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Authors
Recker, Will
McNally, Michael G.
Root, Gregory S.

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Will Recker
Michael G. McNally
Gregory S. Root

Department of Civil Engineering and
Institute of Transportation Studies
University of California, Irvine
wwrecker@uci.edu, mmcnally@uci.edu

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Institute of Transportation Studies
University of California, Irvine
Irvine, CA 92697-3600, U.S.A.
http://www.its.uci.edu

A Model of Complex Travel Behavior:
Part I - Theoretical Development

by

W.W. Recker
Institute of Transportation Studies
and Department of Civil Engineering
University of California, Irvine, CA 92717, USA

M.G. McNally*
Department of Civil Engineering
and School of Urban and Regional Planning
University of Southern California, Los Angeles, CA 90089, USA

and

G.S. Root*
Department of Civil Engineering
University of South Florida, Tampa, FL 33620, USA

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Abstract

This paper presents a policy sensitive approach to modeling travel behavior based on activity pattern analysis. A theoretical model of complex travel behavior is formulated on a recognition of a wide range of interdependencies associated with an individual's travel decisions in a constrained environment. Travel is viewed as input to a more basic process involving activity decisions. A fundamental tenet of this approach is that travel decisions are driven by the collection of activities that form an agenda for participation; the utility of any specific travel decision can be determined only within the context of the entire agenda.

Based on the theoretical model of complex travel behavior, an operational system of models, STARCHILD (Simulation of Travel/Activity Responses to Complex Household Interactive Logistic Decisions), has been developed to examine the formation of household travel/activity patterns, and is presented in a companion paper (Recker et al, 1985).

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*This work was conducted while these authors were research associates at the Institute of Transportation Studies, University of California, Irvine.

1. INTRODUCTION

This paper presents a theoretical model of complex travel behavior that places travel in a broader context than in single-trip methodologies. A fundamental tenet of this approach is that travel decisions are driven by the collection of activities that form an agenda for participation and, as such, cannot be analyzed on a link-by-link basis. Rather, the utility of any specific travel decision can be determined only within the context of the entire agenda.

A significant element in the development involves the formulation of a theory and model of individual choice set formation that includes both the effect of environmental/household constraints and that of individual limitations with respect to information processing and decision making. An alternate view of utility maximization and its relationship to decision making is presented in which the utility of a decision is based on both the outcome of the decision and the decision process itself.

Empirical findings have documented that individuals employ a wide variety of strategies when faced with restrictions imposed by transportation policies (e.g., decreased transit service, gasoline restrictions). These strategies range from simple modal shifts to more complex adaptations involving trip consolidation (i.e., chaining), activity rescheduling, and destination substitution. Conventional travel demand models, however, are unable to reflect (and hence, predict) these complex responses as a result of several theoretical shortcomings. In addition, estimation of the likely impacts of various activity system policies (e.g., flextime, extended hours for service facilities) is outside the realm of the present models. This paper attempts to address these shortcomings by restructuring the prevailing microeconomic theory of travel behavior in a manner that facilitates an increased understanding of complex travel behavior and provides an additional capacity for analyzing policy impacts.

The intent of the proposed theoretical development is to offer a potential explanation of complex travel behavior, characterized by three major facets:

(1) the development of individual activity programs, reflecting basic activity needs and desires, and, additionally, elements of household interaction and environmental constraints,

(2) the generation of activity pattern choice sets from individual activity programs, reflecting the combinatorics of feasible pattern generation, and, additionally, various cognitive decision rules producing distinct and/or non-inferior patterns,

(3) the specification of a pattern choice model reflecting only those attributes consistent with the components of the theory.

The proposed framework integrates a wide range of decision rules in each facet, involving interdependencies in: (a) activity generation and allocation, (b) potential scheduling and participation, and, (c) actual choice, or more accurately, constrained preference and choice. Although the research presented in this paper represents incomplete theoretical development of the each facet, it nevertheless provides an initial exposition of a comprehensive theory and model.

After a review of current approaches to complex travel behavior, the theoretical model is summarized, and the operationalization of its components is presented. A companion paper (Recker et. al., 1985) presents the operational model system and provides a summary of initial model empirical results as well as an extensive discussion of present shortcomings and future promise of the activity-based approach.

2. REVIEW OF CURRENT APPROACHES

The significance of the proposed approach to complex travel behavior is positioned relative to criticisms of past approaches, and within various perspectives offered by researchers active in the field. This prefaces a review of pertinent activity-based studies, which in turn leads to a statement of research objectives.

2.1 Criticisms and Perspectives

The activity-based approach to travel behavior has emerged over the past decade in response to widespread dissatisfaction with trip-based travel demand models. Proponents of the approach have discussed extensively both the weaknesses and limitations of current disaggregate models as well as the basic underlying assumptions that give rise to these shortcomings (Heggie, 1978; Burnett and Thrift, 1979; Jones, 1979; Burnett and Hanson, 1979). These shortcomings may be briefly summarized as:

(1) ignorance of travel as a demand derived from activity participation decisions;

(2) misrepresentation of behavior as an outcome of a true choice process, rather than as defined by a range of complex constraints which delimit (or even define) choice;

(3) inadequate specification of the interrelationships between travel and activity participation and scheduling, including activity linkages and interpersonal constraints;

(4) the construction of models based strictly on the concept of utility maximization, neglecting substantial evidence relative to alternate decision strategies involving household dynamics, information levels, choice complexity, discontinuous specifications, and habit formation;

(5) misspecification of the individual choice set, resulting from the inability to establish distinct choice alternatives available to the decision maker in a constrained environment.

