

A MODEL OF COMPLEX TRAVEL BEHAVIOR: PART II—AN OPERATIONAL MODEL

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Abstract—Based on the theoretical model of complex travel behavior developed in a companion paper (Recker *et al.*, 1986), 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. The system employs a simulation approach in combination with techniques of pattern recognition, multiobjective optimization and disaggregate choice models. Initial empirical verification of the system of models is presented based on results obtained from a sample data set.

1. INTRODUCTION

The model system advanced in this paper is based on a theoretical model of complex travel behavior (Recker *et al.*, 1986) that positions travel in a broader context than in individual-trip methodologies. That previous paper reviewed the critical literature contributing to the development of the approach and presented the theoretical model itself. Reformulation of the derived utility measures into an operational format completed the initial exposition.

A comprehensive activity-based modeling system, STARCHILD (Simulation of Travel/Activity Responses to Complex Household Interactive Logistic Decisions), has been developed which offers one possible direction for the implementation of the theoretical issues advanced in the previous paper. The synthesis of the model uncovered many of the challenges facing the continued development of activity-based frameworks:

1. Analysis of household interaction and the specification of individual activity programs.
2. Combinatorics related to the generation of feasible activity programs.
3. Reduction of feasible courses of action to a set of distinct alternatives.
4. Specification of the choice set formation protocol.
5. Activity pattern choice model.

The discussion presented here centers about these issues and suggests a systematic approach toward their resolution.

2. THE STARCHILD MODEL SYSTEM

The STARCHILD Model system comprises five stages, and integrates a range of methodological approaches to activity analysis including simulation, combinatorial algorithms, pattern recognition and classification, multi-objective programming, and conventional choice models. Figure 1 illustrates the relationship between the theoretical formulation and the operational structure.

2.1 Module 1—analysis of household interaction and the specification of individual activity programs

In light of the interactive household forces that affect the formulation of individual activity programs, it is necessary to simulate these interactions to adequately treat the issue of activity program generation. Although opinions differ on the actual decision-making unit, whether the household or the individual, household interactions do constrain the range of alternatives available to the individual. It is assumed that the household itself has an activity program, that is, a list of activities that can be classified as subsistence (such as work or school), maintenance (such as shopping or personal business) or leisure (general social/entertainment/recreational). Certain activities are associated with specific individuals (particularly subsistence activities) and must be completed by that individual. Other activities provide the household utility, but not from the necessary participation of specific individuals (such as maintenance shopping), and are

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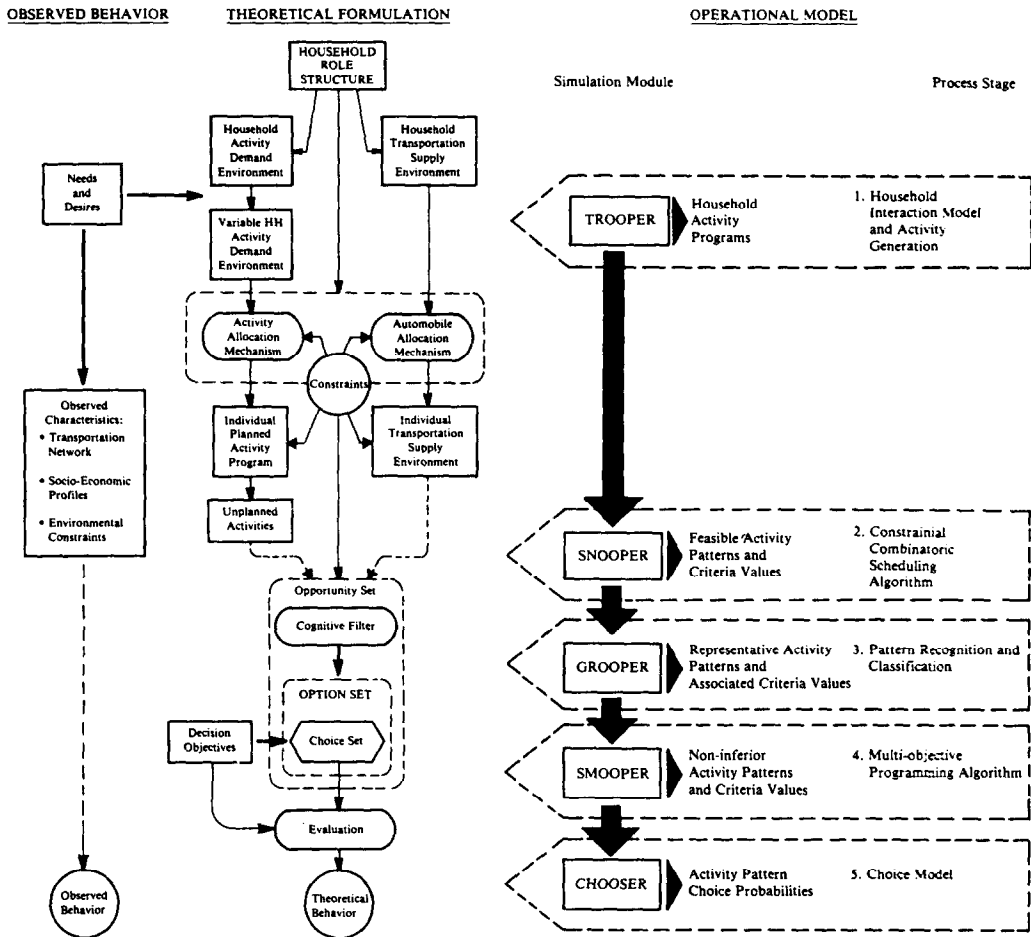


Fig. 1. Preplanned activity pattern formulation schematic.

assigned by the household through some constrained process.

