 1959 and 1967; Marble, 1967). One work by Hanson and Marble in 1969, for example, contains sophisticated statistical manipulations of a flow matrix of travel linkages between land use types. This approach enables some repetitive patterns in the activity linkages of a sample of individuals to be objectively determined. Patterns in the linkages of other aspects of trips (such as the linkage of modes in successive trips), were not, however, investigated. The contribution of this kind of data analytic approach for present purposes is its emphasis on the following: that the individual's travel represents movement through time and over urban space on an extended series of stops; that such complex behavior can be conceptualized and analyzed using mathematical procedures; and that patterns or regularities in the complex behaviors of individuals can be objectively identified, comprising systematic behaviors which should therefore be susceptible to scientific explanation by modeling and theory development (see also Hanson, 1977).

Apparently independently, in the middle of the seventies, as work in the disaggregate modeling of spatial choice (destination choice) progressed outside geography, the question of the linking of trips by individuals, and especially of 'non-work' trips, became important. The notions appeared of trip "chains", "journeys", "tours", "travel patterns" (Spear, 1976; Adler and Ben-Akiva, 1977), which elaborated on the earlier conceptualization of movement by geographers as "trip linkages" and "multiple-purpose travel" on a home-to-home circuit. The appearance of the later concepts of "tours" etc. revealed a recognition that movement in fact is a linking of trips by individuals in sequence over space and time, but one which implies not only trip destination, but also activity (purpose), mode, timing and other linkages as well (see "travel patterns" as theoretically comprising all possible combinations of all trip destination, activity, etc. options for each link in the sequence of trips, (Adler and Ben-Akiva, 1977)). While this shows an awareness of the real complexities of individual movement, little work has been carried out on the further implications of this reconceptualization of travel, namely, that empirical research is required on longitudinal trip data for individuals (admittedly not readily available) to establish what, if any, kinds of linkage patterns exist in reality. So far, complex trip-making has just been arbitrarily redefined as some simple classes of tours, for example, as "trip sequences linked by purposes other than work, and those not so linked, or those tied to residential destinations and those not so tied," (Adler and Ben-Akiva, 1977; Ben-Akiva, 1978; quotation from Burnett, 1978(b), p. 23).

Since implications of considering movement as a sequence of trips by the individual have not been well researched empirically, all the possible theoretical consequences of the reconceptualization of the unit of demand in disaggregate models of movement, which could flow from such research, have not yet been faced. For example, the demand for a mode for a trip is a simple concept, and it seems reasonable to suppose that individuals could conceptualize a few different modes as goods or services described by a variety of attributes to which they can attach utilities, as in some versions of consumption theory. However, there seems to be a primary facie case that it is unreasonable to suppose that individuals can conceive of all the possible permutations and combinations of activities, modes, etc., generated on a sequence of linked trips, let along consider them as separate goods or services and develop utilities for each element of each combination in standard ways. This is even the case when complex trip sequences are arbitrarily simplified and divided into a number of options, such as "work-shop-work" or "home-work-home", as is currently done for modeling, let alone what actually might be the options represented by the more complicated repetitive combinations of trip sequences which could emerge from an appropriate mathematical reconceptualization and related analysis of longitudinal data for travel. One of the principal needs for the development of new models and theories about complex human behavior is therefore to analyze data to see what forms such behaviors might take, and then to reconsider how modeling and theory might handle them.

To facilitate this, the individual's movement is first mathematically reconceptualized here so that it both accords with current thinking on the subject and leads into a preliminary analysis of longitudinal travel data. More sophisticated kinds of data analysis are proposed at the end of the paper to permit appropriate attention in future work to the critical question of suitable objective theoretical and operational definitions of movement as complex human behavior.

Work towards the mathematical reconceptualization of travel as complex behavior has recently been carried out, principally by workers at the University of Lund in Sweden (Lenntorp, 1976; Thrift, 1976; Ellegard, Hagerstrand and Lenntorp, 1977) and the

Transport Studies Unit at the University of Oxford, England (Jones, 1977; Heggie, 1977; Dix, 1977; Heggie, 1978; Heggie and Jones, 1978). The two-dimensional geometric representation of the individual's movement as a space-time path (Fig. 1), attributable originally to Lenntorp (1976), and reappearing inter alia in Thrift (1976) and Dix (1977), represents a first attempt to depict what the individual's movement might be in reality, once it is granted that he/she does not make a trip, but a sequence of trips to different places (stops) over time. However, although work at both Lund and Oxford has involved collecting detailed individual travel data, the utilization of the data has been for different policy and modeling approaches than have been taken here (e.g. Heggie, 1977, 1978; Ellegard, Hagerstrand and Lenntorp, 1977), so that a still sharper mathematical reconceptualization of movement as complex behavior in reality, and accompanying statistical analysis of longitudinal trip records to investigate the appearance of repetitive patterns for individuals and population groups, has not yet been carried out.

One of the less obvious features of the representation of the individual's movement in Figure 1 is that, by portraying it just as a line in two-dimensional space (time of day, distance), information about other aspects of travel (activities, modes, destination type and location) has been collapsed into that space. Technically, Figure 1 is a simplified representation of the individual's travel as a path in n-dimensions, one being time of day, one being distance from last stop to the next, and the others representing the remaining particularly important aspects of travel which are currently considered, namely, mode, activity, type and location of destination, at least. The path, properly represented in the n-dimensional space, would become a line joining a sequence of points, representing stops, each stop possessing a set of coordinates (or 'values') on a separate axis giving at least time of arrival at stop, distance from last stop, location of present stop, mode used to get to stop, and activity conducted at the stop. (It is clear that any other important aspects of travel could be portrayed on further dimensions, e.g. duration of stay at a stop). The more rigorous geometrical representation of the individual's daily travel as a path in n dimensions is shown in Figure 2.

It seems apparent that this portrayal of movement as a path in n-dimensional space does summarize thinking to date on movement as complex behavior. The early work by geographers Nystuen, Marble and Hanson, for example, dealt with travel as a series of linked stops in a one-dimensional space defined by activity or land use; the work by Spear, Adler and Ben-Akiva dealt with portions of the n-dimensional paths as shown in the diagrams of Figure 2 (for example, such portions as may be considered as work-linked or home-linked, by different modes, to different destination locations, for different activities and at different times of day); and, as we have seen, the study of space-time paths descended from Lenntorp also conforms with this representation.

The immediate questions for future empirical, modeling and theoretical work therefore become "What do individuals' trip records look like when represented in this fashion as complex behaviors, and, more importantly, is there any indication of less complex multiple trip sequences (linking one or two modes, activities or destination types) as distinct from highly complex multiple trip sequences, or any indication of tendencies for groups of individuals to have patterns or the same types of paths?" For the purpose of this paper, it is sufficient to show here that paths apparently tend to be uncomplicated rather than highly complex and that individuals of the same group tend to have like paths. This will be a first step in documenting the fact that studying behaviors as complex, and, specifically, studying the individual's travel as a path in n-dimensional space rather than as a simple trip, could lead to the development of the new kinds of model of travel behavior and economic theory outlined in the Introduction.

Data used to document the present conceptualization of travel in Figure 2 and to answer the questions raised should conform to the following requirements. It should consist of recent trip records for a random sample of individuals, of varying socio-demographic characteristics, where each indidivual's record comprises at least each stop visited in sequence over a time period, and details of the activity of the stop, times of arrival at the stop, the mode used to get to the stop, the precise point location of the stop, the land use at the stop, and the distance from the last stop. The Uppsala data set, a collection of the longitudinal travel records over 35 days for sample of 531 individuals in 296 households in Sweden in 1971 were the only available data set meeting all these requirements. The individuals in the set comprise a stratified random sample of persons by life cycle group; Table 1 shows the definition of the group and the distribution of the sample between groups, while Table 2 displays a copy of the daily travel diary for each individual which yielded the data set. It will be noted that the diary for a day is very similar to others used to collect individual travel records (e.g. Charles River Associates, 1978) with the exception that more detailed information, especially address information permitting location geocoding, is requested.

Although this data set was the only one available meeting all requirements, it was particularly suitable for another reason. Recent research (e.g. Fried et al, 1977; Heggie, 1977) indicates that variables describing roles may be most closely associated with travel behavior, and life cycle descriptors seem good operational definitions of these. Thus, utilizing a data set where the sample is stratified on the basis of life cycle, and looking for associations between the complex travel patterns of individuals and their life cycle groups, should be particularly helpful in examining the idea that complex behaviors might exhibit simple structures which systematically vary between population groups.

For the exploratory purposes of this paper, a subsample of 40 individuals was therefore randomly selected, with each life cycle group represented in the subsample in the same proportion as the complete sample. The length of time (numbers of days and stops) over which the observed trip sequences for the subsample of individuals was to be examined was a debatable question, and further research appears necessary to answer it satisfactorily, concentrating on identifying the individual's planning period. At present, it was decided to parallel present work elsewhere on movement as a complex behavior (Hensher, 1976; Jones, 1976; Thrift, 1976), and take the day as the basic time unit for the observation of the path of the individual. This has some justification in that routinized weekday travel patterns seem common (Hensher, 1976); that disaggregate data sets, such as the Baltimore data set now being collected in the USA, will record data for this time period for future modeling and theoretical research; and, finally, that, theoretically, handling trip sequences over one day seems the greatest increment in the level of complexity which might be manageable after conceptualizing travel as a single trip.

Some sample plots of the paths of the 40 individuals, as represented the outlines in Figure 2, as shown in Figure 3. The total number of plots for all 40 numbered 840, so only an illustrative selection can be included. These comprise evidence that:

(1) Individuals have paths with simple rather than highly complex structures, that is, they use one or two modes over a day, limit themselves to a few activities, generally restrict the distance travelled, and do not visit highly dispersed or a large variety of locations;

(2) Some of the paths for different individuals exhibit similarity;

(3) There appear to be differences in the paths for persons in different groups, although these are not necessarily simply related to life cycle; this indicates the need for further investigation into more appropriate role descriptiors which will segment the paths into groups with maximum within-group similarity and maximum between-group dissimilarity.

Even this preliminary analysis of data seems to demonstrate that complex behavior like the individual's movement can be mathematically conceptualized and defined. Therefore, complex rather than simple behavior might be considered as the phenomenon to be explained in future models and theory.

3. IMPLICATIONS OF THE MATHEMATICAL RECONCEPTUALIZATION OF TRAVEL FOR INDIVIDUALS' ALTERNATIVES AND DECISION STRATEGIES

3.1 Derivation of Hypotheses

Given that the present mathematical reconceptualization of travel could be a satisfactory one for future modeling and theoretical purposes, some of its possible implications for the ways in which individuals' choice sets are formed and evaluated may be explored. In doing so, we will provide some empirical support for key alternative axioms to underpin new models of travel behavior and their micro-economic theory base. Such axioms include the assumptions that the individuals' options are more limited than currently conceived and could vary systematically between persons, and that evaluation procedures could be much simpler than normally specified and also vary systematically between individuals. It is not contended that suggestions here as to how individuals' choice sets are formed and evaluated are necessarily precisely those of reality, just that there is some evidence that alternatives might be limited in some predictable way and that evaluation procedures might be more straightforward than currently supposed. It then remains for further research to determine inductively how to specify in detail an individual choice set formation model and to discover and elaborate mathematically precisely what are the individuals decision strategies to flesh out the exploratory-descriptive models of individual and group behavior of Equation 1.

Refer again to Figure 2. The portrayal of movement as a line in an n-dimensional space, where the n-dimensions comprise the features of the individual's travel which are normally of interest (distance, activity, mode, destination location, timing) could imply that, instead of representing kinds of choice, as currently conceived, these features function as critical aspects of stops or places. That is, the units that are demanded by human beings as a result of their need to conduct much of the business of life out of home are not trips, but places, each described by a limited number of critical aspects, namely, distance to get there, the activity which can be performed there, the mode(s) used to get there, the destination location and type, and possible time(s) of visit during the day. (This is a new application of the now-familiar way in which destinations, modes, etc. in choice sets have been assumed to be defined, that is in terms of numerous variables or aspects, such as sets describing price or cost, convenience, service, etc.). The simple reduction of what have been described as simultaneous or sequential decisions about the trip as a unit of demand, to a few critical aspects of places which are demanded, clearly represents a major first step in simplifying the currently formidable complexity of the individual's travel decision problem. Assuming stops are conceptualized in this way, Hypothesis 1 may now be posed for testing.

