Title

Toward a Dynamic Model of Individual Activity Pattern Formulation

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ABSTRACT

This paper presents preliminary thoughts on the development of a theoretical model of complex travel/activity behavior that incorporates both spatial and temporal constraints. The theoretical model is based on the use of individual activity patterns to represent complex travel/activity behavior and assumes the form of a stochastic multiobjective dynamic programming model. A multiobjective dynamic programming approach is utilized due to the presence of conflicting objectives and the influence that past activity/travel decisions have on future choices.

During the last decade, the complex nature of travel behavior has been widely acknowledged among transportation analysts, geographers and urban planners. Unfortunately, only limited progress has been made toward identifying and understanding the various components that give rise to this complexity. Despite an increased emphasis on disaggregate "behavioral" modeling of transportation decisions, relatively little effort has been spent attempting to understand the intricate nature of an individual's daily activities and the implications these activities hold for travel behavior.

The absence of a strong theoretical framework focusing on the individual's movement through time and space has proven to be a major obstacle in the development of improved analytical models. It is ironic that the derived nature of travel demand has been universally accepted but the activities that give rise to this demand have only recently been examined. The reliance on the individual trip as the basic unit of analysis has led to an inability to predict many individual responses to transportation policies such as trip chaining, substitution of alternate activity sites and ridesharing. There are also a wide range of transportation-related policies such as flextime, increased hours of operation for services and changes in the spatial distribution of opportunities, whose effects on travel behavior are unrecognizable with the conventional travel behavior models.

It is important that transportation planners and policy analysts understand the relationships between the various factors which influence how individuals select their activity sites, choose the timing of these activities and construct their travel/activity sequence. This paper presents some initial thoughts on a modeling framework structured to facilitate this understanding. The ideas expressed in this paper should be regarded as preliminary and the subject of an ongoing research project.

2. Theoretical Development

A fundamental tenet of the theoretical model proposed herein is that complex travel behavior is best understood within the context of individual activity pattern analysis. An activity pattern (AP) is an ordered sequence of activities of an individual that takes place within a space-time continuum, the activities being linked via travel. Complex travel patterns, such as those represented by trip chains (or, multiple sojourn tours) are explicit components of the representation. These components are dependent not only on properties associated with each individual activity but also on those associated with the entire set of activities included in the chain.

This approach is also consistent with the position that the logical measure of travel demand is total travel distance (Zahavi, 1979; Burns, 1979) rather than number of trips. Activity pattern analysis represents an extension of that framework via the explicit inclusion of the interdependency between travel distance and temporal budget constraints. In the activity pattern representation, travel and activity participation are linked as a continuous path through time and space; the interaction between travel and the consumption of time (in relation to movement as well as activity participation) is both explicit and inseparable. As such, the substance of the activity pattern is contained in the "total distance" (both temporal and physical) traveled by the individual in the space-time continuum.

Associated with an AP are certain features which characterize its inherent utility to the individual: (1) the total number of activities (and activity types) included in the AP, (2) the time of day each activity was performed, (3) the duration of each activity, (4) the activity sequence, (5) the location of each activity, (6) the total distance traveled and (7) the amount and distribution of flexibility (or space-time autonomy). In the context of the proposed model, flexibility is determined by the volume of the individual's space-time prisms, which is implicitly determined by the locations of the activities, their durations and the individual's travel speed. Consistent with the commonly accepted position that utility is derived from the participation in various activities and not the undertaking of travel, the individual's total utility is assumed to be determined, in part, by the activities to which he/she allocates time. The act of traveling, although allowing the individual to participate in activities outside the home, also results in the individual incurring costs, both monetary and temporal in nature. Since resources are consumed during travel and no utility is directly realized from traveling (in many studies, traveling is considered a disutility of spatial separation) it is likely that the individual possesses both a fixed total travel time budget and a fixed total travel money budget which together restrict the total amount of travel. The existence of such budgets is evidenced by aggregate travel statistics compiled over a wide range of urban areas and time periods (Zahavi, 1978). The model developed in this study can be used to test the hypothesis that such budgets are also stable at the individual level as well as provide a behavioral basis for these budgets.