If activities are assigned to individuals according to their flexibility, beginning with subsistence activities which by definition are least flexible in space, time and participation, the ability of household members to perform more flexible activities is iteratively reduced as each activity is assigned (see Cullen, 1972; Cullen and Godson, 1975). The ability to perform remaining activities is greatly affected by the distribution of the activity locations, the necessary activity durations, destination time constraints and the availability of transport modes within the household, the latter a function itself of the assignment of inflexible activities.

A series of household, in-home constraints reduce the assignment potential, as household members interact jointly, in and out of home, and share the household automobile(s). The assignment of the automobile itself may be a function of activity priority to the household, or a function of individual priority over the automobile. The first simulation module (TROOPER) models these interactive forces internally, so that the resultant individual activity program (or programs) reflects these household constraints (see Fig. 1).

Each individual activity program incorporates five separate data arrays. The Program Parameter Data (PPD)

vector identifies the individual, his/her household, the number of planned activities, the location of the household, and the endpoints of his/her travel day. The latter two variables result from the interaction analysis in the TROOPER module and serve to restrict the simulation period in response to individual constraints.

The Activity Program Data (APD) array forms the individual activity program itself, representing the set of planned activities for that individual and the corresponding spatio-temporal characteristics of each activity. Each row of the array identifies a specific planned activity including only those home activities that are distinctly planned in advance or specified by household constraint (thus, excluding the conventional "return home" trip). Each activity is described by a row vector of characteristics which serve to identify the activity, its desired duration and location, and spatial, temporal and transportation constraints.

In pattern generation, both activity duration and activity location appear as simplifications of actual behavior. Treating duration as deterministic, while simulating the actual observed pattern does not consider the effects of scheduling in planning the activity. Although numerous past studies (e.g. Kitamura *et al.*, 1981) have indicated a correlation between sojourn duration and tour length, the simulation model presently treats these variables as

dependently. Activity duration is thus assumed to be planned in advance. The impact of stochastic effects on duration is incorporated into the model structure in the estimation of utility in which activity durations are sampled from empirical distributions based on activity type, tour characteristics and the individual trip maker. Duration is simulated for non-planned activities.

The destination choice issue is more complex, particularly from the standpoint of an acceptable solution methodology. The assumption in the model is simply that the destination is planned with the activity. The potential is present to introduce variable destinations for unplanned activities, that is, those activities arising during the travel day. If unplanned activities are restricted to take place within existing simulated tours, the reduction in space-time flexibility from other activities, tours, or pegs in the activity pattern could produce a tractable destination choice set. Alternatives to this approach are discussed in Recker *et al.* (1983a); however, this problem is beyond the scope of the present integrated simulation model.

The temporal availability of the household automobile(s) is input through the Modal Availability Data (MAD) array. This data reflects the time periods during which an individual has an automobile available for use. This array may be considered fixed, or may be updated as the automobile becomes available through the scheduling of other individuals within the household. The array may be extended to discriminate among various household automobiles.

Ordering of activities may be specified in the Coupling Constraints Data (CCD) array. If a certain activity must precede or follow any other activity(ies), the CCD array is utilized to remove from the simulation any sequence of activities containing an unacceptable order. The CCD array is augmented within the program to eliminate those sequences which violate timing constraints.

The final array which completes the activity program is the Activity-Distance Array (ADD), which represents the spatial separation between the locations of each planned activity (including the home location). For the combinatoric scheduling element of this module to produce proper activity timing based on realistic travel times between location pairs, existing network travel times were adjusted based on a comparison of network and reported travel times (see Recker *et al.*, 1983a). Adjustments for alternate modes may be made; however, public transit must be treated independently due to obvious spatial and temporal restrictions.

2.2 Module 2—a constrained, combinatoric scheduling algorithm for the generation of feasible activity programs

Once the set of activity programs corresponding to each household member is specified, the set of feasible activity patterns is generated through a constrained, combinatoric scheduling algorithm (SNOOPER), the second module of the simulation package (see Fig. 1).

The simulation is based on a single premise—the set of opportunities available to each household member is contained in the set of all feasible activity patterns which that member could indeed perform, given the individual's

activity program. Two rather prominent issues present themselves in this process—the computational problem of generation and the pragmatic issue of interpretation. The latter issue will be detailed in the discussion of the simulation's third and fourth modules. The former issue is approached through the constrained combinatoric scheduling algorithm. The algorithm has six sequential elements:

(1) *Integration of the activity program.* The first of six basic elements of this module integrates the activity program of a single household member into the simulation procedure. Whereas the generation of the activity programs required the simultaneous consideration of the desired household program with each individual member, the resulting interaction forces are now embedded in the constraints of the individual. For example, a household requirement to be home at a certain hour is represented as a mandatory, planned activity, fixed at home, at that time. Any pattern violating this fixity would be deemed infeasible.