H1: Given that stops (places) are described by a limited number of critical aspects, the choice set of alternative places for an individual to use in a day may be restricted to one or more described by a limited number of values or categories, and perhaps only one value or category, of each aspect.

Thus, shopping-for-other-than-necessities may be only associated with regional shopping center-the auto mode-more than 15 minutes-arrive on the way home from work, while shopping-for-toothpaste may only be associated with local drug/grocery-walk-less than 5 minutes-drop by from home after work. The kinds of association formed, however, may vary systematically by individuals in different socioeconomic groups dependent on their roles. In operational terms, this implies that, in the individual's trip record, a high degree of correlation should exist between observations of the activity, distance, mode, destination type, destination location and time of arrival aspects of stops. Moreover, the kinds of association should manifest some variation for the individuals in different role groups.

It follows from Hypothesis 1 that the individual must find some means of evaluating the one or more places in the choice set, that is, of evaluating the cost and benefits of using the limited number of combinations of activity-destination-location-destination type-distance-mode-time of visit values or categories which describe each possible stop. This implies that some underlying common dimensions might exist in terms of which all the aspects of these combinations can be described and evaluated. Since in the literature on both the disaggregate and aggregate modeling of movement, travel time and cost have time and again been either plausibly argued or demonstrated to be of primary importance in regulating movement, and since recent time and money budget studies (e.g. Szalai, 1971; Zahavi, 1974) tend to confirm this, Hypothesis 2 can be formulated as follows.

H2: The places as defined in H1 are evaluated by each individual on two fundamental dimensions which could be the time and cost expenditures of using them. Systematic differences could also exist between individuals in the ways places are evaluated in terms of time and cost, depending on social roles

In operational terms, this means that the stops in each individual's trip record for a day, defined in terms of the six critical aspects of activity, location, land use, distance, mode, and time of day, should exhibit selection in accordance with a model of judgement conforming to H2.

H1 and H2 together comprise an explanation of observed complex individual travel behavior, as reconceptualized here and as described by the daily trip records for the 40 individuals in the subsample of the Uppsala data set. Consequently, statistical techniques can be used to test the two hypotheses using these records, to show that reconceptualizing behaviors as complex, options as limited and decision procedures as simple, fits standard kinds of travel data just as well as the alternative hypotheses on which current models of movement are based.

3.2 Statistical Tests of the Hypotheses

Hypothesis 1. For each of the 40 individuals in each life cycle group, an intercorrelation matrix was prepared, showing the Pearsonian simple product moment correlation coefficient (r), between observations for each pair of aspects for each of the p stops on the individual's day. The day with a maximum number of stops was selected (typically for an individual, $5 \leq p \leq 15$). If H1 is correct, then the absolute value of each r in the intercorrelation matrix should be high and statistically significant. Moreover, different kinds of association between the variables should be present for different kinds of individuals, some persons perhaps matching bus with regional shopping center, and car with local convenience stores, and others doing the reverse. These expectations prove to be the case when the data for the subsample of Uppsala individuals were analyzed. Table 3 contains a selection of the trip records and intercorrelation matrices for selected individuals to document this.

Hypothesis 2. The correlation coefficients in the matrices for individuals, such as those of Table 3, comprise measures of similarity between the different aspects of stops for each person. These coefficients are the best kinds of similarities (distance or proximity) measures for input into an M D S scaling algorithm which fits the INSCAL model of the evaluation of stimuli to data. The algorithm and the model can be used with the data for the Uppsala individual trip records to test Hypothesis 2 in the following way (following Carroll, 1973, pp. 107-111).

Assume the six critical aspects of stops in the individuals' choice sets comprise stimuli for the individual. Then associations between the aspects of stops might not only reflect the restricted nature of the options in the choice sets, but also the degree of similarity (proximity, discriminability) of the stimuli defining stops when they are evaluated on no more than two basic dimensions, by each and every individual. The aspects (stimuli) defining the stops for each individual over a day should therefore comprise a configuration recoverable in a two-dimensional 'mental' space, with each aspect (stimulus) discriminated along each dimension. However, inter-individual differences should exist in recovered configurations, with systematic differences between groups of individuals, indicating differences in evaluation procedures.

The INSCAL model and algorithm allows for inter-individual differences in the evaluation of stimuli (aspects of stops) in the above ways by:

(1) testing the goodness of fit to the similarities data for stimuli, for m different individuals, of m matching stimuli configurations, each in a two-dimensional space;

(2) producing a group or overall configuration for all individuals as a composite of the individual ones, providing a basis for comparison of the latter;

(3) allowing for individual differences in configurations through variation in the weights in the function used to fit the

similarities (distance) data for each individual, where the function relates the individual and group configurations in the following way:

$$d^i_{jk} = \left[\sum_{t=1}^{r} w^i_t \quad (x_{jt} - x_{kt})^2 \right]^{\frac{1}{2}} \qquad \text{II}$$

where d^i_{jk} is the distance (similarity) between the j^{th} and the k^{th} stimulus for the i^{th} individual, r is the number of underlying dimensions (here assumed to be 2), x_{jt} and x_{kt} are the values of the stimulus on each dimension, and w^i_t are the weights for each dimension, specific to the individual.

On the basis of the preceding discussion, we would expect that, if H2 is true, and using the kinds of intercorrelation matrices of Figure 3 for each individual as proximities input to the INSCAL algorithm:

(1) configurations of stimuli (the six critical aspects of each stop) are recoverable for each individual in a two-dimensional space, with a very good match of the distances between stimuli in each individual configuration to the input similarities (proximity) measures;

(2) stimuli are well discriminated ("spaced out") on each dimension in individual and hence group configurations,

(3) there is considerable inter-individual variation in weights for each dimension, with statistically significant differences in the weights (and hence configurations and evaluations) for individuals in different life cycle groups.

The results of the data analysis, which conform with these expectations, as shown in Tables 4 and 5 and Figure 4. The match of the recovered group and individual configurations to the input data is excellent, as measured by the generally high r values in Table 4, for each individual and for the group, between the distances represented by the input data and the recovered distances for each configuration. This demonstrates that, as hypothesized, two fundamental dimensions are probably used for evaluation, most probably travel time and cost. Perhaps a third or fourth underlying fundamental dimension is used, but including it for analysis clearly would not much improve the goodness of fit to the data produced by using the first two. Figure 4, the group configuration from which individual configurations are derived, reflects how well the stimuli are discriminated in general by the two dimensions. Finally, the expected high inter-individual variability in weights appears (Table 5) and therefore the possibility of grouping individuals in some manner to minimize intra-group and maximize between-group variance in them (and thus group configurations or evaluation functions); however, the expected association of weights simply with life cycle group did not appear (Table 5). Perhaps some further role variables should have been included to help better partition the population into role groups, for example sex as well as life cycle stage could have been used as segmentors. The sample size limitations for INSCAL (m, the number of individuals, could not be more than 40), precluded this, yielding too few persons in sex and life cycle cross-classifications. Indeed, the sample size restriction of the INSCAL algorithm was the reason that the subsample of individual trip records was limited to 40 for the entire exploratory data analysis reported here.

3.3 Conclusion

The exploratory data analysis seems sufficient to support the contention that, once it is granted that the individual's movement is in reality complex and definable as a path in n-dimensional space, then it may be generated by the evaluation of a limited number of options in terms of only several criteria, probably time and cost considerations. These assumptions seem well in accord not only with our data, but also with suggestions from current research on daily activity-travel patterns (Westelius, 1973; Lenntorp, 1976; Jones, 1976), the significance of routinizable behavior for travel (Hensher, 1976), and the importance of time and money budget considerations for individuals (Szalai, 1971; Zahavi, 1974, 1976). Also, it does seem reasonable to suppose that although movement is complex from the researcher's point of view, it is more likely to be viewed as a routine and not a major decision or investment question by most persons, relative to other kinds of decisions with which they are confronted, such as buying a home. It is therefore plausible that travel decision-making is simple, not complex, problem-solving as far as the individual is concerned, consistent with an assumption of a limited number of alternatives and a simple evaluation procedure. Given all these considerations, it seems justifiable to try to develop models and theories based on alternative sets of axioms to those underlying current models and theories used to study movement, which also fit well the kind of travel diary data utilized here. In the case of possible equifinality, potentially the fruitful line for future model and theory development is the more realistic one, so that this part of the paper provides some support for the modeling and theoretical approach of the Introduction. It remains to show that conceptualizing behavior as complex, and evaluation procedures as simple, instead of vice versa, does not lead at once to intractable modeling problems through the increase in the complexity in the dependent variable for modeling work.

4. MEASURING AND CLASSIFYING COMPLEX TRAVEL PATTERNS

The problem of rigorously measuring and classifying n-dimensional paths representing an individual's travel to provide a manageable operational variable for modeling purposes is clearly a difficult one. The diagram of a hypothetical path (Figure 2) suggests that fruitful measurement and classification techniques may be derivable from branches of mathematics not yet drawn on in the study of movement, namely, topology, graph theory, or discrete Fourier analysis. The last, (e.g. Bacon and Broekhoven, 1977), for example, could be used to identify a number of characteristic patterns in the paths of a sample of individuals which represent the 'time series' data commonly used for this procedure. Once a typology of time-space paths has been established, individuals' time-space paths can then be grouped or classified. The appropriateness of these techniques is currently being investigated. Given that these very rigorous methods of measuring and classifying n-dimensional paths pose some new, difficult problems that may be expected to demand a longer-term solution, our purpose here is to present a simpler approach to demonstrate at least the feasibility of statistically classifying complex travel behavior for modeling in the interim. Our approach is based on earlier geographic work that classified travel in terms of only one possible dimension of a stop (namely the type of land use there, representing the type of destination); the following discussion demonstrates how complex travel can be classified in one dimension and then how the method can be extended to encompass additional dimensions of stops.

The method involves manipulations of a flow matrix. For any sample of individuals, travel diary data can be summarized in a square from-to flow matrix in which the rows represent the origins and the columns the destinations of the sequence of out-of-home travel linkages made over some time period. If we focus upon the out-of-home land use characteristics of the origin and destination of each linkage, then cells give the number of times people travelled from land use i (e.g. bank) to land use j (e.g. barber shop) in the course of home-to-home circuits (e.g. Marble, 1964; Hanson and Marble 1969); by next including a home-home cell[2] representing the frequency with which individuals ended one home-home circuit and started another one, circuits are linked together and the matrix properly represents flows over any time period (e.g. a day). Because the directionality of the sequence of stops is retained in the matrix, the matrix is of course, assymmetric. It is also extremely complex. Our goal is to simplify this complex matrix (1) by identifying which travel linkages occur frequently enough to be considered "significant"; and (2) by identifying groups of land uses that tend to occur together on the same path. In order to accomplish this, from the Uppsala travel diaries a flow matrix was constructed indicating the frequency with which a random sample of 143 travellers moved between land use categories.

In order to reduce the complexity of the matrix and to identify "significant" linkages, transaction flow analysis

(Savage and Deutch, 1960; Goodman, 1963) is used. Transaction flow analysis provides a way to eliminate size effects (unequal row and column marginals) that can obscure important patterns and lead to a biased interpretation of the data. The method involves specifying a null or indifference model for determining the expected number of linkages between origins and destinations and then comparing these estimates with the observed interaction data. The null model used to estimate the expected number of links is normally specified as a function of the size or the relative importance of the origins and destinations (i.e. of row and column sums); therefore the residuals calculated from this model are free from the effect of different absolute flow levels between land uses. Following Slater (1974) the expected flow levels, a^*_{ij}, are specified as:

$$a^*_{ij} = U_i V_j \; ; \quad \begin{matrix} i = 1,\ldots,m \\ j = 1,\ldots,n \end{matrix}$$

where

$$U_i = \frac{\sum_j a_{ij}}{\sum_i \sum_j a_{ij}}$$

$$V_j = \frac{\sum_i a_{ij}}{\sum_i \sum_j a_{ij}}$$

and where a_{ij} is the observed interaction between i and j. The residuals from the indifference model are a measure of the strength or significance of the linkages between land uses and, moreover, identify for each land use which other land uses are linked primarily as origins or primarily as destinations to the land use in question. For example, the residuals involving travel to food stores (shown in Table 6) demonstrate that food stores are visited towards the end of multi-purpose home-home-circuits far more frequently than at the start of such trips. This directionality is strongest between food stores and banks and between food stores and post offices. In both of these cases the relationship between food stores as source and the other land use is significantly negative while the relationship between food stores as destination and the other land use is strongly positive. In other words, the residuals in Table 6 demonstrate that food stores are rarely the origin of a linkage while they are frequently the destination of a linkage originating at some other land use.