These theoretical deficiencies appeared as most prominent, perhaps, in the overriding inability of conventional models to adequately perform in complex policy applications. Despite these limitations, conventional approaches continue to provide operational models which perform well in certain well-defined situations (Allaman et al., 1982). Activity approach proponents have suggested continued research and development with conventional disaggregate models (Jones, 1979); however, they are also well aware of associated limitations. Talvitie, et al., (1981) summarize their comprehensive assessment of travel demand models by suggesting the thinking or rethinking of basic concepts and approaches, particularly the theory, which they describe as "incomplete at best."

The rationale underlying the activity approach has been discussed by many authors (Heggie, 1978; Heggie and Jones, 1978; Hanson, 1979; Jones, 1979, 1981; Jones, et al., 1983; Kutter, 1981), and the primary perspective is clear--that of understanding complex behavior. As such, the focus of activity-based research has turned toward the explanation of behavior rather than its prediction, and the key issue raised is what constitutes activity behavior. Damm (1983) reviews several alternate interpretations of the dimensions of activity behavior (depicted as activity patterns) ranging from a few isolated explanatory variables (Adler and Ben-Akiva, 1979; Damm, 1980) to a multitude of dimensions, either stated explicitly (Burnett and Hanson, 1979) or implicitly (Hägerstrand, 1974; Jones, et al., 1983; Recker, et al., 1980). Damm (1983) concludes that once agreement on this issue is attained, then comprehensive theories and testable hypotheses will follow.

2.2 The Activity-Based Approach

The activity-based approach to complex travel behavior analysis often has been characterized as fragmented and lacking a sound methodological foundation. In a classification of activity-based approaches, Golob and Golob (1983) suggest this lack of cohesive theory is "compensated for by a profusion of concepts and methods."

This profusion of research directions, while contributing strongly to a growing empirical base (see, for example, Damm, 1983) and further illustrating the failures of existing analysis techniques and the promise of the activity approach, has made only marginal contributions toward a new theoretical basis.

The lack of such a comprehensive theory can be advantageous to a growing field in providing a wealth of potential contributions, but also requires that research hypotheses and results be scrutinized to focus the field on promising avenues of future research. Reviews of the field abound. Damm's (1983) comparison of empirical results closely parallels the critical analysis and research taxonomy of Root, et al. (1981). Jones (1983) provides an assessment of practical applications of activity-based models, and Golob and Golob (1983) nicely position advances in activity-based methods relative to conventional approaches to the analysis of travel behavior. Sociological, geographical, and other approaches are reviewed by Hanson (1979, 1982) and by Wigan and Morris (1981).

Faced with a methodological approach already quite complex, most research has focused on the individual as the base unit of analysis. Those studies which were conducted at a household level did so through a fairly aggregate approach such as introducing household characteristics into econometric or other empirical models (Hartgen and Tanner, 1970; Damm, 1979; Adler and Ben-Akiva, 1979; Kitamura, et al., 1981; Landau, et al., 1980). Although early research had established empirical regularities in household linkages (Hanson, 1979), the individual was taken as the decisionmaker of interest (Landau, et al., 1980; Supernak, 1981).

The Swedish constraint-based framework (Hägerstrand, 1974; Pred, 1973, 1977) strongly suggested the influence of household interdependencies in travel behavior, and many of the concepts have been explored in depth by the Transport Studies Unit of Oxford (see Jones, et al., 1983). A host of other researchers have expanded and refined the Hagerstrand framework, including Cullen's (Cullen, 1972; Cullen and Godson, 1975) work on the decision structures leading to the organization of individual activity patterns, Lenntorp's PESASP model (Lenntorp, 1976), the methodological approach to accessibility of Burns (1979), and research on behavior definition and measurement issues by Burnett and Hanson (1982). Each of these approaches focused on individual activity patterns, but sets the individual decision process "within the context of the household" (Clarke, 1985). Studies of household interdependencies have integrated lifestyle and role concepts into activity pattern analysis (Kutter, 1973; Chapin, 1974; Fried, et al., 1977; Brog and Erl, 1982; Salomon and Ben-Akiva, 1982).

In a similar vein, the analysis of observed behavior in early research studies focused on elements of travel and activity participation, such as tours or periods of the day (Chapin, 1974; Damm, 1979; Kitamura, et al., 1981). The complexity of daily activity patterns stymied comprehensive empirical research, since patterns were difficult to quantify and thus classify. Recker, et al., (1980, 1983b) and Pas (1982) developed techniques to classify observed activity patterns and produce meaningful interpretations, referred to as representative activity patterns. Clarke (1985) questions the representativeness of daily patterns due to fluctuations over longer periods of time, and cautions that researchers should consider this when classifying patterns. Pas and Koppelman (1983) and Hirsh, et al., (1984) have analyzed weekly activity patterns as a sequence of daily patterns. These methods classify patterns within a population, and do not focus on individual pattern formation.