(2) *Activity combinatorics.* Combinatorics are introduced in the module's second element through a two-stage process. The individual's activity program consists of a list of planned activities with no consideration of intermediate, unplanned, return-to-home trips. The simulation process, however, in consideration of all feasible activity patterns, must generate all possible variations of simulated tours which incorporate the planned sojourns of the program. All tours are formulated as ultimately home-based. Potential intermediate home activities are inserted at each possible location of each activity ordering, generating all potential tour arrangements. The duration of these inserted home activities is simulated in the fifth element of the module. The first sequencing stage produces the number of intermediate home inserts, and the second stage iteratively produces all permutations of the activities.

Combinatorial algorithms are frequently limited by the rapid increase in potential arrangements as additional "items" are included. For example, increasing the number of planned activities from four to five produces an order of magnitude increase in the number of distinct combinations (from 192 to 1,920). The increase in potential arrangements becomes somewhat intractable computationally at about six planned activities (23,040 distinct orders). Several factors reduce this potential problem including coupling constraints and evidence of activity program size from various data sets (see Recker *et al.*, 1980).

The second element performs a test for violations of coupling constraints, both specified and implied. Any sequence which violates an activity constraint is removed from consideration. The simulation element performing this test also avoids all additional sequences which contain the misspecified orderings. This is accomplished in a manner similar to Clarke and Dix (1980).

(3) *Modal combinatorics.* Mode choice is introduced to the simulation procedure by a similar combinatoric procedure. The assumption of the simulation is that each tour is completed utilizing a single mode, and, therefore, a change in mode may occur only at home. In other

words, each tour is mode specific, with the mode choice decision assumed to occur when the tour is initiated.

Use of a coded travel network facilitates modal analysis for private modes, given the spatial and temporal flexibility of the automobile. The inclusion of walking trips is possible through a modification of the network, and possibly a distance restriction for pattern feasibility. The integration of public travel modes, however, is considerably more complex due to their characteristic inflexibility—both spatially and temporally. The restrictions of fixed routes and fixed schedules produce more rigorous constraints on the feasibility of any given pattern. A test for spatial connectivity, by a specific public mode, must be performed followed by a calculation of travel time based on the appropriate schedules.

The issue of connectivity for transit involves not only the consideration of direct routes, but also connectivity through transfer to intersecting routes. This, of course, complicates the timing calculations as the scheduling problem must consider the transfer route, and its temporal availability. To complicate matters further, the feasibility of the entire simulated tour must be established rather than feasibility on a link-by-link basis as with automobiles. Since it has been assumed that changes in mode may occur only at home, a restriction imposed by combinatorics, a tour is mode specific. If any one link of a tour cannot be successfully completed, due either to system connectivity or suitable scheduling, then that tour and simulated pattern become infeasible.

In the transit sub-module, a feasibility test for spatial connectivity is made and a maximum distance restriction placed on walk trips (if desired) to ensure overall feasibility of the tour. Once feasible modal sequences are assigned, a test of scheduling feasibility is performed.

(4) *Scheduling feasibility.* Once an activity program has been sequenced in an acceptable order and assigned modes, the simulation model schedules the activities. Using the earliest and latest unconditional starting and ending times, the desired activity duration, and the travel times between locations, a test for pattern feasibility is formulated based on two constructed vectors:

1. Earliest conditional starting time.
2. Latest conditional starting time.

Pegs established by the unconditional start and the unconditional ending times, the duration of an activity, and the corresponding travel time to or from a second activity, may preclude the given order of activities. For example, consider a desired shopping activity which may be performed from 8:00 a.m. to 9:00 p.m., with an associated duration of one-half hour. If a fixed work activity occurs from 9:00 a.m. to 5:00 p.m., the shopping activity may only occur before the work activity if the travel time between the two is less than 30 min. However, if the work activity were flexible (that is, the differences between the unconditional pegs is greater than the desired duration) then a greater travel time could be acceptable.

The earliest conditional starting time may be interpreted as the earliest that a particular activity may begin based on the scheduling of previous activities. The latest

conditional starting time may be interpreted as the latest an activity may commence given the scheduling restrictions of activities which follow. The last task of this element is to determine scheduling feasibility of the proposed pattern through a comparison of these two constructed vectors.

(5) *Activity scheduling.* The scheduling flexibility of various activities (taken here as a positive difference between the latest and earliest conditional starting times) may produce a range of similar, yet distinct patterns. The number of potential starting times for the initial activity of a sequence is computed based on this flexibility. All succeeding planned activities on the simulated tour are assumed to occur as soon as possible after the execution of the previous activity. The time associated with a scheduling delay due to conditional starting times is considered waiting time. It is important to realize that at no time in the constrained combinatoric scheduling algorithm is any attempt made to establish the superiority, or inferiority, of any given activity patterns. Rather, the sole function of this module is to produce the entire set of feasible activity patterns available to each household member.

The range of start times for inserted home activities is computed through the incorporation of acceptable waiting time. The vector of activity scheduling variation and the computed durations for home inserts enter the actual scheduling algorithm to produce the fully-scheduled activity pattern. A number of pattern variations are produced for each feasible activity sequence, based on the flexibility. However, the nature of the calculation of duration for home inserts ensures that patterns are not formed by extending the waiting time at an activity location by reducing the duration at the previous home insert, which would have produced a series of virtually identical patterns.

The scheduling algorithm is a simple, embedded, iterative scheme with the number of levels based on the number of activities to be scheduled and the number of iterations based on the schedule variation of each activity. For an initial start time for the first activity, each subsequent activity is scheduled within the extent allowed, the last activity being tested at all possible variations, for each variation of a previous activity, and so on back to the initial activity. For home insert activities the duration estimated previously is incremented by the dwell time at home and the net result is a full-schedule activity pattern with the order, initial start time, and all durations specified. At the end of each level of the iterative scheme, the pattern specification function is accessed.