Due to differnces in locational attributes (e.g., size, price, quality) some activity sites will offer a higher level of service to an individual than others and, all else being equal, the individual is assumed to prefer activity sites offering higher levels of service to those offering lower levels of service. If each individual choice of destination is examined in isolation from the entire set of destinations selected, it is likely that some of the destinations may be considered "poor" choices in the sense that they fail to offer the individual a high level of service. However, if the entire collection of destinations is examined as a whole (i.e., the entire activity pattern is considered), it may be that the entire set offers more total utility to the individual than any other set of destinations. It is also reasonable to assume that because of the complexity of the decision process individuals do not select the optimal activity pattern, but rather, their set of decisions results in an activity pattern that can be termed non-inferior (Cohon, 1978).

It is further hypothesized that the amount and temporal distribution of flexibility associated with a particular activity pattern influences the inherent utility of that pattern. Indeed, this "flexibility" may enable the individual to: (1) participate in additional activities, (2) participate in activities over a wider range of alternate activity sites or (3) increase the duration of participation in selected activities. These "benefits" derived from "flexibility" are highly interrelated. The decision to participate in additional activities limits the ability to travel to more remote activity sites and/or spend more time at selected activities. The logical converses of this statement are, of course, also true. The utility derived from flexibility is directly related to the spatial distribution of activity sites. For example, consider two individuals, A and B, where individual A has a much larger amount of space-time autonomy than individual B. If the spatial distribution of activity sites for individual A is much less dense than that of individual B, the two individuals may derive similar utility from their respective amounts of flexibility. In extreme cases, individual B may derive more utility from the smaller amount of space-time autonomy than does A.

The formation of complex tours (i.e., the execution of consecutive non-home activities without intermediate returns home, or tripchaining) is a means whereby individuals can "extend" their fixed travel budgets to allow the incorporation of additional sites (an increase in trip rate) or activity sites offering higher utility (an increase in trip distance) into the activity pattern. Tripchaining ties individual trips into complex tours, where the total distance traveled is "allocated" over multiple sojourns. The net effect, initially, is a decrease in total distance traveled. However, given specific monetary and time budgets, the tripmaker may then be able to increase his/her total distance traveled to the original level of the budget constraints, gaining utility from increased spatial opportunities (Zahavi, 1978). Despite these obvious benefits, the corresponding expected levels of trip chaining in the population have not been realized. Potential explanations for this include the following:

(1) Certain activities (in particular, those of a social or recreational nature) may offer much greater utility to an individual when they are performed jointly with other members of the household and, consequently, participation in such activities is often scheduled at times when other members of the household are available. In such cases, the feasibility of trip chaining is greatly reduced since it implies extended coordination of the household member's activity patterns.

(2) Ridesharing commitments with non-household members most likely preclude complex tours that are coincident with the needs or wants of the ridesharing partners.

(3) Trip chaining requires significantly more advanced planning/scheduling than does a simple single-sojourn tour. The disutility associated with the effort expended in scheduling a complex tour may outweigh the gains in utility resulting from the chaining itself, especially when the number of sojourns to be chained is large.

(4) Trip chaining also requires the individual to spend increased amounts of time away from his/her place of residence during the execution of the chain and often this conflicts with specific in-home requirements. Empirical studies have shown that the conditional probability of returning home, given that an activity has been completed at time t, is an increasing function of time (Kitamura, et al., 1981).

(5) Finally, successful trip chaining requires either that the durations of planned activities are reasonably stable or, if there is substantial variation in the duration of a particular activity, that there is sufficient "slack-time" (time between the completion of one activity and the commencement of the next) in the activity pattern. Since trip chains are formulated on the duration of planned activities as well as on the speed at which an individual can travel, unplanned increases in the duration of any particular activity or unforeseen travel delays may cause the entire chain to "break."

The choice mechanism by which an individual selects the linked set of tours and sojourns that comprise his/her activity pattern is postulated as a two-stage process involving a pre-travel phase and a travel phase.