In this manner transaction flow analysis enables us to determine which cells in the flow matrix contain significant linkages; transaction flow analysis does not, however, tease out groups of land uses that tend to occur on the same path. In order to classify paths on the basis of land use linkages, principal components analysis of the flow matrix was carried out.

Factor analysis has been extensively used as a grouping or regionalization technique (e.g. Berry, 1966; Baker and Goddard, 1972). In the analysis of directed flow matrices a standard R-mode principal components analysis will yield factors that represent destinations with similar patterns of linkages to the set of origins. The factor scores from an R-mode analysis provide information on the origins that tend to be identified with each factor. Groups of highly interacting land uses can be derived by combining sets of land uses with high factor loadings and sets of land uses with high factor scores. Thus we identify destinations with similar source patterns (via the factor loadings) and the common sources associated with these destinations (via the factor scores).

The results of the R-mode principal components analysis of the flow matrix (of travel linkages between out-of-home land uses) using the Uppsala travel records are presented in Table 7. These results are remarkably similar to those obtained by Hanson and Marble (1969) in a comparable analysis of travel diary data gathered in Cedar Rapids, Iowa in 1949. In the Cedar Rapids study four types of trips (where a trip is a home-to-home circuit) were identified: single-purpose trips for convenience goods/services; single purpose trips for specialty goods/services; multiple-purpose shopping trips; multiple-purpose trips involving one or more stops at the workplace.

In Table 7 the land uses with high loadings on Factor 1 are those with strong, direct links to home; these are places that tend to be visited primarily on single purpose trips and also that tend to provide specialty goods or services. The second factor clearly identifies those places that are frequently visited in the course of the journey to work. Factor 3 contains those land uses usually contacted in the course of multi-purpose shopping trips on which the traveller indulges in comparison shopping. The land uses with high loadings on the fourth factor are those offering convenience goods or services; unlike the Cedar Rapids situation in which convenience goods were most frequently acquired on single-purpose trips, convenience shopping in Uppsala is evidently often undertaken on multi-purpose trips devoted almost entirely to convenience shopping. An important point here is that shopping goods and convenience goods are rarely sought on the same trip. The fifth and sixth factor identify additional multi-purpose trip types that are somewhat anomolous and therefore difficult to interpret given the typology derived in the Cedar Rapids study. Factor 5 seems to contain multi-purpose trips devoted to carrying out personal business while Factor 6 identifies the land uses most frequently visited in connection with visits to sporting goods and toy shops. Clearly the first four factors yield a classification of complex travel that is easily interpretable. These land use groups derived via principal components analysis are based on the pattern of direct linkages contained in the flow matrix.

An alternative grouping procedure that takes into account the indirect linkages contained in the flow matrix is to use one of the many algorithms available for grouping observations. All grouping algorithms for interaction data must address the problem of unequal row and column sums (Hirst, 1977). In our case, this problem can be ameliorated by applying the grouping procedure to the matrix comprised of the residuals from the null independence model described above rather than to the raw linkage matrix. The groups derived from a standard hierarchical grouping procedure suffer, however, from the fact that at any given step in the aggregation process, the previous groupings are taken as given; hence a globally optimal solution is unlikely.

The classification methods discussed thus far have considered only one aspect (dimension) of each stop in an individual's path. Since we need to be able to classify complex travel patterns in n dimensions (where n is at least 5, the number of dimensions associated with each stop), we need to consider how these methods could be extended to encompass the dimensions of travel other than simply land use.

One approach is to build a flow matrix in which each row/column is a composite of any of the limited number of dimensions of travel considered of interest. Clearly some simplification or refinement is necessary to keep the size of such a matrix manageable. The following is suggested as one viable solution. Consider only the following dimensions of a stop: activity type (shop, recreation, work, personal business, social, and home-based-activity); mode of travel (auto, bus, bike, walk); distance travelled from last stop (classified in discrete distance categories); time of day (also classified in discrete categories). Each row/column then represents a unique combination of activity, mode, distance, and time, and the flow matrix is a record of the individual's path in four dimensions. Analysis of such a flow matrix should yield those activity-mode-distance-time bundles that occur frequently on the same path, and enable the classification paths in four dimensions similar to the typology of travel derived from analysis of the matrix of travel linkages between land uses. The same approach could be extended to paths in a larger number of dimensions, depending on the size of sample of individual daily trip records.

As can be seen from the above, the methods of analysis of the flow matrix are not complicated, given the current statistical procedures in widespread use for segmenting individuals into groups and estimating the parameters of current travel models. Although still more rigorous scientific methods for measuring and classifying the properties of the 'lines' in n-dimensional space shown by Figure 2 remain to be determined, we have indicated adequately how complicated trip sequences can be empirically investigated in objective ways, how n-dimensional paths for individuals can be allocated to classes, and thus how a manageable dependent variable might be defined for new, more realistic models of movement as complex human behavior.

5. CONCLUSION

This paper has comprized a lengthy introduction to a new paradigm for the study of the movement of individuals and population groups within cities. Although it clearly draws on past work in travel modeling, and on present pioneering work investigating the effects of constraints on choice and/or new kinds of optimizing decision rule (e.g. Heggie and Jones, 1978, Wermuth, 1978) it does represent a significant departure by:

(1) Synthesizing the results of research on the critical underlying assumption in current models of movement;

(2) Advocating rigorous empirical-inductive approaches to first, refefining the individual's behavior as complex rather than simple; to second, studying constraints on choice sets for all kinds of travel decision as a fundamental theoretical and policy-related question; and to third, investigating and formulating the different, simple decision strategies which individuals in different situations might use;

(3) Suggesting the development of a 'more realistic' explanatory-descriptive model of the movement of individuals and groups;

(4) On the basis of (3), rewriting the micro-economic theory base from which models of movement are derived, to provide ultimately for approaches to modifying human behavior more in accord with longer run political decision-making for urban systems in difficult social, economic and environmental circumstances.

In this paper, we have presented as succinctly as possible the rationale for this reorientation of work for the study of human movement, and also some data analysis to support our contention that our approach is a desirable one.

FOOTNOTES

1 The dangers of all social scientists using an instrumentalist approach is that they will provide no markedly different alternatives to either status quo, or 'modified status quo' planning for dynamic urban systems with very great social and economic problems.

2 The home-home cell is an "artificial cell" linking circuits; as it reflects no movement between two different bases, as other cells in the flow matrix, it is omitted from subsequent analyses of travel linkages.

Acknowledgements

The support of Grant No. SOC7728468 from the National Science Foundation is gratefully acknowledged. The preliminary development of some of the ideas for this project was, however, during the first phase of a contract from the Federal Highway Administration for a study in "The Application of New Travel Forecasting Procedures," December 1977, to May, 1978. Our thanks to Louise Skinner who made this work possible.

REFERENCES

1. Adler, T. and M. Ben-Akiva, 1978. "Directions for Improving Urban Travel Forecasting Procedures." Draft White Paper, Applications of New Urban Travel Forecasting Procedures Conference, F.H.W.A, Washington, D.C.

2. Bacon, D.W. and L.H. Broekhoven, 1977. "The Fast Fourier Transform and its Application to Time Series Analysis," in Statistical Methods for Digital Computers, K. Enslein, A. Ralston, and H.S. Wilf (eds.), New York:Wiley and Sons.

3. Baker, L.L.H. and J.B. Goddard, 1972. "Inter-sectoral Contact Flows and Office Location in Central London", in Patterns and Processes in Urban and Regional Systems, A.G. Wilson (ed), London:Pion Ltd.

4. Berry, B.J.L., 1966. "Commodity Flows and the Spatial Structure of the Indian Economy", Research Paper 111, Department of Geography, University of Chicago.

5. Brög, W., D. Heuwinkel, and K. Newmann, 1977. Psychological Determinants of User Behavior, Round Table 34, O.E.C.D., Paris.

6. Burnett, P., 1973. "The Dimensions of Alternatives in Spatial Choice Processes", Geographical Analysis 5:187-204.

7. Burnett, P., 1978(a). "Non-utility-maximizing Models of Spatial Choice within Time-Geographic Constraints", Paper presented at the Annual Meetings, Association of American Geographers, New Orleans, April.

8. Burnett, P., 1978(b). "Choice and Constraints - Oriented Modeling. Alternative Approaches to Travel Behavior", Draft paper for "Application of New Urban Travel Forecasting Procedures", Conference, Washington, D.C., 1978; forthcoming in revised form, October, 1978, F.H.W.A., Washington, D.C.

9. Carroll, J.D., 1972. "Individual Differences" in Multidimensional Scaling, Theory and Applications in the Behavioral Sciences, R.N. Shepard, A.K. Romney, and S.B. Nerlove (eds)., New York:Seminar Press.

10. Charles River Associates, 1976. Disaggregate Travel Demand Models:Project B8-13 Phase I Report, Washington, D.C. N.C.H.R.P.

11. Curry, L. 1962. "The Geography of Service Centers within Towns: The Elements of an Operational Approach," Lund Studies in Geography, B, 24:31-53.

12. Dix, M.C., 1977. "Report on Investigations of Household Travel Decision-Making Behavior", Working Paper 27, Transport Studies Unit, Oxford, England.

13. Fried, M., J. Havens, and M. Thall, 1977. Travel Behavior'a Synthesized Theory, Final Report for NCHRP Project B-8-14, Laboratory of Psychosocial Studies, Boston College, Chestnut Hill, Massachusetts.

14. Goodman, L., 1963. "Statistical Methods for the Preliminary Analysis of Transaction Flows", Econometrica 31:197-208.

15. Hanson, S., 1973. Information Levels and the Intra-Urban Travel Patterns of Swedish Households. Unpublished Ph.D. Dissertation, Department of Geography, Northwestern University, Evanston, Illinois.

16. Hanson, S., 1977. "Urban Travel Linkages: A Review." Resource Paper, Third International Conference on Behavioral Travel Modeling, Tanunda, South Australia.

17. Hanson, S. and P. Hanson, 1978. "The Activity Patterns of Urban Residents: Dimensions and Relationship to Personal Characteristics," paper presented at the annual meeting of the Association of American Geographers, New Orleans.

18. Hanson, S. and D.F. Marble, 1971. "A Preliminary Typology of Urban Travel Linkages", East Lakes Geographer 7:49-59.

19. Heggie, I.G., 1977. "Putting Behavior into Behavioral Models of Travel Choice". Working Paper 22, Transport Studies Unit, Oxford, England.

20. Heggie, I. and P.M. Jones, 1978. "Defining Domains for Models of Travel Demand," Working Paper, forthcoming, Transport Studies Unit, Oxford, England.

21. Hensher, D., 1976. "The Structure of Journeys and Nature of Travel Patterns", Environment and Planning 8:655-672.

22. Hirst, M.A., 1977. "Hierachical Aggregation Procedures for Interaction Data: A Comment", Environment and Planning 9:99-103.

23. Jones, P.M., 1977. "New Approaches to Understanding Travel Behavior: The Human Activity Approach". Resource paper, Third International Conference on Behavioral Travel Modeling, Tanunda, South Australia.

24. Lenntorp, B., 1976. Paths in Time-Space Environments: A Time Geographic Study of Movement Possibilities of Individuals, Lund Studies in Geography, Lund:CWK Gleerup.