(6) *Activity pattern specification.* The sixth and final element of the second module produces the actual simulated activity pattern in a standard format. It is assumed that travel to the first activity is planned such that the arrival time at the activity location is equal to the activity start time with no associated waiting time. For each succeeding activity, the arrival time is set to the previous activity's finishing time plus the travel time between the two locations. The activity start time is taken as the maximum of the arrival time and the earliest unconditional start time. Wait time before activity commencement is the difference between start and arrival times,

and activity finishing time is simply start time plus activity duration.

A full pattern is specified for every combination accepted based on (a) insertion of home activities, (b) activity permutations, (c) modal permutations and (d) individual activity scheduling. The simulation is completed for each individual in the household in question, for as many households as desired.

Several observations should be made regarding the constrained, combinatoric scheduling algorithm. First, the algorithm generates the full set of potential activity patterns available to an individual given a specified activity program. No decision rules or basic behavioral hypotheses are invoked, and no claim is made on the nature of the results being representative of an actual individual choice set. The third and fourth modules of the simulation model produce a tractable choice set for the individual and his/her household. The importance of the present module is its simultaneous consideration of the range of choice attributes in the formation of an activity pattern. Not only are sequence and duration simulated, but a fully scheduled activity pattern results. Implicit to the formation of the patterns are the concepts of tours and mode selection and, most importantly, an extensive range of household and environmental constraints are embedded in the resultant structure. As such, this module of the model system represents a significant advance relative to similar, existing scheduling algorithms developed by Lenntorp (1976) and by Clarke (Clarke and Dix, 1980; Clarke, 1985).

2.3 Module 3—reduction to a distinct pattern set

The individual's feasible pattern set resulting from the second simulation module may be of considerable magnitude in even a significantly constrained situation. There is not, in general, any guarantee that the alternatives of the feasible set are perceived by individuals as distinct options. Certain sets of activity scheduling decisions, because of their similarity on several dimensions, may be perceived as indistinguishable and therefore should not be treated as separate options for the individual. When such similarities arise, the set of feasible patterns must be modified in a way that ensures that each of the resulting options is as distinct as possible. Recent empirical research (Recker *et al.*, 1980; 1983b; Pas, 1982) has demonstrated the potential of various classification techniques in formulating "representative activity patterns" (RAP) defining homogeneous groups of distinct patterns. An added result of classification is reduction of the feasible set to a manageable option set, defined by the classification algorithm as independent (in the statistical sense), alternate activity patterns.

The third simulation module (GROOPER) has been developed and implemented to identify an independent pattern set through the specification of representative activity patterns. Although the present formulation has focused on a method explicitly devised for pattern analysis—a multiple scale, scoring function classification technique—the potential for analysis by other techniques is embedded (such as pattern transformation by Walsh/

Hadamard or Haar transformation algorithms).[†] The variables used in the scoring function are specified directly from the set of feasible patterns. Additional attributes may include the number of accompanying individuals and activity waiting time (pre- and post-activity). The variables are listed in the original order of activities in the activity program to ensure that characteristics of a specific planned activity will be compared with similar characteristics in alternate patterns for the same planned activity; thus, pattern sequence is implicit to the classification process. This procedure follows intuitively since activity information should be compared with similar information in alternate patterns to produce meaningful representative patterns. Characteristics of unplanned activities are considered as attributes of the preceding planned activity.

Several feasible patterns are randomly selected and assigned as representative patterns to initiate the scoring function for each individual. A range of desired groupings (i.e. number of RAPs) is specified, influenced perhaps by the size of the feasible pattern set, or by limitations associated with a realistic choice set.

The random assignment of patterns commences an iterative process where succeeding patterns are assigned to the RAP with which it is scored closest. After all patterns are assigned, new RAPs are estimated, and the assignment process repeats. The process converges when all feasible patterns are assigned to the "best" representative activity patterns, and the process is stabilized. The algorithm provides for alternate random initialization points and automatically adjusts the range of RAPS acceptable at each iteration.

The pseudo *F*-ratios associated with each homogeneous grouping (RAP) executed are compared, with the pattern set associated with the maximum *F*-ratio considered the "best" distinct pattern set. The full set of feasible activity patterns generated in the constrained, combinatoric scheduling algorithm is now depicted as "members" of a limited set of fully specified, representative activity patterns. The opportunity set of feasible patterns is now reduced to the option set of representative patterns.

The observed activity pattern for each household member, translated into classification variables, is then compared to each RAP in the selected option set. A pairwise comparison is made by reentering the pattern recognition algorithm, utilizing the option set RAP's as the random patterns, and assigning the observed pattern to the "best" RAP.