PRE-TRAVEL PHASE

It is postulated that on a given day an individual has a set of desired activities in which he/she wishes to participate. Associated with each activity in this set is a corresponding desired (or, expected) duration. Based on the individual's perceptions of the utility of the various activity sites available for each activity, the spatial and temporal availability of the activity sites, the costs (both time and money) associated with accessing each site and the size of the individual's travel budget, the individual constructs a planned activity program that inherently includes decisions regarding choice of destinations, time of day, activity sequence, mode, etc.

The proposed framework to model this process is described as follows. Consider an individual with a collection of needs and desires which he/she wishes to fulfill. This collection of needs and desires can be specified by the set of desired activities, $\underline{Q}$, and the corresponding desired duratons of the activities. That is, let:

a = a desired activity type to be performed

T_a = the desired duration of activity type a

Then, the individual's needs set, $\underline{N}$, can be represented as:

$$N = \{(a,T_a)\}_{\forall a \varepsilon Q} \qquad (1)$$

Since activity sites are distributed both spatially and temporally, not all locations will be able to satisfy the individual's needs at all times of the day. Due to their spatial separation, activity sites can be accessed only with a corresponding consumption of the individual's time. Each potential site for the performance of an activity in $\underline{Q}$ has, associated with it, an attendent travel time to access the site that is dependent both on the speed of travel as well as the path chosen to the site (which, in turn, is dependent on the sequence of $\underline{N}$). Alternatively, if the traveller is assumed as the frame of reference, potential activity sites can be viewed as "arriving" at different points in time, shown conceptually below:

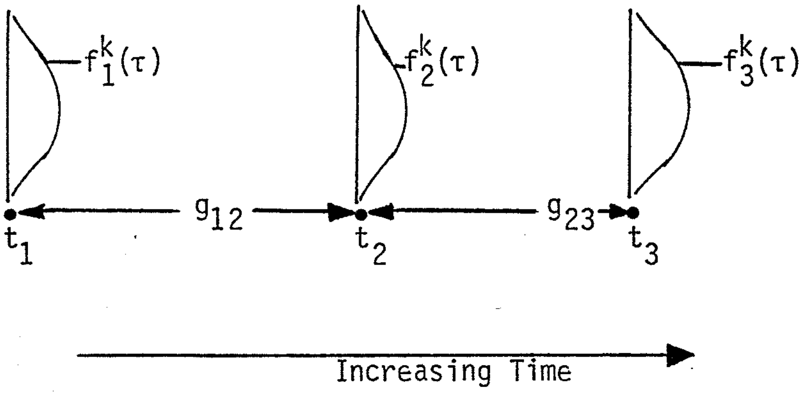

FIGURE (1) ACTIVITY SITE ARRIVAL PROCESS

where: t_i = the time of arrival of activity site i

$g_{i,i+1}$ = the temporal gap between the arrival of activity site and activity site i + 1

$f_i^k(\tau)$ = the distribution of the duration of activity k at site i

If we let:

C_i^k = the arrival time of the completion of the kth activity at site i

X_i = the distance of activity site i from the individual's current location

τ_i^k = the expected duration of activity k at site

$= E\{f_i^k(\tau)\}$

S_k = the speed of travel

b_i = the start of temporal availability for activity k at site i

e_i^k = the end of temporal availability for activity k at site i

then:

$$C_i^k = \frac{X_i}{S} + \tau_i^k \quad , \quad \text{if} \quad \frac{X_i}{S} \geq b_i^k \tag{2a}$$

$$C_i^k = b_i^k + \tau_i^k \quad , \quad \text{if} \quad \frac{X_i}{S} < b_i^k \tag{2b}$$

or, more compactly,

$$C_i^k = \{\frac{X_i}{S}\} + \{\tau_i^k + [\max(0, b_i^k - \frac{X_i}{S})]\} \qquad (3)$$

Equation (3) shows that the arrival process of activity sites is determined in part by the spatial distribution (the first term enclosed in braces) and in part by the temporal distribution (the second term in braces) of activity sites. However, not every activity site that arrives can be utilized by the individual as a result of constraints imposed by the needs set N̲.