25. Lerman, S. and T. Adler, 1976. "Development of Disaggregate Trip Distribution Models," in Behavioral Travel Demand Models, P. Stopher and A. Meyburg (eds.), Lexington, Mass:Lexington Books.

26. McFadden, D., 1978. "Quantitative Methods for Analysing Travel Behavior of Individuals:Some Recent Developments." Paper read at T.R.B. Meetings, Washington, D.C., January.

27. Marble, D.F., 1959. "Transport Inputs at Urban Residential Sites," Papers of the Regional Science Association, 5:253-266.

28. Marble, D.F., 1964. "A Simple Markovian Model of Trip Structures in a Metropolitan Region", Papers, Regional Science Association, Western Section, 150-156.

29. Marble, D.F., 1967. "A Theoretical Exploration of Individual Travel Behavior", in Quantitative Geography Part 1:Economic and Cultural Topics, W.L. Garrison and D.F. Marble (eds.), Northwestern University Studies in Geography Number 13, Evanston, Illinois:Northwestern University Press.

30. Marble, D.F., and Bowlby, S.R. 1968. "Shopping Alternatives and Recurrent Travel Patterns" in Geographic Studies of Urban Transportation and Network Analysis, F. Horton (ed.), Northwestern University Studies in Geography Number 16, Evanston, Illinois:Northwestern University Press.

31. Nystuen, J., 1967. "A Theory and Simulation of Intraurban Travel", in W.L. Garrison and D.F. Marble (eds.), Quantitative Geography, Part 1, Northwestern University Studies in Geography No. 13, Evanston, Illinois:Northwestern University Press.

32. Pred, A., 1977. "Planning-Related Swedish Geographic Research", Economic Geography, Special Edition, July.

33. Recker, W. and R. Stevens, 1977. "An Attitudinal Travel Demand Model for Non-work Trips of Homogeneously Constrained Segments of a Population," Transportation Research 11:167-176.

34. Savage, R. and K.W. Deutsch, 1960. "A Statistical Model of the Gross Analysis of Transaction Flows", Econometrica 28:551-572.

35. Slater, P.B., 1974. "Exploratory Analyses of Trip Distribution Data", Journal of Regional Science 14:377-388.

36. Slovic, P., B. Fischoff and S. Lichtenstein, 1972. "Behavioral Decision Theory," Psychological Review, 79:280-299.

37. Smith, T.E., 1975. "A Choice Theory of Spatial Interaction", Regional Science and Urban Economics, 5:137-176.

38. Stopher, P. and A. Meyburg, 1976. Behavioral Travel Demand Models. Lexington, Massachusetts:Lexington Books.

39. Szalai, A. (ed.), 1972. The Use of Time. The Hague:Mouton Press.

40. Tardiff, T., 1976. "Perception of the Availability of Transportation Alternatives for Various Trip Purposes," Transportation Research Record #592.

41. Wermuth, M.J., 1978. "Structure and Calibration of a Behavioral and Attitudinal Binary Mode Choice Model between Public Transport and Private Car." Paper presented at P.T.R.C. Meetings, Warwick.

42. Westelius, O., 1973. The Individual's Way of Choosing Between Alternative Outlets, Stockholm:Svensk Byggtjänst.

43. Williams, H. and N. Thrift, 1978. The Effects of Variable Choice Sets and Non-utility-maximizing Decision rules on the Parameters of Travel Demand Models. Unpublished manuscript in process of preparation, School of Geography, University of Leeds, Leeds, England, July.

44. Zahavi, Y. 1974. Travel Time Budgets and Mobility in Urban Areas. FHWA Report, Washington, D.C.

45. Zahavi, Y., 1976. Travel Characteristics in Cities of Developing and Developed Countries. Staff Working Paper 230, World Bank, Washington, D.C.

TABLE TITLES

Table 1

Group No.	Characteristics	Number of Households in Sample	Number of Individuals in Sample
1	Head of household 67 or older	47	68
2	Head of household between 50 and 66; no children living at home	51	80
3	Head of household between 18 and 49; single persons only	26	27
4	Head of household between 18 and 49; two person household with no children	51	99
5	Head of household between 18 and 49; at least one adult and at least one child over seven years of age: no pre-school children	62	141
6	Head of household between 18 and 49; at least one adult and at least one child less than seven years of age	59	116
TOTALS		296	531

Source: Field surveys conducted in Uppsala, Sweden, 1971

TABLE 2

CONFIDENTIAL

Household Travel Survey
Uppsala, Sweden - 1971

Name ______________________ Date _________ 1971

When did you leave home? _________ hours

Is this a continuation from another sheet? Yes No

Stop number _______ Did you plan to make this stop when you left home? Yes No

Means of Travel 1 foot 2 bicycle 3 bus 4 car (driver) 5 car (passenger) 6 taxi 7 moped 8 other _________

Were you accompanied by someone from your household? Yes No If yes, by how many? _________

Where did you make this stop? (please give address) New? _____

When did you arrive at this place? _________ hours When did you leave this place? _________ hours

What did you do at this place? Expenditure
1) ______________________ _________
2) ______________________ _________
3) ______________________ _________
4) ______________________ _________

Stop number _______ Did you plan to make this stop when you left home? Yes No

Means of Travel 1 foot 2 bicycle 3 bus 4 car (driver) 5 car (passenger) 6 taxi 7 moped 8 other _________

Were you accompanied by someone from your household? Yes No If yes, by how many? _________

Where did you make this stop? (please give address) New? _____

When did you arrive at this place? _________ hours When did you leave this place? _________ hours

What did you do at this place? Expenditure
1) ______________________ _________
2) ______________________ _________
3) ______________________ _________
4) ______________________ _________

Is this trip continued on the next sheet? Yes No
If, No, fill in the section below.

When did you return to home? _________ hours

Means of Travel 1 car 2 bicycle 3 bus 4 car (driver) 5 car (passenger) 6 taxi 7 moped 8 other _________

Were you accompanied by someone from your household? Yes No If yes, by how many?

Table 3a

A. Correlations[b] in the Individual's Daily Trip Record between Aspects of Stops, Individual ID #110525, Elderly Life Cycle Group (Group 1)

	Mode	Time	Land Use	Activity	N-S Location	E-W Location	Distance
Mode	-	-.70	+.33	-.66	-.54	+.67	+.99
Time	-.70	-	+.68	+.99	+.75	-.99	-.69
Land Use	+.33	+.68	-	-.69	+.70	-.64	+.34
Activity	-.66	+.99	-.69	-	+.79	-.99	-.66
N-S Location	-.54	+.75	+.70	+.79	-	-.77	-.56
E-W Location	+.67	-.99	-.64	-.99	-.77	-	+.67
Distance	+.99	-.69	+.34	-.66	-.56	+.67	-

B. Individual ID #1301 01, Elderly Life Cycle Group (Group 1)

	Mode	Time	Land Use	Activity	N-S Location	E-W Location	Distance
Mode	-	-.25	+.71	+.31	+.13	-.18	+.78
Time	-.25	-	-.38	+.45	+.64	+.87	-.46
Land Use	+.71	-.38	-	+.27	+.04	-.36	+.74
Activity	+.31	+.45	+.27	-	+.96	+.70	+.34
N-S Location	+.13	+.64	+.04	+.96	-	+.87	+.15
E-W Location	-.18	+.87	-.36	+.70	+.87	-	-.24
Distance	+.78	-.46	+.74	+.34	+.15	-.24	-

Table 3a (Contd.)

C. Individual ID #151410 , Middle Aged with Children (Group 5)

	Mode	Time	Land Use	Activity	N-S Location	E-W Location	Distance
Mode	-	-.48	+.17	-.73	-.75	-.83	+.72
Time	-.48	-	+.37	-.18	-.35	-.24	+.02
Land Use	+.17	+.37	-	+.04	-.23	-.19	+.08
Activity	-.73	-.18	+.04	-	+.53	+.63	-.49
N-S Location	-.75	-.35	-.23	+.53	-	+.90	-.24
E-W Location	-.83	-.24	-.19	+.63	+.90	-	-.38
Distance	+.72	+.02	+.08	-.49	-.24	-.38	-

a The proportion of r's which were statistically significant at the 5% level in all matrices was .79. The proportion for individual matrices varied from .32 to .95. Although each matrix comprised mixed data, r was used because it is the best measure of similarities between stop aspects to be used also as input to the INSCAL algorithm to test hypothesis 2.

b Tables A, B and C reflect the interindividual variations in the choice sets of individuals. Differences in the signs for the same pair of aspects of stops between individuals indicate differences in the kinds of association of different aspects. A multiway analysis of variance (life cycle groups, aspect pairs) showed no statistically significant difference between the correlation coefficients of individuals by life cycle group. This leaves open the possibility of some other grouping procedure identifying significant groups.

Table 4

Correlation						
Group .895483						
Individual	1	.881361	14	.831145	27	.567975
	2	.828531	15	.764530	28	.718454
	3	.691990	16	.609176	29	.849543
	4	.820661	17	.619236	30	.648269
	5	.820961	18	.816674	31	.816215
	6	.512941	19	.874279	32	.732914
	7	.733039	20	.873872	33	.621152
	8	.631778	21	.550332	34	.581234
	9	.617555	22	.528632	35	.851186
	10	.609835	23	.646401	36	.764260
	11	.358989	24	.640377	37	.812975
	12	.640775	25	.734304	38	.836420
	13	.840689	26	.773128	39	.795324
					40	.793309

Table 5

Individual	Dimension 1[a]	Dimension 2[b]	Individual	Dimension 1[a]	Dimension 2[b]
1	126.91	142.35	21	102.55	131.60
2	75.09	76.20	22	56.03	65.87
3	113.99	107.46	23	58.74	101.31
4	112.12	131.28	24	66.04	110.62
5	73.52	99.78	25	77.06	105.54
6	29.82	86.15	26	48.05	62.73
7	49.07	51.40	27	112.51	149.58
8	99.98	135.09	28	20.21	78.80
9	62.61	85.81	29	38.06	31.88
10	70.73	125.66	30	122.07	101.07
11	20.61	47.17	31	38.14	49.10
12	36.40	47.95	32	115.23	108.05
13	48.42	69.13	33	59.12	56.31
14	95.78	124.13	34	75.15	72.14
15	67.64	69.07	35	112.42	101.32
16	49.44	59.22	36	116.85	86.59
17	67.63	115.13	37	79.23	67.21
18	106.92	129.67	38	86.31	88.14
19	87.39	88.68	39	54.53	60.49
20	109.44	108.22	40	61.52	70.25

a For dimension 1, t tests of the difference between the means of weights for each pair of life cycle groups were significant at the 5% level in only 3 of 21 pairs. The coefficient of variation of all weights is 30.2%.

b For dimension 2, t tests of the difference between the means for each pair of life cycle groups were significant at the 5% level in only 6 of 21 pairs. The coefficient of variation of all weights is 34.8%.

Table 6

Land Use	Residuals	
	grocery as source	grocery as destination
bakery, café	2.51	- .35
clothing, jewelry	-1.74	2.08
department store	-2.59	3.82
cinema	-2.59	0.08
bank	-3.96	4.44
home furnishings	-0.91	2.82
post office	-2.50	6.08
car reparis	-3.30	0.75
gas station	-0.37	-1.52
own home	13.61	1.41
work place	-9.68	- .57

Table 7

Factor	(Destination) Land Use	Factor Loading	(Source) Land Use	Factor Score
1	Outdoor Recreation	.928	Own Home	4.771
	Train, Bus Station	.914		
	School	.892		
	Meeting Places	.887		
	Indoor Recreation	.881		
	Work Place	.869		
	Other Person's Home	.868		
	Doctor, Dentist	.842		
	Cinema, Theater	.831		
	Hospital	.800		
	Church, Cemetary	.793		
	Cleaner, Shoe Repair	.696		
	Public Offices	.660		
	Barber Shop	.548		
	Post Office	.531		
Explained variance:	36.1%			
2	Restaurant	.884	Work Place	3.945
	Kiosk	.799		
	Car Repairs	.793		
	Bank	.792		
	Photography Shop	.756		
	Liquor Store	.603		
	Grocery Store	.595		
Explained variance:	20.2%			

Table 7 (Contd.)