2.4 Module 4—specification of the choice set formation model

Implicit in the approach outlined above is the assumption that the number of representative activity patterns (i.e. alternatives) resulting from the pattern recognition/classification algorithm is of sufficiently small size so that the individual decision-maker can compare

[†]These transforms are discussed explicitly in Recker *et al.* (1980). A rotational transform is used, the transformed data matrix reduced, classified and inverted, and the representative patterns are produced.

the utility of each alternative and select the one that maximizes that utility. However, those individuals who have very few constraints imposed on them by their environment will have, in general, a large number of opportunities available to them which, in turn, may result in a large number of distinct alternatives. Recent studies in the fields of psychology and marketing research have presented evidence that there exists a strong relationship between the complexity associated with a choice situation and the decision rule used by an individual. Results obtained from controlled experiments conducted by Payne (1976) and Park (1976) revealed that individuals often use non-compensatory decision rules (often some type of conjunctive rule) in complex choice situations and compensatory decision rules in choice situations involving small numbers of alternatives. Foerster (1977), concluded that transportation researchers and planners should "... consider the possibility of non-additive decision rules and test a broad range of choice models before adopting any one model as an explanation of individual choice behavior." As a preliminary attempt at investigating whether or not individuals do, in fact, employ different decision mechanisms based on the size of the decision problem, a prototype choice set formation model has been formulated, wherein the choice of a specific activity pattern is viewed as a multi-objective decision problem.

One concept that is inherently tied to decision making in the presence of multiple, conflicting objectives is the concept of noninferiority. As stated by Cohon (1978), "a feasible solution to a multiple-objective decision-making problem is non-inferior if there exists no other feasible solution that will yield an improvement in one objective without causing a degradation in at least one other objective."

It is assumed that individuals maximize the utility they can achieve from the set of non-inferior opportunities (as opposed to the set of total opportunities); i.e. the feasible opportunities actually evaluated using a utility maximization decision rule are those opportunities judged by the individual to be non-inferior based on the individual's decision objectives.

In concert with this approach, a multi-objective programming algorithm has been developed that identifies those solutions that are non-inferior based on a set of decision objectives. The algorithm (SMOOPER) initializes the first feasible activity pattern as non-inferior and iteratively adds subsequent non-inferior patterns to the set. Any pattern within the set which subsequently is found inferior as new patterns are added is deleted from the non-inferior set. Once these non-inferior solutions are identified they may be input to the classification algorithm, or choice probabilities can be estimated.

The reduction of the distinct feasible activity pattern set to the subsidiary non-inferior set was executed primarily to eliminate inferior pattern alternatives from individual consideration. The effect of this operation also produces a more tractable alternative set. Figure 1 depicts the translation of the opportunity set, made up of feasible patterns, into the option set composed of distinct, representative patterns, then into a choice set of independent, non-inferior pattern alternatives. These translations may

be applied independently, or sequentially, with the net result being a specified individual choice set.

2.5 Module 5—activity pattern choice model

Any existing choice model [e.g. random utility (LOGIT) or non-compensatory] may be utilized to establish pattern choice based on the specified choice set from the third or fourth modules. Currently, the model is based on a multinomial logit choice model, employing only those utility components derived explicitly from the theory advanced herein. An application of the model system is discussed in the next section.

3. APPLICATION OF THE PROTOTYPE MODEL SYSTEM

Initial testing of the STARCHILD Model System focussed on the sequential application of each of the program modules to a small sample data set, and served to illustrate model operation rather than provide an exhaustive treatment of potential model applications. The overall intent was to illustrate the specifications of activity programs within the household, and the generations of individual activity patterns, followed by the estimation of an activity/travel pattern choice model based on a selected simple choice set formation postulate. Prior to a discussion of preliminary results, a brief summary of the data is provided.

3.1 Data and activity program specifications

The STARCHILD Model System requires a data set somewhat more complex than information provided in conventional travel diaries. The Constrained, Combinatoric Scheduling Algorithm in Module 2 utilizes information relating to both individual, household, and environmental timing constraints including knowledge of operating hours, fixed activities (relative to time of participation), and general temporal constraints involving commencement and/or termination of various activities and tours. The data chosen for preliminary estimation, drawn from the 1979 Windham Regional Travel Survey (Davis *et al.*, 1981), provide the necessary information, but is lacking in regard to in-home activities, information which is clearly desired, yet not crucial to preliminary model estimation. Although the structure of the model system accounts for in-home activities, their absence in the data is an unfortunate limitation on interpretation of model performance and, thus, potential.

With the exception of the first module (TROOPER) which deals explicitly with the impact of household interaction on activity program specifications, the remainder of the model system treats the individual as the unit of analysis. Explicit treatment of "unplanned" activity participation which potentially involves "unplanned" interaction with household members is not dealt with in this module, but is integrated into the program's second module (SNOOPER). Preliminary testing therefore utilized a random sample of 77 individuals from the full data set, and did not necessarily include full households in choice set formation and choice models, although full household information was utilized in establishing indi-

vidual activity programs. Selected summary data are provided for the 77 individuals in Table 1.

Module 1 (TROOPER) of the STARCHILD Model System is essentially a data preparation routine which constructs all required input files for subsequent modules. In general, four types of information are synthesized. On the regional scale, a coded travel network is input, as well as in the estimation of distributions for potential activity participation and travel. Furthermore, the sample drawn traveled exclusively by automobile, thus no transit use was simulated.

On the household level, the activity/travel diaries of all individuals are input and used to produce individual activity programs which incorporate planned activity data, mode availability, coupling constraints, and travel time data. All spatial, temporal, and transportation constraints resulting from the interaction of the desired individual activity list and the household transportation supply environment are imbedded in the structure of the activity programs. An additional output of this procedure is a mapping of home transition times which chart the flow of household members to and from the home location throughout the travel day. Finally, the actual observed activity pattern for each individual is constructed in standard format for subsequent utilization in each program module. This procedure is repeated for each household in the data set.