Let:

T_j^n = the time at which an individual is constrained to be at some location j to participate in the nth activity

${}_f t^n$ = the latest time an individual can remain at the activity site associated with the nth activity

then,

$$ {}_f t^{n-1} = T_j^n - \frac{X_j}{S} \qquad (4)$$

$$ {}_f t^{k-1} = {}_f t^k - \tau_{j(k)}^k - \frac{X_{j(k)}}{S} \qquad k=1,2,\ldots,n-1$$

The set of potentially feasible activity sites (i.e., those that could be selected by an individual) thus satisfy the following criteria:

$$C_{i(k-1)}^{k-1} + \tau_i^k + \frac{X_i}{S} \leq C_i^k \leq \underset{\forall k \in Q}{\min}(e_i^k, {}_f t^k) \qquad (5)$$

Equation (5) states that the arrival time of the completion of the activity at site i must be less than or equal to either the ending time of the temporal availability of the activity site or the latest possible time an individual can remain at location i, and that the sequence of activities be maintained.

Due to the large number of interdependencies that prevail, the individual's selection of an activity program is viewed as a special type of resource allocation problem. More specifically, the focus is on the problem of determining how much of the available travel budget should be expended in travel to fulfill each of the individual's needs included in $\underline{N}$.

If we let:

t_i^a = the time of arrival of potentially feasible activity site i for activity type a.

v_i^a = the value (level of service) of potentially feasible activity site i for activity type a.

then,

$(t_i, c_i, v_i)_a$ will be used to denote a potentially feasible activity site for activity type a.

Associated with each type of activity is a potentially feasible activity site (PFAS) arrival process which describes the successive arrivals of potentially feasibly activity sites, $(t_1,c_1,v_1)_a,(t_2,c_2,v_2)_a,\ldots(t_N,c_N,v_N)_a$. This arrival process is dependent on the individual's position in time and space. The question then arises: what level of service (i.e., activity site) should the individual choose for a particular activity given 1) the specific PFAS arrival process and 2) the other activities that the individual has to perform during the same day. The level of service that should be accepted for any given actitity is determined as a result of a trade-off between the level of service afforded by each potential activity site and the total level of service expected to be obtained for all the remaining activities using the travel budget that would remain after the selection of a specific activity site. More specifically, if we let:

$\underline{A}$ = the subset of desired activities $(a_1, a_2, a_3, \ldots a_N)$ yet to be completed at any time t

$\underline{A}^{a_1}$ = the set of desired activities after a_1 has been completed

$v_i^{a_1}$ = the level of service afforded by the ith activity site for activity a_1

$t_i^{a_1}$ = the time of arrival of the ith activity site for activity a_1

$U(v_i^{a_1}, t_i^{a_1})$ = the utility of the ith activity site for activity a_1

$E\{U(\underline{A}^{a_1})\}$ = the expected total utility obtained for the set of desired activities after a_1 has been completed

$V_*^{a_1}$ = the level of service afforded by the activity site selected for activity a_1 given that the ith activity site is not selected

$t_*^{a_1}$ = the time of arrival of the activity site selected for activity a_1 given that the ith activity site is not selected

$U(v_*^{a_1}, t_*^{a_1})$ = the utility of the activity site selected for activity a_1 given that the ith activity site is not selected

$tt_i^{a_1}$ = the travel time budget available after the ith activity site is selected for activity a_1

$tt_*^{a_1}$ = the travel time budget available after the activity site is selected for activity a_1

then the individual should select activity site i for activity a if

$$U(v_i^{a_1}, t_i^{a_1}) + E\{U(\underline{A}^{a_1}) | tt_i^{a_1}\} > E\{U(v_*^{a_1}, t_*^{a_1}) | t_*^{a_1} > t_i^{a_1}\} + E\{U(\underline{A}^{a_1}) | tt_*^{a_1}\} \quad (6)$$

and should continue to search for an activity site for activity a_1 otherwise. The complexity of the problem is manifest with the realization that the expected utility of a set of desired activities is dependent, in part, on the expected values of the activity sites selected which, in turn, are dependent on the interrelationship between the activity site arrival process and the individual's movement through time and space (as reflected in the activity sequence).