3	Clothing, Jewelry	.910	Clothing, Jewelry	2.757
	Department Store	.828	Department Store	2.678
	Book Store	.700		
	Hardware, Paints	.656		
	Library	.654		
	Home Furnishings	.540		
Explained variance: 9.8%				
4	Bakery, Cafe	.645	Grocery Store	2.799
	Drug Store	.618	Doctor, Dentist	1.921
	Barber Shop	.543	Drug Store	1.472
	Flower Shop	.495	Kiosk	1.090
Explained variance: 4.2%				
5	Insurance, Other Offices	.769	Bank	3.107
			Post Office	1.944
	Gas Station	.600	Bakery, Cafe	1.306
	Post Office	.523	Insurance	1.286
			Parking Place	1.210
Explained variance: 3.9%				
6	Sports, Toy Stores	.762	Sports, Toys	2.204
			Department Store	1.840
			Hardware, Paints	1.729
			Restaurant	1.310
			Other Person's Home	1.060
			Post Office	1.027
Explained variance: 2.9%				

TOTAL EXPLAINED VARIANCE: 77.1%

FIGURE TITLES

FIGURE 1 The Individual's Path in Time and Space Dimensions (after Thrift, 1976, p. 18; Dix, 1976, p. 20).

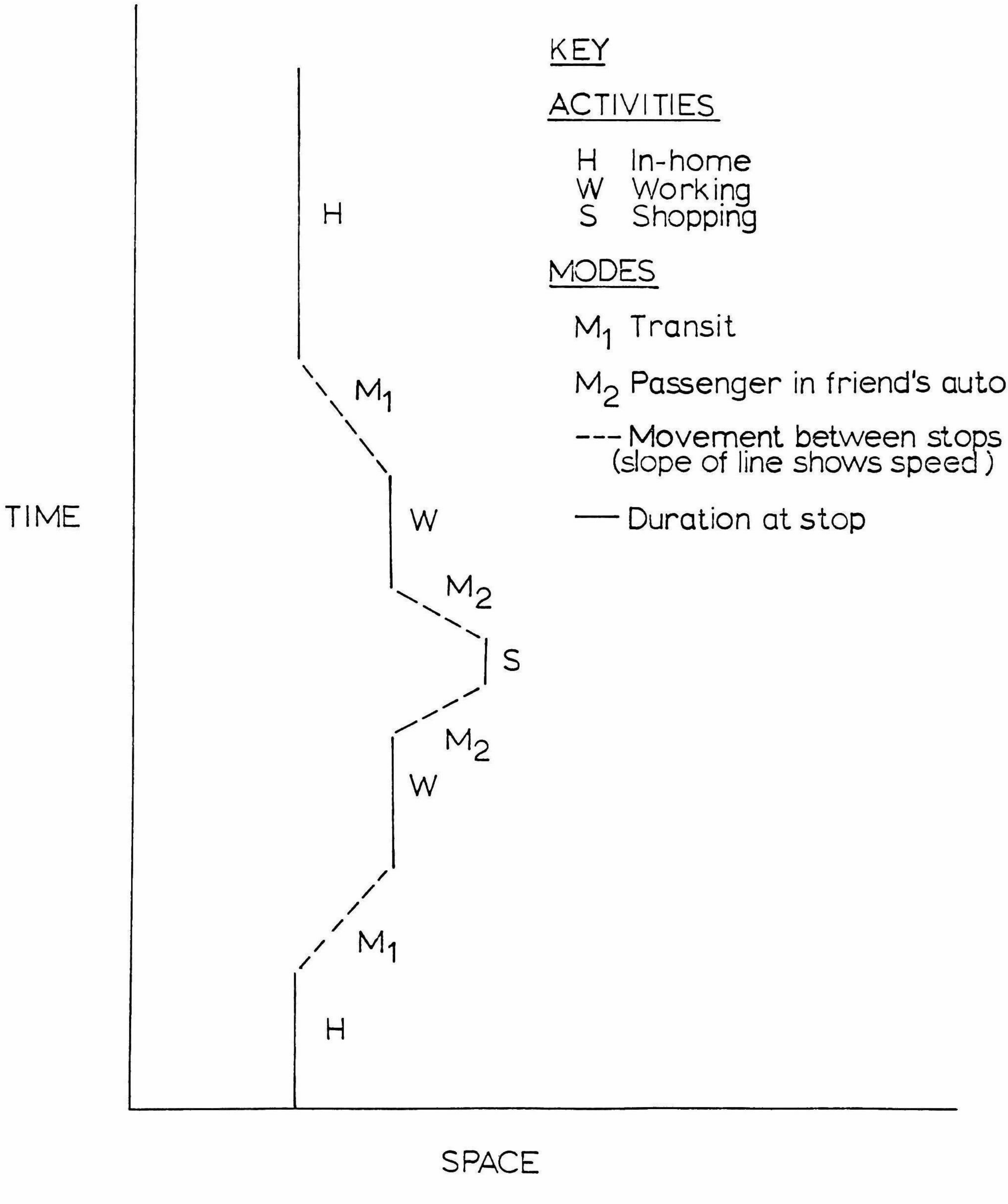
FIGURE 2 Sample Diagrams for Representing the Individual's Path in n Dimensions through a Series of 2-Dimensional Cross-Sections. (All cross-sections are: DT, DA, DL_1, DL_2, DU SM: TA, TL_1, TL_2, TU, TM; L_L, L_2, L_1U, L_1M; L_2U, L_2M; UM

Where D is Distance, T is Time, A is Activity, L_1 is N-S Locational Coordinate, L_2 is E-W Locational Coordinate, U is Land Use, M is Mode).

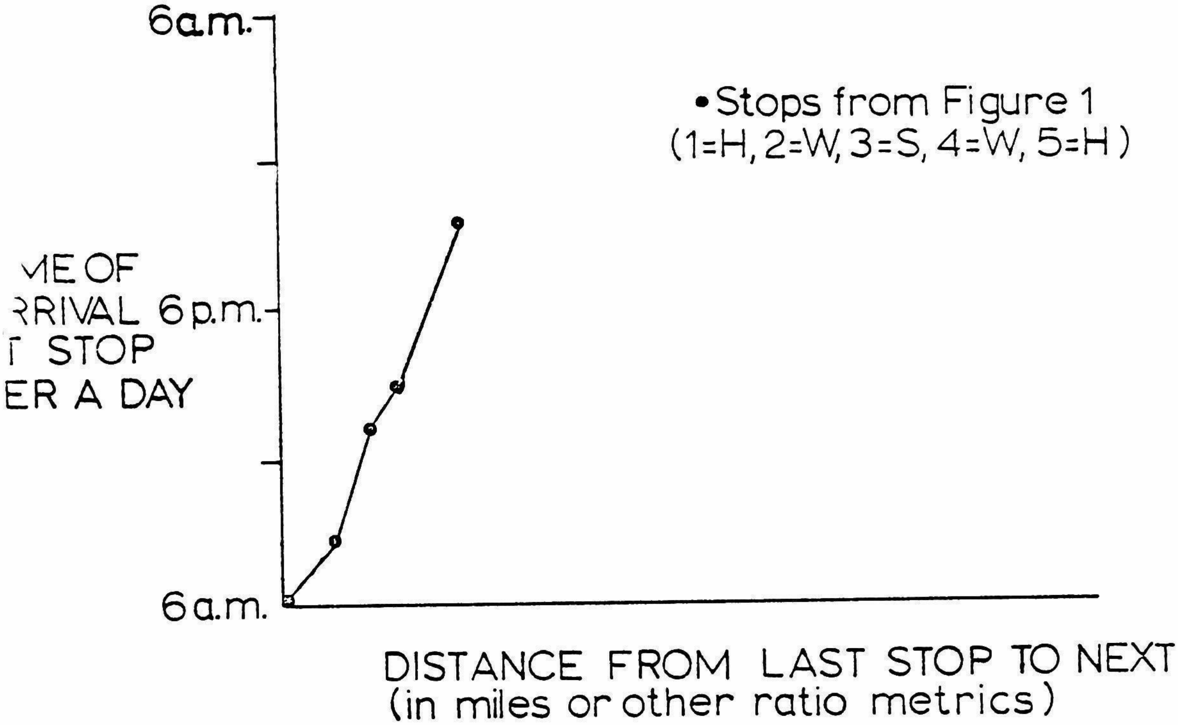
FIGURE 3 Plots of Representations of the n-Dimensional Paths of Selected Individuals in the Uppsala Data Set; Individuals 23051 and 3302 of Life Cycle Group 3 and 32021 of Life Cycle Group 2.

Note the simple structures, with interindividual differences implying some groups could be found: systematic differences appear between life cycle groups, but high within-group variation exists.

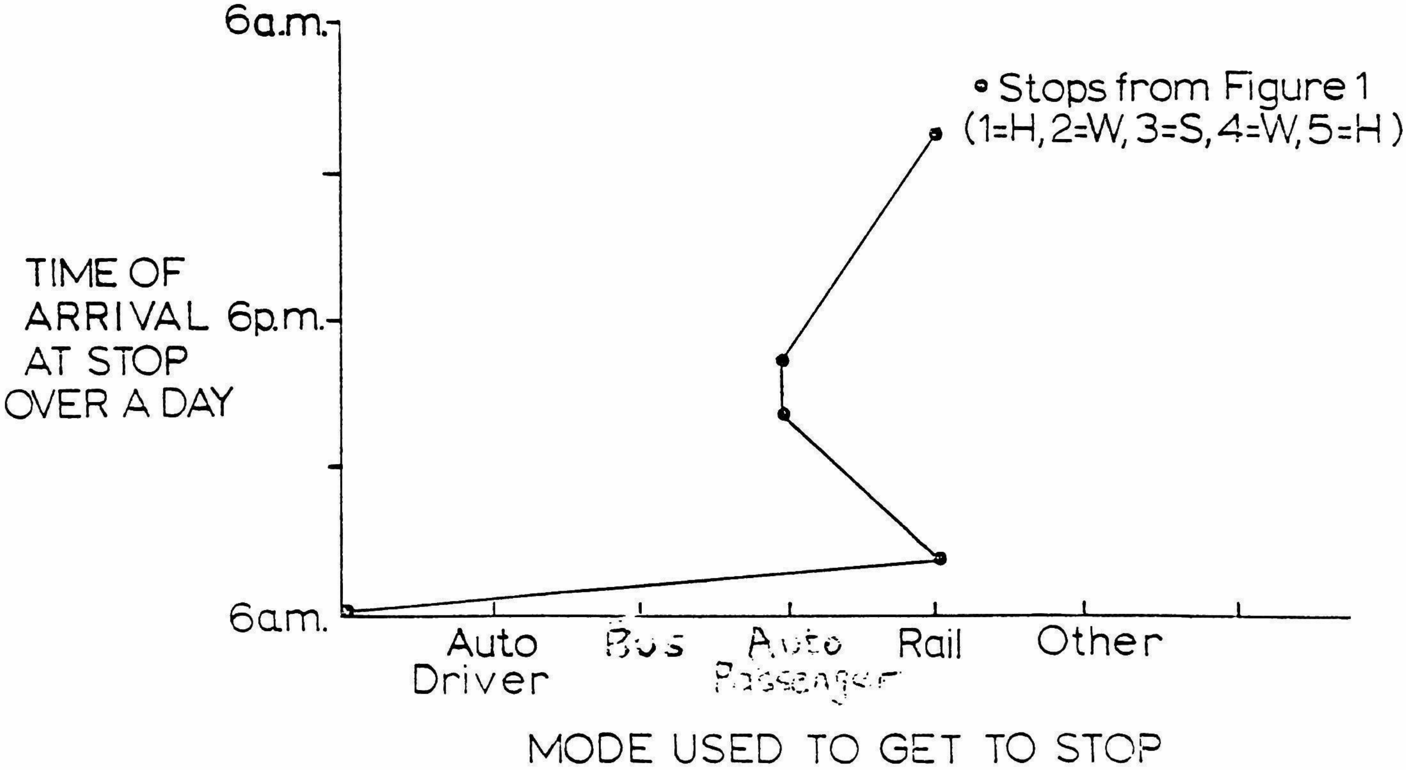
FIGURE 4 Plot of Group Space Derived from INSCAL Analysis of Trip Records of Aspects of Stops used in a Day
1 = MODE; 2 = TIME; 3 = LAND USE; 4 = ACTIVITY;
5 = N-S LOCATION COORDINATE; 6 = E-W LOCATION COORDINATE;
7 = DISTANCE