3.2 Generation of activity/travel patterns

The constrained, combinatoric scheduling algorithm embedded in the second module (SNOOPER) iteratively generates feasible, fully specified activity patterns from the individual activity programs. There are many factors which contribute to the range of generated patterns, including the number of planned activities, the number of available modes and modal availability, degree of fixity of each activity, coupling constraints, and length of the travel day. Specification of these variables is, of course, solely dependent on the characteristics of the individual, the household, and reported activities. Modal simulation was unnecessary since all trips used automobile (no transit service was available at the time of the survey).

Table 2 summarizes the results of the SNOOPER Module. A complete set of activity patterns was generated for each individual. Discretionary home activities were simulated in 15-min time increments, with a maximum of five potential patterns generated for each block of time devoted to discretionary activities.

The set of feasible activity patterns forms the opportunity set, as discussed in the theoretical development, for each individual. The range of generated patterns is in itself only representative of the true range of patterns, the imprecision being a function of the simulation parameters. While not ensuring a truly completely exhaustive set (an impossible task), the process minimally ensures a more than adequate selection representative of those choices actually available. Only 22% of the sample were characterized by limited opportunity sets (under ten feasible patterns). This limitation, of course, is a function of the constraints imposed on that individual. Those individuals with such limited opportunity sets might well

consider each feasible pattern as a distinct choice, and may therefore utilize no additional decision rules in choice set formation. To avoid imposing a subjective threshold on hypothesized decision rules, all individuals were subject to additional analysis prior to choice model estimation.

3.3 Specification of the pattern choice set

In general, there is no assurance that individuals perceive each feasible activity pattern as a unique alternative. The iterative nature of the constrained, combinatoric scheduling algorithm virtually guarantees that similar patterns will be produced, particularly for extremely flexible activity programs. Table 2 depicts the range of patterns available in individual opportunity sets, and further illustrates the problem of utilizing feasible patterns as a true set of device alternatives.

Each sample individual was processed through the third STARCHILD module, GROOPER, for a potential range of two to nine representative patterns (RAPs). The upper limit was subjectively set for this analysis, although subsequent results indicated that 80% of the sample had eight or fewer RAPs. A summary of the pattern recognition and classification component is provided in Table 3 and Table 4. Correlations between the number of feasible patterns generated and the number of representative patterns classified were weak for the sample as a whole ($r = 0.175$).

The observed activity patterns are also classified relative to the option set of representative patterns for each individual. Although the model system is suitably accurate to generate the observed pattern as a feasible pattern, distortions may occur upon classification. The observed pattern is always classified as a member of the RAP to which it is statistically closest; however, the degree of similarity varies over the sample. In the present analysis, synthesized representative patterns were replaced for subsequent modeling by selecting the member of the RAP which is closest to the classification mean, allowing the use of precomputed feasible pattern utility measures, but potentially introducing additional distortion into the choice set.

3.4 Estimation of the pattern choice model

The final step in initial testing of the STARCHILD Model System was a preliminary estimation of the activity/travel pattern choice model. Utility measures consistent with those components outlined in the attendant theoretical development were computed for each representative activity pattern (RAP) contained in the derived choice sets of each of the 77 individuals comprising the Windham data subsample. The actual variables tested in the initial model specification are identified in Table 5.

A multinomial logit model of selection of activity/travel pattern was then estimated using only those variables which arise directly from the theoretical development. Estimation results shown in Table 6 summarize the final estimation of the prototype model incorporating variables significant at the 95% level. All parameters in each preliminary estimation were plausibly signed. The model was able to predict 82% of the pattern choices,

Table 1. Observed sample characteristics

	Full Sample	No. of Planned Activities					Work Status		Travel Complexity*	
		2	3	4	5	8	56	21	71	6
Sample Size	77	10	42	17	8	56	21	71	6	
Mean Activity Characteristics										
Planned Activities	3.3 (0.8)**	2.0	3.0	4.0	5.0	3.4 (0.9)	3.1 (0.7)	3.4 (0.8)	2.3 (0.5)	
Sojourns per tour	2.4	1.4	2.4	2.6	3.3	2.4	2.5	2.6	1.0	
Total non-home activity budget (hours)	7.5 (3.6)	9.6 (4.3)	6.7 (3.9)	7.7 (2.2)	8.4 (2.5)	9.3 (2.2)	2.7 (1.7)	7.4 (3.6)	9.3 (3.7)	
—work activities (hours)	5.7 (3.8)	6.8 (4.3)	5.2 (4.0)	5.7 (3.3)	6.7 (3.0)	7.8 (1.7)	0.0	5.6 (3.8)	6.3 (3.7)	
—non-work activities (hours)	1.8 (1.7)	2.8 (1.8)	1.5 (1.6)	2.0 (2.0)	1.7 (1.3)	1.5 (1.6)	2.7 (1.7)	1.7 (1.7)	3.0 (1.9)	
Mean Travel Characteristics										
Trips	3.9 (1.1)	3.4 (0.5)	3.5 (0.8)	4.5 (0.7)	5.8 (0.9)	4.0 (1.1)	3.6 (1.2)	3.8 (1.2)	4.7 (1.0)	
Tours	1.4 (0.6)	1.4 (0.5)	1.3 (0.5)	1.5 (0.6)	1.5 (0.5)	1.4 (0.6)	1.2 (0.4)	1.3 (0.5)	2.3 (0.5)	
Trips per tour	2.9	2.4	2.7	2.9	3.8	2.9	2.9	3.0	2.0	
Mean Trip travel time (hours)	0.31	0.32	0.35	0.24	0.28	0.30	0.32	0.31	0.29	
Travel Budget (hours)	1.21 (0.64)	1.09 (0.43)	1.21 (0.67)	1.07 (0.63)	1.60 (0.68)	1.23 (.58)	1.14 (.81)	1.19 (.66)	1.36 (.38)	