The development of a theoretical framework within which individual behavior can be explained through the generation of activity pattern choice sets and choices has been slow. Havens (1981) reviews three similar comprehensive abstract models (Hartgen and Tanner, 1970; Fried, et al, 1977; and Allaman, et al, 1982) which are intuitively acceptable, yet not formulated sufficiently to allow operationalization of model components. Most successful empirical research has proposed less grand theoretical schemes, yet have added an empirical base upon which the research presented herein builds. Clarke (1985) categorizes the major studies as either "choice-based" or "constraint-based." The former group include the work of Damm (1979, 1980, 1984) on activity scheduling, Van der Hoorn's (1979, 1983a, 1983b) comprehensive logit-based full pattern generation model, and the work of Hirsh, et al., (1984) focussing on the weekly activity pattern. The constraint-oriented studies employ similar pattern choice set generation routines. Lenntorp's PESASP model (1976, 1978) generates the number of pattern choice alternatives in a constrained environment, but is limited in that no potential choices may be identified. Clarke's CARLA (Clarke, 1980, 1985; Jones, et al., 1983) is more complex and focused more on the choice set generation process. Finally, the work of Recker, et al., (1983a, 1983b, 1985a) extends the generation process to include an actual pattern choice model. The ongoing development of the STARCHILD Model System (Recker, et al., 1983a; Recker and McNally, 1985b) reflects an attempt to establish a comprehensive methodological framework capable of analyzing travel behavior decision processes as an integrated whole.

2.3 Modeling Approach

The model presented in this paper is characterized by several significant departures from current approaches. First, in contrast to many studies of travel behavior, activities are treated explicitly. Travel demand is specified in terms of a set of desired activities (an activity program) and travel is viewed as arising from a more fundamental process of scheduling the activities within an available period of time. Second, by focusing on the individual's entire activity pattern, the theoretical development incorporates the interrelationships among individual activity scheduling decisions. Third, the effect of the spatial and temporal characteristics of the transportation and activity systems on travel behavior is explicitly incorporated in the theoretical model--a feature that allows a much wider range of transportation related policies to be analyzed. Fourth, the interdependencies among individual members of a household are introduced through the use of several household constraints (e.g., activities performed jointly by several household members, the temporal availability of household automobiles) and decision objectives (e.g., maximizing the amount of time spent at home with other household members). Fifth, a choice set estimation procedure is advanced that recognizes the individual's perceptual thresholds and limited evaluative capabilities and is employed to reduce the choice set to a size that can be accommodated by existing choice models.

The potential for future research advances is built into the model framework. Investigation of the effects of household structure on activity scheduling behavior may be approached through the estimation and testing of activity pattern choice models for separate life-cycle groups, or by expanding the proposed pattern choice along dimensions beyond the theoretical derivation (e.g., constants, socio-economic variables). An investigation of the relationship between choice complexity and individual decision rules can be performed via the specification and statistical testing of different types of choice set formation models.

From a policy perspective, the proposed model provides a methodology whereby the potential impact of various transportation-related policy options on the travel/activity behavior of individuals can be assessed. A preliminary policy application may be found in Recker and McNally (1985a).

3. THEORETICAL DEVELOPMENT

A myriad of behavioral hypotheses have been advanced offering (predominantly) partial constructs directed toward a better understanding of complex travel behavior. Clearly, the advancement of a more comprehensive theoretical framework necessarily demands specification of exactly what behavior is to be understood, explained and, perhaps, predicted. Disaggregate analysis of individual complex behavior, while both intuitively attractive and acceptable, must be approached contextually from the standpoint of household decision structures. While the behavior in question is clearly focused on the individual as the "unit" which implements decisions resulting in travel and activity participation, the decision structure itself is heavily influenced by interdependencies at the household level.

The consensus of prior activity-based research suggests that there are three integral concepts which are central to a comprehensive theory:

(1) travel as a derived demand

(2) a constrained choice environment, and

(3) interdependencies within the decision making process.

The first, a fundamental tenet of activity-based approaches, is most closely associated with individual behavior, and will be discussed in detail below. The role of constraints is manifold, simultaneously defining the limits of potential activity participation and affecting the decision structure itself. Indeed, preference is best stated as constrained preference in activity models, and choice is often more of a constrained outcome than a true selection process. Whereas temporal, spatial, and transportation constraints are quite readily integrated within the individual behavior paradigm, interpersonal constraints which exist on the household level affect not only the execution of travel patterns, but the generation of activities as well.

It is postulated that the generation and allocation of activities occurs at the household level, from any of a variety of household decision rules (see Recker, et al., 1985b). A household activity program spawns individual activity programs, each implicitly reflecting decision rules and constraints at both the household and individual levels. Activity participation is formulated as an individual constrained choice process subject to the outcome of activity generation and allocation. The individual, of course, participates to some degree in the household decision making processes. The generation and allocation decision rules are beyond the scope of the present paper; the participation decision rules are discussed below.

The behavior in question is characterized by not only the decision-making unit, but also the timeframe defining those decisions. The actual generation and allocation of activities occur continuously over a multitude of timeframes, however, the execution phase is most conveniently conceptualized as a daily pattern when the actual participation and scheduling choices are implemented. The theoretical model proposed in this paper attempts to explain behavior at the household level, for any timeframe, but does so by constructing individual daily activity programs which result in daily activity patterns. Figure 1 depicts the proposed theoretical framework in parallel with observed behavior, and illustrates the interaction of the basic concepts.