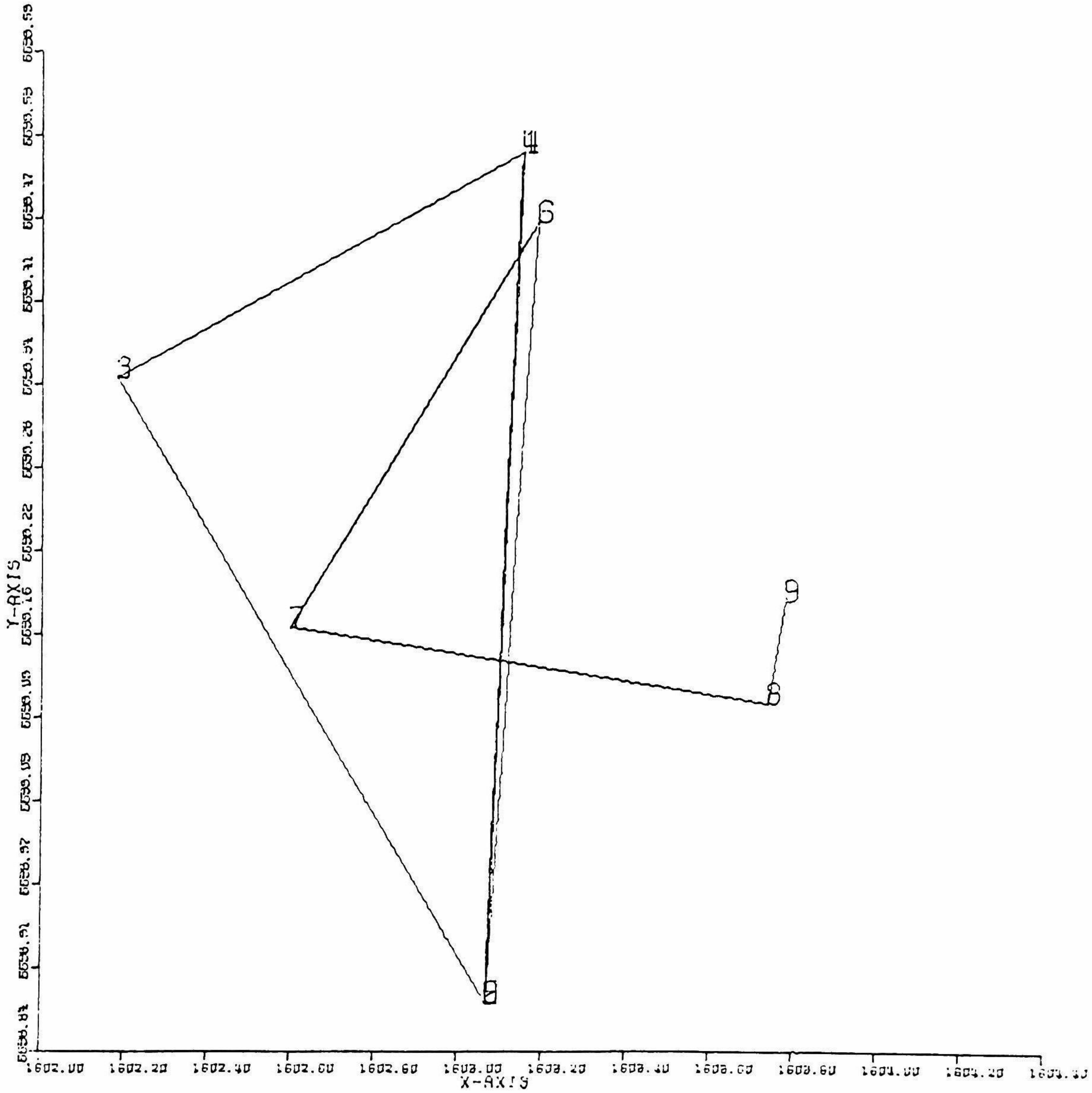

KEY
ACTIVITIES
H In-home
W Working
S Shopping
MODES
M1 Transit
M2 Passenger in friend's auto
--- Movement between stops (slope of line shows speed)
— Duration at stop
TIME
SPACE
H
M1
W
M2
S
M2
W
M1
H

A.

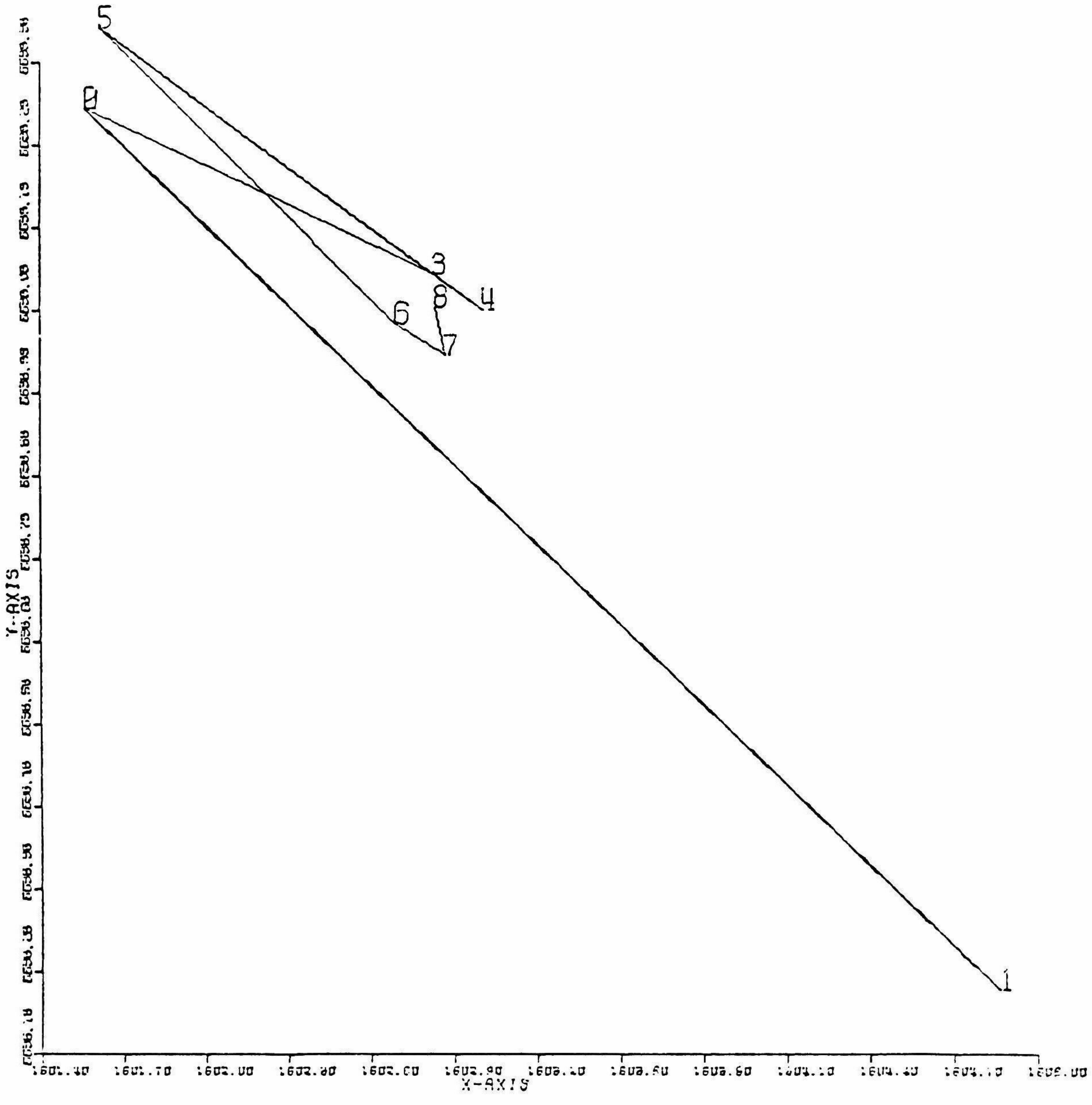

6a.m.
• Stops from Figure 1
(1=H, 2=W, 3=S, 4=W, 5=H)
ME OF
RRIVAL 6p.m.
T STOP
ER A DAY
6a.m.
DISTANCE FROM LAST STOP TO NEXT
(in miles or other ratio metrics)

B.

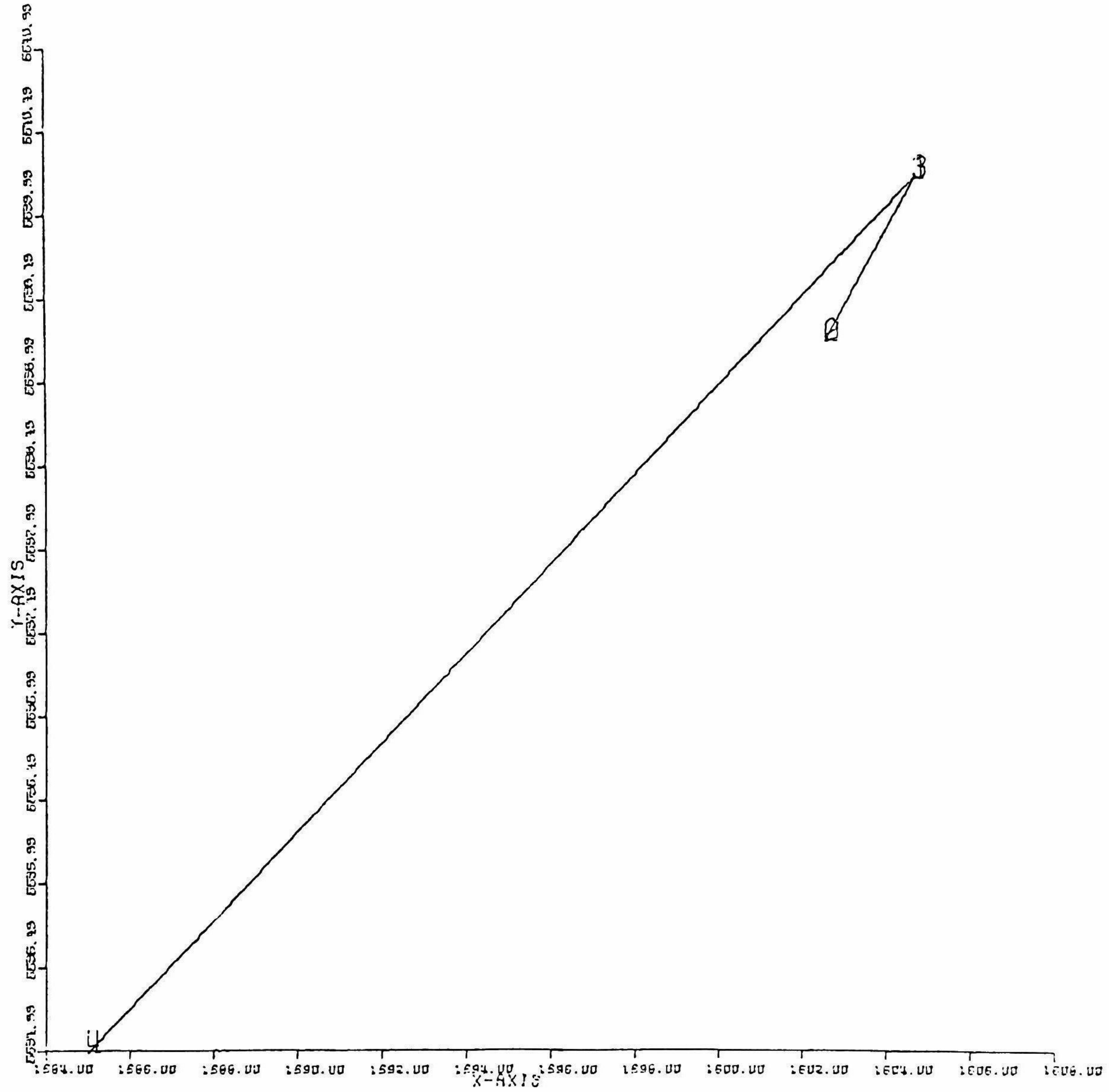

6a.m.
• Stops from Figure 1
(1=H, 2=W, 3=S, 4=W, 5=H)
TIME OF
ARRIVAL 6p.m.
AT STOP
OVER A DAY
6a.m.
Auto
Driver
Bus
Auto
Passenger
Rail
Other
MODE USED TO GET TO STOP