The individual is assumed to have a selection criterion, i.e., a transformation that associates a function, w, to every potential activity site, such that a potential activity site with $v_k \geq w(t_k)$ can be accepted while one with $v_j < w(t_j)$ is rejected. At each time of arrival, t, w(t) defines the current "aspiration" level for the level of service of the potential activity site (Weibull, 1978). The function w, can be called the aspiration curve for the PFAS arrival process and in general there will be one aspiration curve for each different activity type and PFAS arrival process. To determine which activity site is selected (since there will probably be more than one activity site possessing a level of service above the aspiration curve) the individual must evaluate the level of service that can be obtained for all the remaining activities given the remaining travel budget, hence the aspiration curves for all the activities must be examined when choosing an activity program.

The process that has been described above considers only the locational attributes of activity sites and the utility resulting from these attributes. There also exists a certain utility associated with how the travel to activity sites is structured. Included here is the utility of the total flexibility provided by the travel structure, the disutility of the total time spent away from home during the execution of each tour and the disutility of the level of coordination required for each tour. For example, trip chaining although allowing an individual to visit higher quality activity sites within the constraints of the travel budget, also increases both the amount of cumulative time an individual must spend away from home during the execution of the chain and the amount of planning/scheduling that the individual must do to ensure an "efficient chain." Also, despite increasing a person's total flexibility (since the time and money spent traveling to and from home is now free to use for other purposes), trip chaining may significantly alter the distribution of this flexibility; increasing the individual's flexibility before and after the chain but decreasing the flexibility during the execution of the chain.

Because of the presence of these conflicting objectives and interrelated constraints, a multi-objective programming approach (Cohon, 1978) to the individual's allocation of travel resources to specific activity sites is appropriate. The imposition of a single objective approach to the problem of predicting individual's travel/activity behavior (choice of destinations, timing, sequencing, etc.) is both restrictive and unrealistic. Alternatively, multi-objective programming assumes that the individual's choice of a specific activity program is the result of a series of trade-offs among conflicting objectives resulting in the selection of non-inferior courses of action. The multi-objective programming formulation is as follows:

$$\underset{Dp}{\text{Max}}\Big(\sum_{\forall a\varepsilon Q} U_a, U_f\Big), \underset{Dp}{\text{MIN}}(U_o^\ell, U_h^\ell; \forall \ell) \tag{7}$$

s.t.

$$\sum_{\forall a\varepsilon Q} m_a \leq TM \tag{8}$$

$$\sum_{\forall a\varepsilon Q} tt_a \leq TT$$

$$C^{k-1}_{i(k-1)} + \tau_i^k + \frac{x_i}{S} \leq C_i^k \leq \min(e_i^k, {}_f t^k); \forall k\varepsilon Q$$

where: U_a = the utility of the level of service of activity a

U_f = the utility of the flexibility provided by the activity program

U_o^ℓ = the disutility of the total time spent away from home during tour ℓ

U_h^ℓ = the disutility of the level of coordination required for tour ℓ

m_a = the monetary cost of the trip to perform activity a

tt_a = the time consumed on the trip to perform activity a

TM = the total travel money budget

TT = the total travel time budget

Dp = the set of feasible activity programs available to the individual

TRAVEL PHASE

The pre-planned activity program constructed during the pre-travel phase may not always be realized by the individual due to unforseen events that occur. Crowded activity sites often cause delays in customer service resulting in unplanned increases in activity duration. Activity sites that fail to satisfactorily accomodate an individual's needs often lead to unplanned trips to additional activity sites.

To incorporate the stochastic nature of travel and activity participation into the model structure the following simulation is performed. Upon completion of each activity in the individual's activity program a reassessment process is invoked, during which time the individual a) determines if the actual activity pattern is temporally "synchronized" with the activity program, and b) if not, decides what alterations to the remaining portion of the program must be made. The various adjustment strategies available to the individual will depend on whether the activity pattern is "ahead" or "behind" the activity program.

If the individual's activity pattern is ahead of his/her activity program, three basic options are available:

(1) select an activity site (or sites) with a higher level of service than previously planned;
(2) perform additional non-home activities for one or more purposes; or
(3) return home to carry out additional home activities.