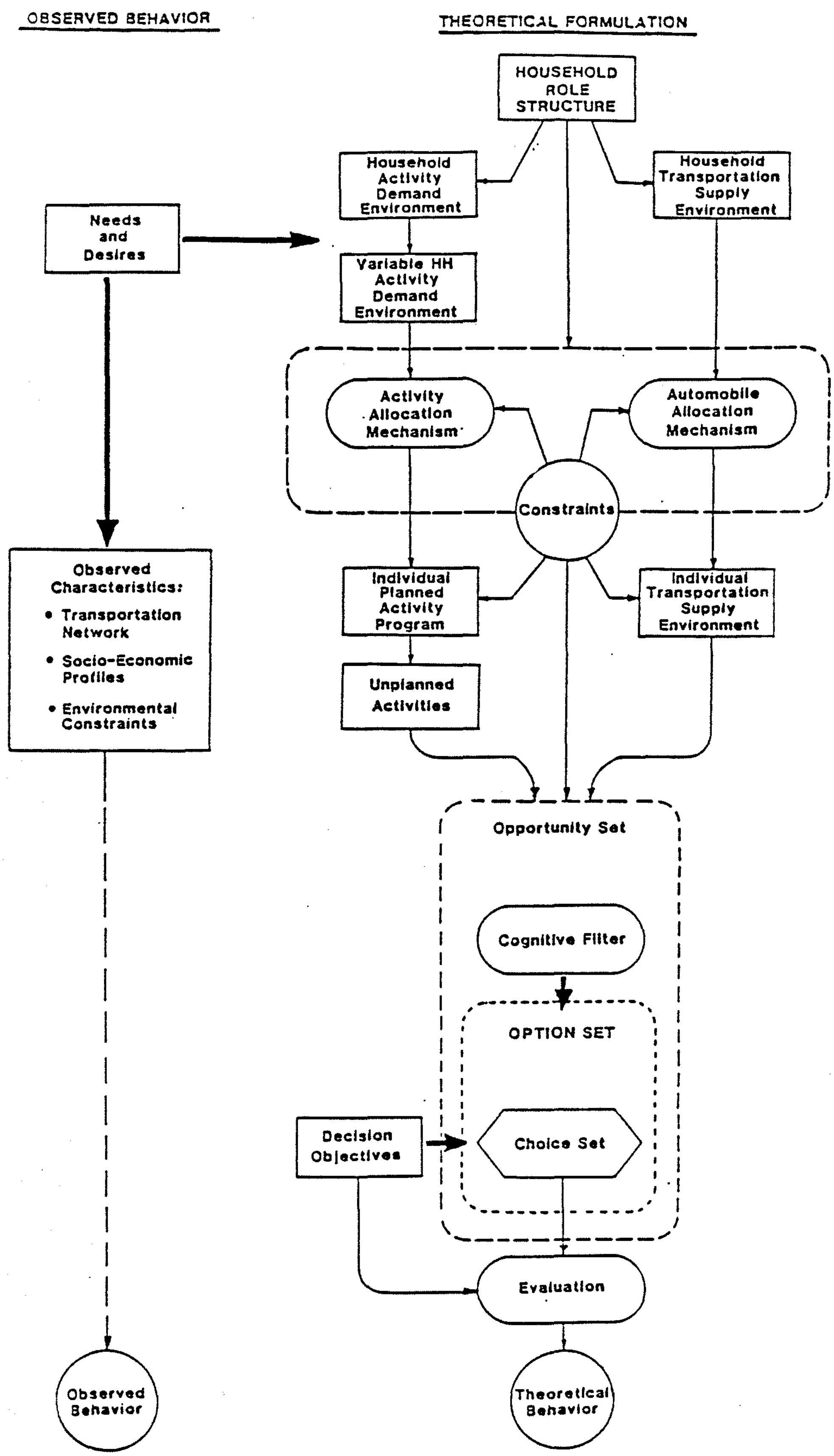

FIGURE 1 - THEORETICAL MODEL

3.1 The Relationship between Travel and Activity Scheduling

Travel decisions are subsidiary to activity participation decisions in accord with the accepted characterization of travel as derived from the need to participate in various activities distributed over space and time; travel choices are viewed as arising from a more fundamental set of activity participation choices. The set of activities, together with their salient attributes, generated and allocated to a household member and scheduled for completion during a specified time interval, is designated the individual's activity program, P, which represents the demand for travel during that time interval. Individuals are faced with a set of decisions involving the scheduling of the activities contained within the activity program and, correspondingly, the travel linkages which connect the activities in the time-space continuum. Once implemented, these activity scheduling decisions transform the individual's activity program into an activity pattern, AP, which is an ordered sequence of activities and travel accomplished during some time period, termed the action period. This sequence can be represented as:

$$AP = d \circ P \; ; \; d \in D \qquad (1)$$

where: d = the set of activity scheduling decisions made by a particular individual

D = the total collection of feasible activity scheduling decision sets available to a particular individual.

Implicit in an individual's selection and implementation of a specific activity pattern is the selection and implementation of an entire set of decisions concerning the scheduling of activities. Within this context, travel is seen as the mechanism that allows an individual to schedule activities in a particular manner and consequently, complex travel behavior is the resultant of complex activity scheduling behavior.

Prior to the examination of the resultant set of activity scheduling decisions made by the individual (i.e., the observed activity pattern), those sets of activity scheduling decisions that could be implemented by the individual (i.e., the feasible activity patterns) must be identified. A variety of constraints that limit the number of feasible activity patterns is specified by the nature of the transportation supply environment; the actual opportunities available to the individual are the result of the interaction between this environment and the individual's activity program (see Figure 1).