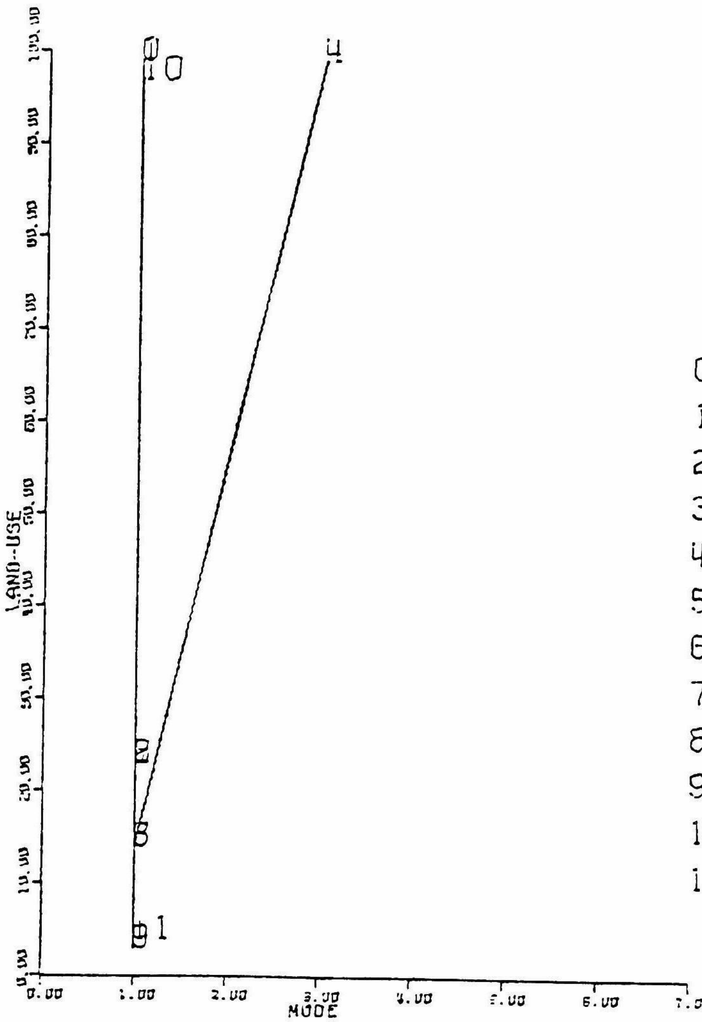
23051 3



33032 33

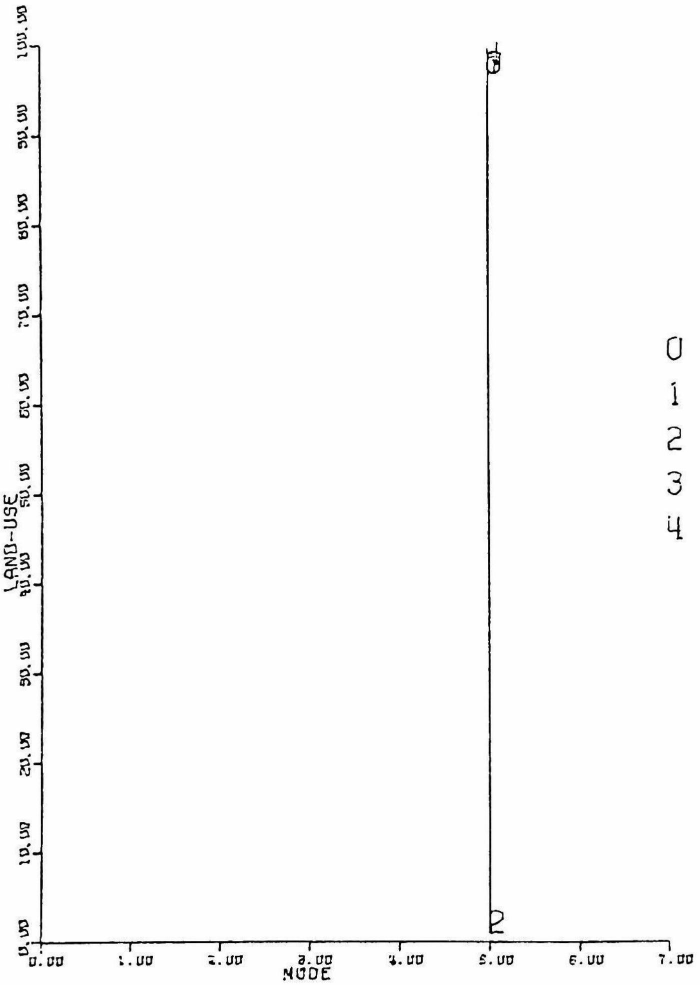


32021 20



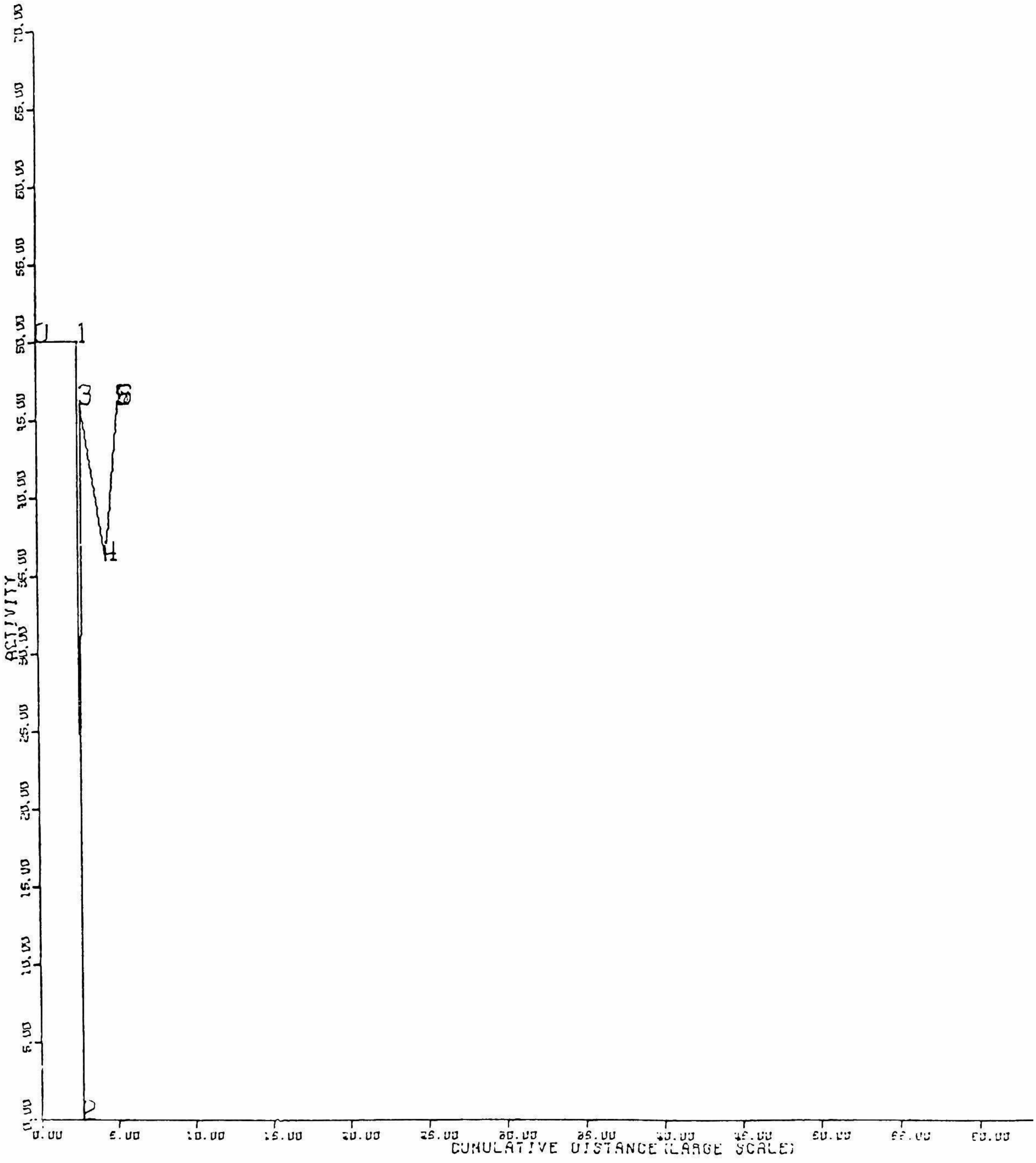
	MODE	LAND USE
0	1.00	99.00
1	1.00	99.00
2	1.00	23.00
3	1.00	14.00
4	3.00	99.00
5	1.00	14.00
6	1.00	23.00
7	1.00	23.00
8	1.00	23.00
9	1.00	3.00
10	1.00	97.00
11	1.00	4.00