*Travel complexity indicates whether an individual performed any complex tour (i.e. more than 1 sojourn)

**Figures in parenthesis indicate standard deviation.

Table 2. Summary of activity pattern generation

Number of Planned Activities	Number of Individuals	(%)	Number of Generated Patterns		
			Mean	Std. Dev.	(MIN, MAX)
2	10	(13.0)	10	11.2	(3, 40)
3	42	(54.5)	53	59.5	(3, 168)
4	17	(22.1)	112	87.5	(4, 262)
5	8	(10.4)	129	97.1	(9, 282)
Total	77	(100)	68	76.1	(3, 282)

where "correct" is taken in the sense that the predicted probability of the observed choice is greater than that of a nonobserved alternative.

Two characteristics directly related to travel time were found to significantly impact the choice of activity/travel pattern: the travel time to activities that are considered very important to the well-being of the household, TRAVEL TIME:VI; and the travel time associated with the return trip to home from activities of all types, TRAVEL TIME:HM. Important activities tend to be repetitive and typically involve only the traveler; the majority of work and personal business activities fall in this category. The variable TRAVEL TIME:HM measures the time required to return home following an out-of-home activity rather than continuing onto a succeeding out-of-home activity. As such, it reflects the additional travel time associated with nonoptimal (in the travel sense) travel behavior.

Although the estimated coefficients for the two travel time variables included in the model are comparable, their respective elasticities are noticeably dissimilar. The choice of activity/travel pattern is marginally elastic with respect to the travel time associated with activities considered very important to the well being of the household (-0.98) and relatively inelastic with respect to travel time home from activities (-0.37).

Travel time associated with activities that are judged as being less than very important to the well being of the household was found to be insignificant in the choice of patterns. A potential explanation is rooted in an understanding of the nonrepetitive nature of the types of activities which typically fall within this category. The implication is that, because these are "rare" events, not much attention is devoted to "fine tuning" the repetitive portion of the activity/travel pattern to minimize travel to these activities. A second feature typical of these activities is that they tend to involve more than one member of the household. Virtually all potential travel time sav-

ings associated with the pattern choice alternatives involved complex travel behavior (i.e. trip chaining) of one form or another. The implication is (expectedly) that trip chaining is not conducive to activities involving coordination among several individuals.

Although data limitations prevent an analysis of time at home by activity types, this issue was approached, as it was in the theoretical model, relative to other household members present at home. Estimation results indicated a tendency among individuals to choose patterns which allow them to be home at times when all other members of the household are there (HOME TIME:ALL). The individual's choice of specific pattern is highly elastic relative to this characteristic of the activity/travel pattern (4.55).

The proposed theory of complex travel behavior hypothesized that individuals consider their potential to participate in unplanned activities when selecting an activity schedule. The utility of the total potential to participate in unplanned activities involves both temporal and spatial characteristics of potential activity participation as well as the probability of such participation arising as a function of the time since the last participation. The significance of the estimated coefficient indicates that individuals are sensitive to the possibility of unforeseen events arising and schedule "flexibility" into their activity/travel patterns.

The final variable employed in the model is related to the risk associated with not being able to participate in a planned activity due to stochastic variations in travel time (and/or activity duration, although not included in this study). Risk was calculated as the sum of the probabilities that sufficient time would not be available to complete each activity, categorized according to the importance of the activity and assuming that the random component of travel time to any particular activity was uniformly distributed around the minimum and maximum

Table 3. Summary of representative pattern classification

Number of Planned Activities	Number of Individuals	(%)	Number of Representative Patterns	
			Mean	Std. Dev.
2	10	(13.0)	4.4	2.3
3	42	(54.5)	6.5	2.4
4	17	(22.1)	5.6	2.5
5	8	(10.4)	4.4	1.9
Total	77	(100.0)	5.8	2.5

Table 4. Distribution of representative patterns

No. of RAPS	2	3	4	5	6	7	8	9
No. of Individuals	2	21	9	5	6	7	10	17
Percent	2.6	27.3	11.7	6.5	7.8	9.1	13.0	22.1
Cumulative Percentage	2.6	29.9	41.6	48.1	55.8	64.9	77.9	100.0

reported travel times for the trip in question. It was further assumed that the duration of any discretionary activity at the home location was indeterminate and flexible; accumulated "risk" could not be carried forward to succeeding tours.

Calibration results indicate that individuals are sensitive to the risk involved in not being able to participate in activities deemed important to the household (RISK:VI+I). These results indicated that the additional travel time to home while between activities, which biases choice toward patterns which involved trip chaining, may be counterbalanced by the risk involved in chaining activities together. That such risk is insignificant where unimportant activities are involved suggests that the preferred positioning of activities in complex tours is one reflective of decreasing activity importance.

No socio-economic variables or alternative-specific constants were used in these preliminary estimates so as to focus on the effect of the theoretical model's hypotheses on travel behavior. Overall, model estimation appears quite reasonable, both in a statistical sense, and relative to the theoretical model.