The set of opportunities theoretically available to the individual comprises all of the feasible activity patterns, that is, all of those activity patterns that do not violate any of the constraints imposed by the interaction between the individual's activity program and his/her transportation supply environment. This pattern set is termed the opportunity set (see Figure 1). This set formation process restricts the number of available options; yet that number, in general, will be quite large--a consequence that is problematic from both operational and behavioral points of view. Furthermore, there is no guarantee that the resulting feasible activity patterns are perceived by the individuals as distinct options. Certain activity patterns, because of their similarity along a number of dimensions, may be perceived by the individual as being indistinguishable and therefore not treated as separate alternatives. It is hypothesized that a classification reduction process operates on the opportunity set in such a manner that distinct elements are produced. Various decision rules may be applied before or after the classification process, further narrowing the set of alternatives (the option set of Figure 1). Consequently, the actual choice set can be represented as:

$$C = \psi \circ F \qquad (2)$$

where: C = the perceived choice set of an individual

F = the opportunity set (or, alternatively, the option set) available to a particular individual

ψ = a classification reduction process that operates on the opportunity set in such a manner that distinct (independent) options are produced.

The output of this classification and decision procedure consists of a smaller set of distinct activity patterns that comprise the individual's choice set. This resultant choice set can be characterized by the following properties:

(1) The number of alternatives contained in the choice set is smaller than the total number of opportunities available to the individual.

(2) The choice set is composed of distinct alternatives.

(3) The alternatives reflect the effects of both environmental and household constraints.

(4) The choice set varies across individuals and over time (as a result of the variations in constraints and activity programs).

3.2 Representation of the Activity Program

In general, the activity program of an individual can include both planned and unplanned activities, or:

$$A = \{Z, X\} \qquad (3)$$

where:

A = the set of n activities $(a_1, a_2, \ldots, a_j, \ldots, a_n)$ comprising the individual's activity program.

Z = the subset of planned activities $\{Z_O, Z_H\}$

X = the subset of unplanned activities $\{X_O, X_H\}$

The subscripts "O" and "H" are used to designate out-of-home and in-home activities, respectively.

In the context of the present development, the term "planned" refers to those activities for which the scheduling process occurs prior to the action period, while "unplanned" refers to those activities for which the scheduling process occurs during the action period. Both types of activities occur, of course, during the action period. When an individual commences an action period, the corresponding activity program comprises planned activities only, with a probability of occurrence associated with potential unplanned activities.

Formally, the activity program, P, comprises a list of activities and their salient attributes including activity type, expected duration, and desired location for planned activities, and distributions of duration and location for potential "unplanned" activities. This activity program is transformed thorough a set of activity scheduling decision rules (Eq. 1) into a set of feasible activity patterns, each fully specified according to location, mode and travel time to the activity, arrival time, waiting time, activity commencement and completion time, or:

$$AP = \{(j, \ell_j, d_j, g_j, s_j, c_j),\ \forall\ j;\ (j^*_j, \ell^*_j, d^*_j, g^*_j, s^*_j, c^*_j),\ \forall\ j^*\} \qquad (4)$$

where:

j = the jth planned activity

ℓ_j = the location of the jth planned activity

d_j = the departure time of the trip to activity j

g_j = the arrival time at ℓ_j

s_j = the starting time of participation in activity j: $s_j \geq b_j$

b_j = the beginning of temporal availability of activity j

c_j = the completion time of participation in activity j: $c_j \leq e_j$

e_j = the end of temporal availability of activity j and where the starred "*" quantities are similarly defined for unplanned activities.

In theory, the activity program reflects the range of constraints which delineate the extent of feasible participation and travel. Temporal, spatial, and transportation attributes are primarily fixed once the action period commences; interpersonal constraints are best handled in a dynamic fashion, as the scheduling behavior of two or more individuals is in question. The proposed model, however, represents planned, individual activity programs explicitly, which give rise to a static, quasi-equilibrium activity pattern for that individual, and represents unplanned activities and some interpersonal constraints, in a stochastic fashion, as characteristics of the activity program as a whole.

3.3 The Utility of the Activity Pattern

The utility of any specific activity pattern to an individual is assumed to be comprised of the utilities of each of its time-component parts. Each activity segment of an activity pattern can be represented as a triad consisting of: (1) travel time (if any) to the activity, (2) waiting time (if any) for the activity to commence, and (3) actual participation time.

It is convenient to visualize the action period as comprising these time segments for each activity. The total time, Q_j, associated with any activity j is given as:

$$Q_j = D_j + T_{j,j-1} + W_j \qquad (5)$$

where:

D_j $= c_j - s_j$

= time spent participating in the jth activity

$T_{\ell\ell'}$ = time spent traveling from location of activity ℓ' to location of activity ℓ

W_j $= s_j - g_j + d_j - c_{j-1}$

= time spent waiting prior to participation in the jth activity;

and the summation over all activities in the program must equal the length of the action period.

In addition to their inherent attributes, activities have two functional classifications of importance: the first involving whether or not knowledge that the activity would be performed preceded the action period during which it is performed (i.e., planned vs. unplanned), and the second relating to whether or not the activity is performed at home (i.e., in-home vs. away-from-home).

Planned activities are functionally different from their unplanned counterparts in that the latter must be inserted into an existing activity pattern which may already contain commitments with varying degrees of rigidity. Indeed, the probability that unplanned activities may arise during the action period can be expected to influence the amount of flexibility built into the "planned" executable activity program on an individual's agenda at the commencement of the action period.

The home is an activity location of special significance that simultaneously offers the maximum amount of privacy from non-household members and the maximum potential for interaction among household members. More importantly, it represents the base for staging an individual's activity pattern. The value of time spent at this location may be as much determined by the activity schedules of other members of the household as by the inherent characteristics of the location itself.

The discussion that follows is organized according to these functional classifications.