33031 26

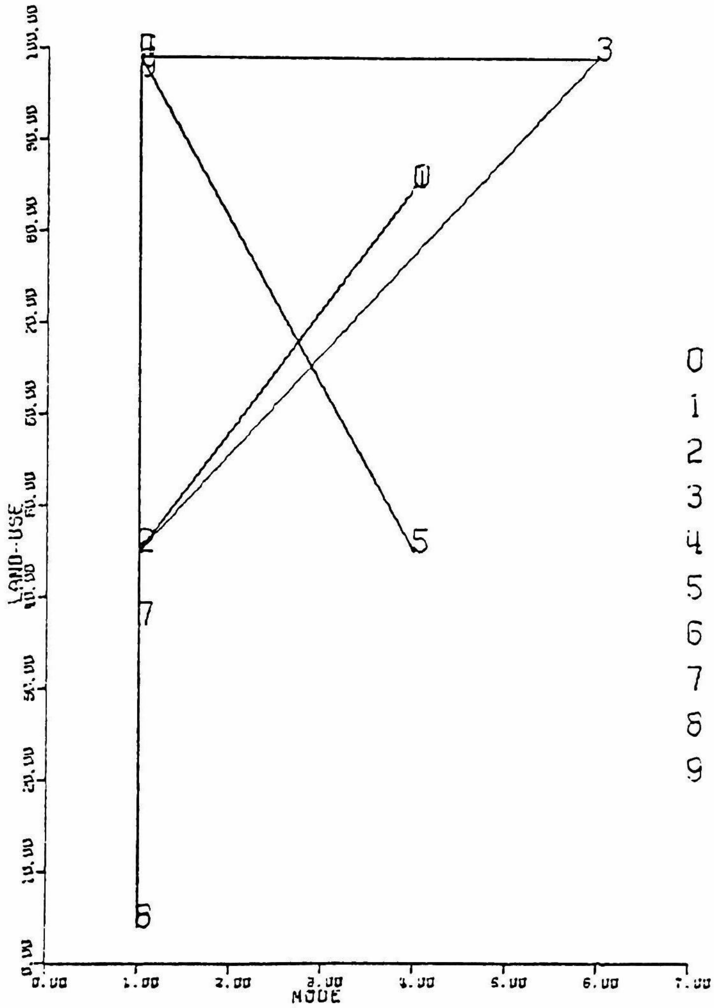


	MODE	LAND USE
0	5.00	97.00
1	5.00	97.00
2	5.00	1.00
3	5.00	97.00
4	5.00	98.00

32021 20

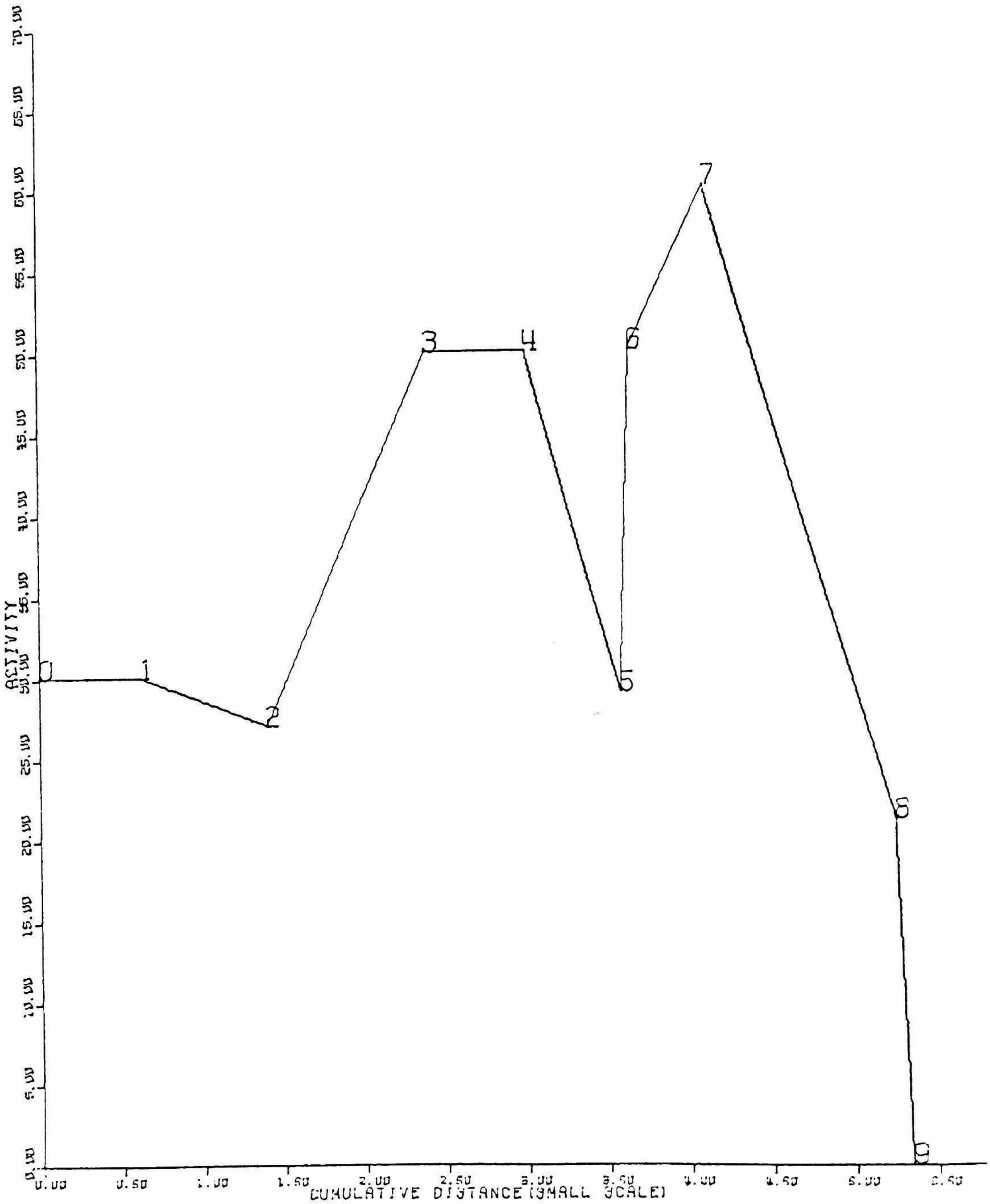


33032 33

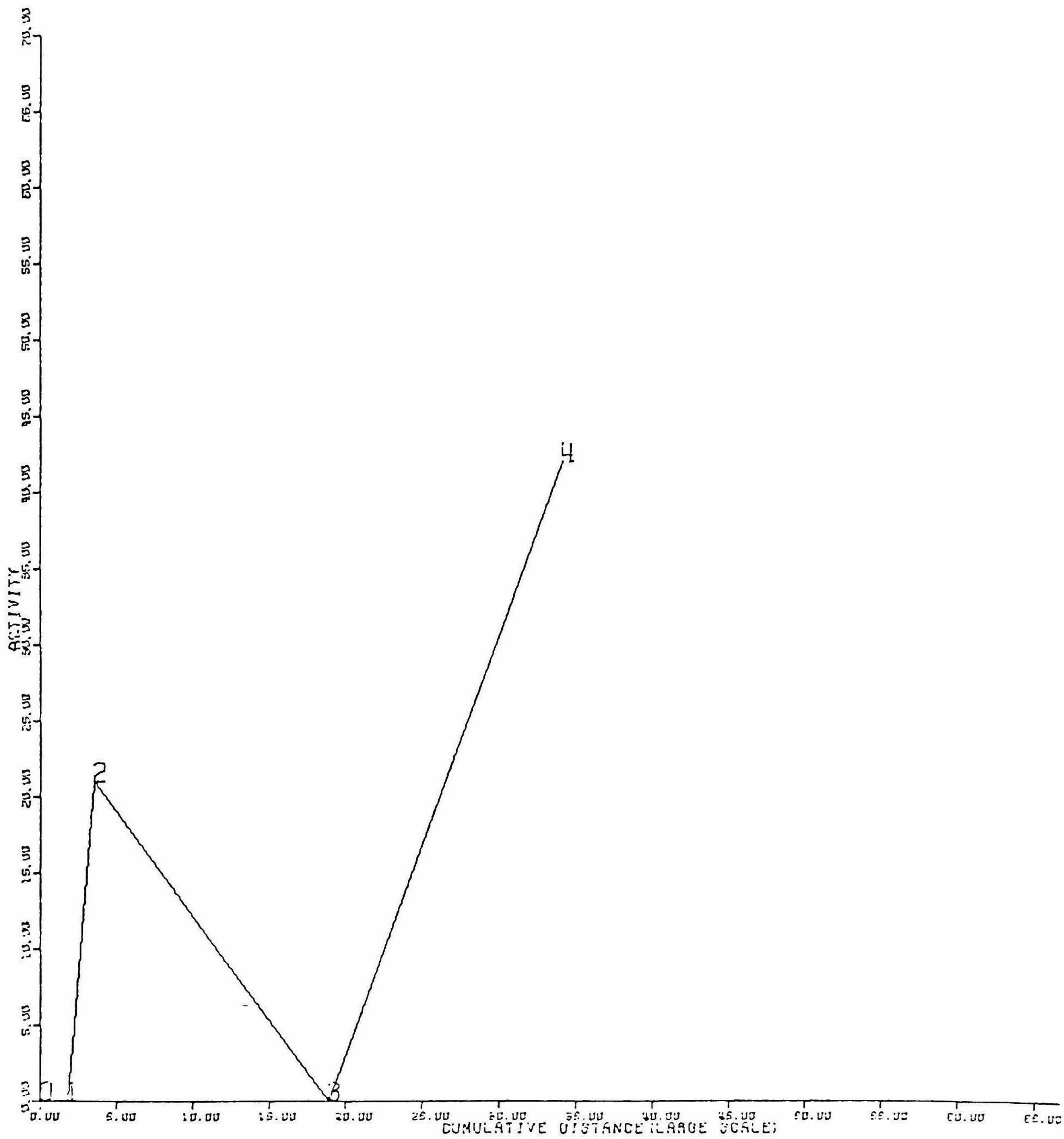


	NODE	LAND USE
0	4.00	85.00
1	4.00	85.00
2	1.00	45.00
3	6.00	99.00
4	1.00	99.00
5	4.00	45.00
6	1.00	99.00
7	1.00	37.00
8	1.00	4.00
9	1.00	97.00

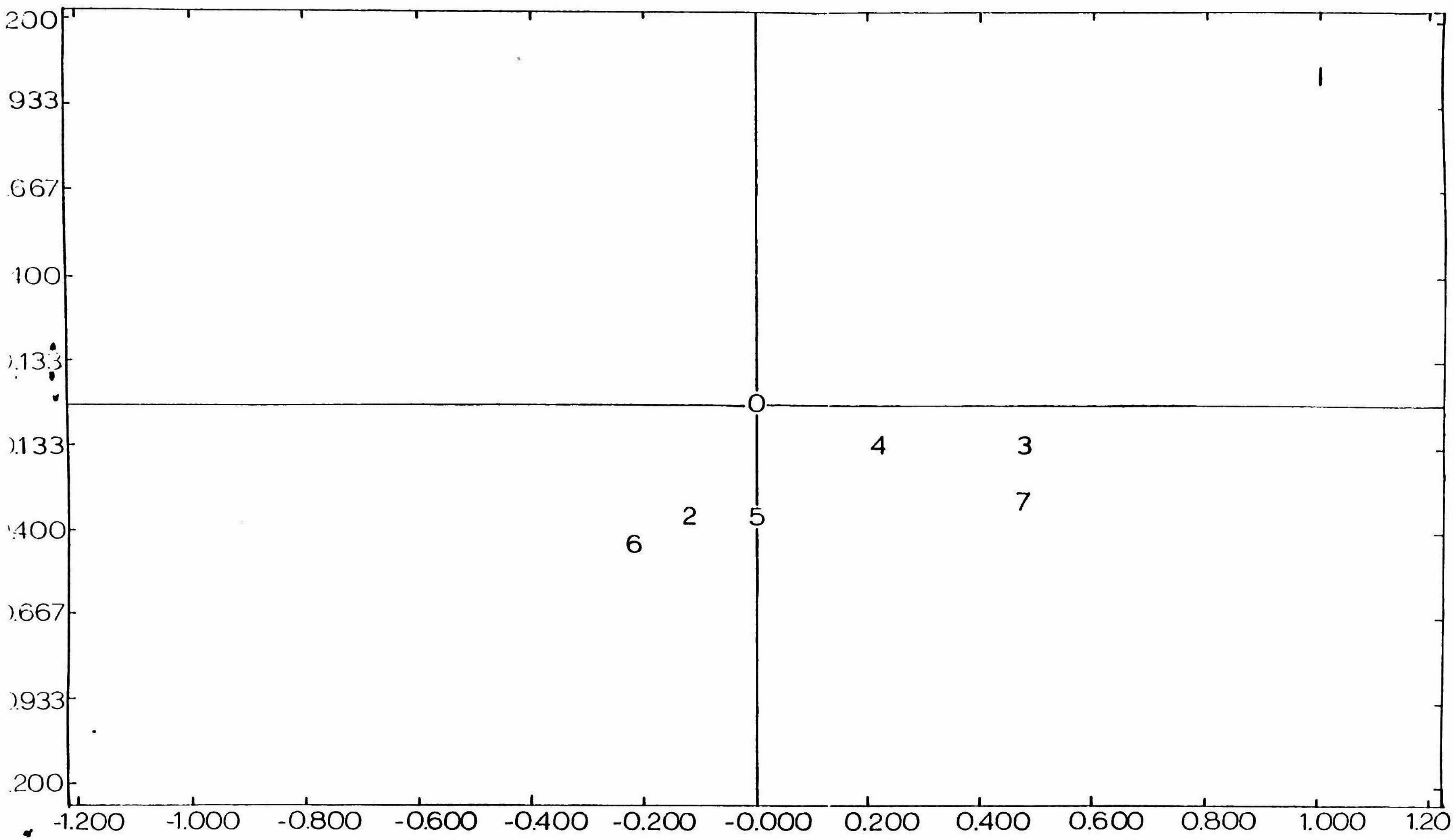
23051 3



23051 3



32021 20


200
933
.667
100
.133
0
.133
.400
.667
.933
.200
-1.200
-1.000
-0.800
-0.600
-0.400
-0.200
-0.000
0.200
0.400
0.600
0.800
1.000
1.20
1
2
3
4
5
6
7