4. SUMMARY AND CONCLUSIONS

This paper summarizes an attempt to formulate a comprehensive framework for the theoretical and empirical

analysis of complex travel behavior. Although extensive work has been accomplished, the theory and the model system are by no means complete. The theory advanced (Recker *et al.*, 1986) represents merely the kernel of a developing approach to complex travel behavior, and the STARCHILD model system, although a useful operational tool through which to explore activity and travel behavior, is basically a flexible framework designed to permit experimentation with alternate constructs of activity pattern formation.

The proposed theory and model have been strongly influenced by prior activity-based research, especially the framework of Hagerstrand and his followers (Lenntorp, Cullen, Burns, etc.), the exemplary work at Oxford (Clarke, 1985; Jones *et al.*, 1983), and independent advances of individuals such as Van der Hoorn, Kutter and Hanson. Many aspects of their work are integrated into the STARCHILD model and theory; much further work remains.

4.1 What has been accomplished?

An overall theoretical framework has been proposed (Recker *et al.*, 1986), positioning the individual as the decision maker who implements activity programs integrating various scheduling rules, available resources, and a multitude of constraints. This process is dependent on basic concepts of utility maximization within a con-

Table 5. Variable definitions

Variable	Definition
1. TRAVEL TIME:RU&U&I	Travel time to activities deemed either unimportant, relatively unimportant, or important to the well-being of the household
2. TRAVEL TIME: VI	Travel time to activities deemed very important to the well-being of the household
3. TRAVEL TIME: HM	Travel time to discretionary in-home activities
4. WAIT TIME	Time spent waiting (at the activity location) for a scheduled activity to commence
5. HOME TIME:S&N	Time spent at home either alone or with some (but not all) other members of the household
6. HOME TIME:ALL	Time spent at home with all other members of the household
7. POTENTIAL:ACT	A measure of the potential to meet unplanned activities should such need arise
8. POTENTIAL:TRAV	A measure of the expected travel time to meet unplanned activity needs
9. RISK:RU&U	A measure of the probability of not being able to participate in a planned activity, that is deemed either unimportant or relatively unimportant to the well-being of the household, due to stochastic variations in travel time and/or activity duration
10. RISK:VI&I	A measure of the probability of not being able to participate in a planned activity, that is deemed either important or very important to the well-being of the household, due to stochastic variations in travel time and/or activity duration

Table 6. Estimation results choice of activity/travel pattern

Variable	Coefficient	STD. Error	T
1. TRAVEL TIME:VI	-0.23806E+01	0.85895E+00	-2.772
2. TRAVEL TIME:HM	-0.21382E+01	0.83780E+00	-2.552
6. HOME TIME:ALL	0.75132E+00	0.38921E+00	1.930
7. POTENTIAL:ACT	0.21786E+01	0.63477E+00	3.432
9. RISK:VI&I	-0.17727E+01	0.36977E+00	-4.794

Percentage of choices predicted correctly = 82%
Pseudo R^2 = 0.34
Number of observations = 77
Number of alternatives = 429
 $L^*(0)$ = -140.31
 $L^*(\theta)$ = -92.11

strained environment, and results in observed travel/activity behavior. The generation of activity programs is posited to occur on the household level, and as of yet has not been fully conceptualized.

An operational model has been constructed which synthesizes individual activity programs, resources, and constraints (including a range of interpersonal constraints) and produces the set of feasible pattern alternatives. Programs are composed of planned activities and distributional properties for unplanned activities. A variety of methodologies are available for pattern choice set formation based on techniques of pattern recognition and classification and also on multi-objective programming. Conventional choice models are applied to the resultant choice set using pattern attributes (utility components) derived from the attendant theory. The model system is policy sensitive and preliminary tests have been reported elsewhere (Recker and McNally, 1985a).

4.2 What remains to be accomplished?

The proposed theory is, at best, incomplete. Activity program generation, incorporating household interactions, is a major shortcoming. However, the individual choice process itself requires refinement, particularly in identification of pattern attributes which form the utility components. Specifically, no cost element is present (a data availability rather than an operational limitation). The influence of habit on travel behavior presents theoretical implications, but could be integrated into the choice model as a pattern attribute. Extensive rethinking of planned versus unplanned activities appears appropriate.

The STARCHILD model itself must integrate theoretical developments in activity generation and allocation, as well as a less static simulation structure which can reflect pattern formation as a dynamic process (see Clarke *et al.*, 1982). Tests of the multi-objective programming approach to choice set formation and choice itself must be completed, but requires more thought on the pattern attributes which affect the establishment of noninferiority in patterns or representative patterns. Other refinements include explicit incorporation of activity duration as a stochastic component (a relatively simple problem) and introduction of destination choice (a relatively difficult problem). Application to data sets containing all in-home activities must be made to complete verification of the

pattern construction module (again, a data limitation, as planned activities are treated similarly, whether in or out of the home).

Only preliminary policy analysis has been attempted using the proposed framework, an unfortunate characteristic of much of the activity-based research. The potential contributions of these approaches appear considerable and are discussed by Damm (1984), Jones (1983), Kutter (1981), and Clarke (1985). With the lack of cohesive theory, perhaps these approaches are best applied in conjunction with existing techniques, while focussing research on advancing theory and operational models within an integrated framework. The work presented herein is a step in that direction.

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