Planned Activities

Participation in planned activities, whether in-home or away-from-home, is predicated on the availability within the individual's activity pattern of a segment of time greater than or equal to the time required to complete the activity. Since both the actual travel times to activity locations as well as the activity durations themselves are stochastic in nature, the individual can be expected to have incomplete information regarding the availability of time in the planned activity pattern. Because of the cumulative effect of these stochastic events, the individual can reasonably be expected to have more confidence in estimates of scheduling requirements associated with trips and activities that occur early in complex tours than with those that occur late in such tours, and also more with simple tours than with complex tours. Given that the utility of participating in an activity is only realized if the participation actually takes place, and there exists a non-zero probability that participation will not take place, individuals are assumed to consider the expected utility of participation in planned activities. Specifically,

$$E\{U(D_j)\} = U(D_j) \cdot P_j \qquad (6)$$

where:

$U(D_j)$ = the utility of time D_j spent participating in planned activity j,

P_j = the probability that sufficient time will be available to complete the planned activity associated with the jth position in the activity pattern,

and where $E\{\cdot\}$ denotes expected value. Examples of calculations of corresponding values of P_j can be found in Recker et al, (1983a)

Participation in certain activities may be dictated by schedules inherent to the activity (e.g., theater, physician visits). Arrival at a location prior to the scheduled start of an activity will, in such cases, result in a period of time spent by the individual waiting for commencement. It is assumed that individuals derive only disutility from time spent waiting to participate in out-of-home planned activities.

Waiting time associated with planned in-home activities is treated in a separate section. Travel is assumed to offer utility only within the context of the access it provides to a desired activity. Arguments relative to the disutility of travel are well documented and will not be repeated here. Rather than attempt to select a precise functional form, it will suffice to assume that the utility of time spent traveling to a planned activity is inversely related to the amount of time spent traveling and directly related to activity importance.

Potential Participation in Unplanned Activities

As a result of the possibility that unplanned actvities may arise during the action period, utility may be derived from reserving, within the planned activity pattern, the potential to participate in unplanned activities, that is, the flexibility to meet unforeseen needs. This potential is, in the most general sense, a function of the number of activity locations that an individual can access within a time sufficient to participate in the activity. The number of activity locations is itself a function of the volume of the space-time prism (Hägerstrand, 1973; Burns, 1979), the spatial and temporal distributions of activity locations, and the time required to complete the activity. The set of all points (k,t) in space-time that comprise the space-time prism, ρ, is defined by:

$$\rho = \{(k,t) \mid C_j + T_{kj} \leq t \leq S_{j+1} - T_{j+1,k}\} \qquad (7)$$

The maximum segment of time available for the performance of an unplanned activity is the difference between the latest starting time of the succeeding planned activity (a value itself dependent on attributes of the remainder of the activity program) and the completion time of the present planned activity, adjusting for both temporal availability of, and for travel time to and from the unplanned activity location.

The utility of reserving flexibility in the planned activity pattern for such unforeseen events is dependent upon the likelihood that they may arise. Specifically, the utility of potential participation is assumed to equal the utility of the expected time spent participating in an unplanned activity at a given location; that is, the product of the probability that the desire for the unplanned activity will arise, the probability that a given location will be selected given the activity's occurrence, and the actual utility of participation. This may be expressed as:

$$U_k(V_{j*}) = U_k\,(D_{j*k}) \cdot P_t\,\{k \mid j*\} \cdot P_t\,(j*) \qquad (8)$$

where:

$U_k(V_{j*})$ = The utility of the potential, V, to participate in unplanned activity j* at location k,

$U_k(D_{j*})$ = the utility of time spent participating, D, in unplanned activity j* at location k,

$P_t(k|j*)$ = the probability that unplanned activity j* will be participated in at location k given that unplanned activity j* occurs during time t,

$P_t(j*)$ = the probability that unplanned activity j* will occur during time t.

and where the utility of the total potential to participate in unplanned activities, U(V), is (assuming linearly additive utilities) simply the summation of $U_k(V_{j*})$ over all potential activities in the unplanned activity set and all potential locations for those activities.

The probability of occurrence of an activity is dependent both on the frequency of occurrence of the activity as well as on the time that has elapsed since the last occurrence of the activity.

In addition to the utility that is associated with the potential to perform unplanned activities, there will also be some utility (disutility) associated with the additional travel time that may be incurred if the individual participates in an unplanned activity. As in the case of planned activities, it is assumed that the utility of the additional travel time spent traveling to participate in an unplanned activity is directly related to the importance of the activity and inversely related to the amount of time spent traveling. However, since both the unplanned activity j^* and its location ℓ_{j^*} are unknown before the decision to perform the activity, the individual is assumed to act on the expected values of the potential activity and its associated travel time.

Finally, as in the case of planned activities, individuals are assumed to derive only disutility from expected time spent waiting to participate in unplanned non-home activities.

Discretionary Home Activities

As in the case with out-of-home activities, in-home activities may be planned in advance of the action period. In terms of any theoretical development, such cases do not differ fundamentally from out-of-home planned activities. A similar statement may be advanced regarding unplanned in-home activities. However, there is a third category of in-home activities that has no real counterpart in the away-from-home world--those that arise as a by-product of decisions that form the out-of-home activity schedule. For example, the decision not to chain two successive trips together implicitly creates an in-home activity that may simply be a default state for the individual.

In general, there may be many options within an activity program to include in-home activities. It is hypothesized that the utility of time spent participating in home activities, $U(D_h)$, is a function of the activities available to the individual during the stay at home. Information concerning the specific nature of activities available to individuals at home is often unobtainable from conventional travel diaries, however, one apparently reasonable assumption is that the utility of time spent at home is directly correlated to the number of activities available to the individual and that this number, in turn, is highly related to both the amount of time spent at home and the number of household members at home during the stay.

Since the number of household members at home at any time is dependent on their activity patterns (which are also stochastic in nature), an individual may not know with certainty these values but, rather, is assumed to act relative to the expected value.

The utility of travel time to home activities which are planned in advance of the action period does not differ, in any fundamental respect, from that associated with planned activities in general. For those home activities which arise as a by-product of activity/trip scheduling decisions, however, the trip purpose dependency is degenerative and the utility of the travel time associated with the trip to home is assumed to be inversely related to only the expected amount of time spent traveling.

There is no waiting time inherent to home activities that arise as by-products of activity/trip scheduling decisions. Waiting time associated with planned home activities does, however, differ fundamentally from that associated with out-of-home activities and is equivalent to time spent on in-home activities that arise as by-products. The corresponding utilities associated with such time are also equivalent, i.e., the utility of waiting time for planned in-home activities is presumed to equal that associated with an equivalent amount of time spent on unplanned, discretionary, in-home activities.

3.4 The Activity Schedule

The sequencing, prior to the action period, of the activities in the activity program constitutes the individual's planned activity schedule. The implementation of this schedule, subject to the possibility of unforeseen occurrences such as unplanned activities or travel delays, constitutes the individual's activity pattern. It is posited that the observed activity pattern is the manifestation of the individual's attempt to select the activity schedule which maximizes the utility of the activity pattern that can be expected to be executed during the action period. It is hypothesized that the individual will select activity schedule S_k if:

$$U(AP_k) > U(AP_p); \quad \forall S_p \in F \qquad (9)$$

where:

AP_k = the expected activity pattern that will arise from activity schedule S_k

$U(AP_k)$ = the total utility of the expected activity pattern arising from activity schedule S_k

This view is consistent with the notion that observed activity patterns which contain unplanned activities are derived from activity schedules which allowed for the possibility of their occurrence.

The total utility of the expected activity pattern derived from the activity schedule then can be represented as being comprised of the individual components of utility associated with each element of the pattern. In summary, these components are:

(1) the utility of participation and the utility of travel for planned activities,

(2) the expected utility of participation and the expected utility of travel for unplanned, non-home activities, and

(3) the utility of travel and the utility of time spent at unplanned and discretionary home activities (represented by the expected value of both time spent at home and the number of household members present during that stay).

4. QUANTIFYING THE UTILITY COMPONENTS

The basic assumption embodied in the theoretical development of the model is that individuals choose their daily activity schedule in such a way that they maximize their travel and activity utility. The operationalization of this theory as a model requires establishment of quantifiable measures of the utility components; these have presented below as developed for a prototype model of activity pattern choice.

4.1 Planned Activities: Participation and Travel

The expected utility $U(D_j)$ associated with time D_j spent participating in planned activity j is predicated on sufficient time being available to satisfactorily complete the activity. As such, it is reasonable to assume that, for any activity j, $U(D_j)$ is invariant with respect to D_j and dependent only on the nature of the activity. This is operationalized in the model by assuming that the $U(D_j)$ are dependent only on the importance of the activity to the household (rather than on the actual type of activity), categorized as: (1) very important, (2) important, (3) relatively unimportant, and (4) unimportant, consistent with information contained in the data set used for estimation of the prototype model.

To calculate the probability (P_j) that sufficient time will be available to complete the planned activity associated with the j^{th} position in the tour, a probability density function for the random component of travel time must be assumed. For example, if it is assumed that the random component of travel time to activity j is uniformly distributed over the interval $[-\delta_j/2, +\delta_j/2]$, then

$$P_j = \min\left[o\left(\frac{\omega_j}{\delta_j}\right), 1\right] \qquad (10)$$

where the expression

$$\omega = e_j - [d_{j-1} + E\{T_{j,j-1}\} + D_j] \qquad (11)$$

can be thought of as the "slack time" associated with the j^{th} activity in the tour since it is the difference between the expected participation completion time of the j^{th} activity in the tour (the sum of departure time from the previous activity, d_{j-1}, the expected travel time, $E\{T_{j,j-1}\}$, and the planned activity duration, D_j) and the latest time that participation can take place (e_j). If the slack time associated with an activity is large, then an individual could arrive at the activity location later than planned and still participate in the activity.

Equation (10) states that as the variation in the travel time from the $(j-1)^{st}$ activity to the j^{th} activity increases relative to the amount of slack time available, the probability that an individual will be able to participate in the j^{th} activity decreases. Although other assumed density functions will, in general, produce other forms for P_j, the simple uniform density assumed in this example is used in the estimation of the prototype model.

Individuals are assumed to travel only as a result of their need to participate in activities that are spatially separated, and consequently, are assumed to derive no utility from travel other than within the context of the activity being accessed. Since the act of traveling consumes time which could otherwise be spent performing activities, it is hypothesized that individuals desire to minimize the amount of time spent traveling. It is also hypothesized, however, that individuals place different weights on the utility they receive from traveling to activities based on the specific nature of the activities, and furthermore, that it is not the actual type of activity that influences the disutility of the associated travel but rather the importance to the household of participation in that activity. Correspondingly, the total amount of time spent traveling to activities in each of the four importance categories is calculated and distinct utility weights are proposed to exist for each of these four variables.

4.2 Unplanned Activities: Potential Participation and Travel

It has been hypothesized that individuals consider their potential to participate in unplanned activities when selecting an activity schedule. Under the assumption that the utility of participating in unplanned activity j is independent of location characteristics and duration (given sufficient time to complete the activity), the utility of the total potential to participate in unplanned activities can be expressed as

$$U(V^*) = \sum_{j} \sum_{k \epsilon \Omega^*} \mu_j \cdot P_t\{k|j\} \cdot \frac{1}{\gamma_j} \qquad (12)$$

where the probability of participation at location κ is approximated as:

$$P_t\{k|j\} = M_{kj}/M_j \qquad (13)$$

and

M_{kj} = aggregate number of trips to location k for activity j

M_j = aggregate number of trips to all locations for activity j

γ_j = average time between occurrences of activity j

μ_j = constant utility of participation time for a specific activity j

Ω^* = the set of all potential locations for which participation in activity j is feasible.

Since μ_j, M_j, and γ_j are constant for each particular value of j and M_{kj} is constant for any specific kj pair, then the utility of the potential to participate in unplanned activities will increase as the set of feasible activity locations increases. Before determining the set of feasible activity locations, the total set of locations at which activity type j can be performed must be identified as well as the space-time constraints (the locations of the planned activities and the times than an individual must arrive at and is free to leave from these locations).

Location k is included in the set of feasible locations if and only if the following two conditions are satisfied:

(a) the individual's expected time of participation completion in unplanned activity j at location k is less than or equal to the ending time of the availability of participation in unplanned activity j at location k,

(b) the individual's expected time of arrival at the location of the succeeding planned activity is less than or equal to the time required to commence participation in that planned activity.

These two conditions simply state that a location is included in the set of feasible locations if there is sufficient time for an individual to travel to the specific location, spend the desired amount of time participating in the activity and then reach the next planned activity prior to the time when he/she must participate in it.

The procedure outlined above determines whether or not a specific location should be included in the set of feasible locations for a particular type of activity. This procedure is then repeated for each of the other locations at which a specific activity could be performed, as well as for all other types of activities and for each pair of space-time constraints contained in the activity schedule.

To achieve some computational efficiency, the individual activity locations are aggregated into zones and the set of activity types that are evaluated as potential unplanned activities are aggregated into the following five categories: (1) grocery shopping, (2) clothes/small appliance shopping, (3) shopping other than (1) and (2), (4) restaurant, and (5) other (banking, post office, visiting a friend, etc.). The mean duration of each of the five activity types was calculated and used as the required duration of the unplanned activities. Only the durations of activities that were not planned at least twenty-four hours in advance were included in the calculation of the mean durations. Finally, the probability of an individual participating in an unplanned activity was set equal to the inverse of its frequency as this probability is equal to the mean time interval between occurrences of that activity.

In addition to the utility that would result from an individual's participation in an unplanned activity, there would also be some disutility associated with the travel time to and from the location of the unplanned activity. This disutility, however, would not be associated with the total amount of time spent traveling to and from the location of the planned activity but rather with the additional amount of time spent traveling over and above that which would be spent traveling directly from the most recently completed planned activity to the subsequent planned activity. This additional travel time must then be multiplied by the probability of participating in the unplanned activity at a specific location to yield the expected disutility of travel to that unplanned activity location. This process is repeated for all other feasible location, activity types and space time constraints, and then the values are summed to obtain the total expected disutility of travel to unplanned activities.

4.3 Discretionary Home Activities

The utility that an individual receives as a result of participating in activities at home has been hypothesized to be a function of both the amount of time the individual spends at home and the number of household members present during that time. Since this latter quantity, in general, is not constant over the entire period of time, the total amount of time an individual spends at home during each stay must be categorized based on the number of household members present. In the current formulation, time spent at home is categorized as time spent when:

(1) no other household members are present,

(2) at least one (but not all) other household member is present, or

(3) all other household members are present.

Since these activities are discretionary (i.e., the individual is not obligated to return home at the observed time to perform a particular activity), the importance of these activities is generally not available. As a result, the utility (disutility) associated with traveling to home is hypothesized to be simply a function of the amount of time spent traveling. By calculating the total amount of time spent traveling to home for all discretionary activities and treating this as a separate travel time variable, the differential weighting of the disutility of travel to and from home for planned activities and travel to home as a discretionary return trip can be investigated.

5. SUMMARY OF THE THEORETICAL MODEL

This paper has sketched a theoretical framework for analyzing travel decision within the context of the collection of such decisions which form an individual's daily activity pattern. The theoretical development has focused on synthesizing rational components of utility for inclusion in an operational model of activity pattern choice. The utility framework attempts not only to assess the utility associated with participation in activities as manifested by the individual's activity pattern (including in-home activities) but also to quantify the benefits associated with reserving the potential to accommodate unforeseen travel needs (which may or may not ultimately be realized). This approach permits the modeling of the interaction among travel decisions involving temporally and spatially displaced activities while incorporating elements of uncertainty surrounding travel plans.

The operationalization of the proposed theory requires that quantifiable utility measures be established--reasonable formulations for the three components have been presented. Although the state of the theoretical model is incomplete, a comprehensive activity-based modeling system, STARCHILD (Simulation of Travel/Activity Response to Complex Household Interactive Logistic Decisions) has been developed and reflects the proposed theory and associated utility measures as presented herein. This model system and initial empirical experimentation is the subject of a subsequent paper (Recker et al, 1985).

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