Alternatively, if the activity pattern is behind the activity program, the available options include:

(1) selecting an activity site (or sites) with a lower level of service than previously planned;
(2) forego some previously planned activities; or
(3) forego some intermediate trips to and from home (i.e., trip chain).

The selection of a particular strategy will be determined by such factors as (1) the individual's expectations about the level of service associated with as yet unreached potential activity sites, (2) the arrival rate of the as yet unreached potential activity sites, (3) the size of the remaining travel budget, (4) the number of activities remaining in the activity program and (5) the amount of time that has been spent away from home during the current tour.

After each subsequent "new" activity has been added to the activity pattern, the multi-objective optimization procedure is repeated, although on a subset of activity programs (sub-programs), since the initial starting point of the optimization becomes the completion time and location of the last activity completed.

The theoretical framework presented above can be illustrated with the conceptual model shown in Figure 2. During the pre-travel phase, the conceptual allocation model serves as the mechanism whereby the individual's needs/desires are transformed into a planned activity program. Input into this allocation model consists of the arrival processes of the potential activity sites, the levels of service available at the different activity sites and the total amount of travel resources available to the individual. Outputs of the model include probability distributions for the arrival times of the chosen activity sites, the levels of service of the chosen activity sites, the number of tours in the activity program, etc.

The travel phase commences with the execution of the first activity included in the individual's activity program. Depending on the occurrence of random disturbances (e.g., actual activity durations exceeding expected duratons, actual travel times exceeding expected travel times, etc.) the actual activity pattern (which results from the completion of activities in the activity program) may not duplicate the activity program. In the event of discrepancies between the two, alterations in the individual's planned activity program will be necessary before the next activity (and corresponding trip) can be carried out. These alterations will depend on the current state of various factors such as the size of the remaining travel budget, the amount and distribution of remaining travel budget, the amount and distribution of remaining flexibility, the expectations concerning levels of service afforded by future activity site arrivals and the number of activities remaining to be completed. The current levels of these variables are input into the simulation to determine the response(s) to the random disturbance(s). After each travel/activity participation response is executed the entire process is repeated. The dotted line connecting the next travel/activity decision and the planned activity program indicates that all or a portion of the planned activity program may be readjusted by the individual prior to the execution of the next activity.

The use of dynamic programming (Bellman, 1957) to model activity/travel behavior is consistent with the view that an individual's activity/travel decisions constitute a multi-stage decision process that lies somewhere between the two extremes of complete independence and total integration of decisions. Dynamic programming, which is amenable to the highly stochastic nature of travel time, activity duration and level of service, is based on the principle of optimality, which states that the best decision at each stage in the decision-making process is the decision that optimizes the remainder of the process. Once the utility of individual decisions is determined, a dynamic programming model can be developed. If we let:

X_n = the state of the individual at the nth stage of the process
y_n = the activity/travel decision made by the individual at the nth stage of the process
Y = the admissable set of travel/activity decisions
$U_n(X_n,y_n)$ = the utility of the travel/activity decision made by the individual at the nth stage of the process
$f_n(X_n)$ = the maximum utility over the n remaining stages beginning in state X_n and using an optimal policy

then, the dynamic programming model is of the following form:

$$f_n(X_n) = \underset{y_k \varepsilon Y}{\text{MAX}}[U_n(X_n,y_n) + f_{n-1}(X_{n-1})] \tag{9}$$

The major drawback associated with the use of dynamic programming to analyze travel/activity decision-making is that dynamic programming simulates optimal decision-making whereas travel/activity decision-making is apt to be suboptimal. However, Rappoport (1969) has developed algorithms that deal with different planning horizons and has shown that sub-optimal behavior can be incorporated into a dynamic programming formulation.

3. CONCLUSIONS

Although still far removed from a comprehensive theory of individual's complex travel/activity behavior, this paper has described some initial elements which may serve as "building blocks" in the design of such a theoretical framework. Structural forms for the relationships between many of these elements have been presented along with a discussion of some mathematical techniques in an attempt to facilitate the incorporation of these elements into a mathematical model or model system. Still further research is needed, however, with respect to the linking mechanisms that will eventually "tie" all these elements together into a unified analytical model of individual travel/activity behavior.

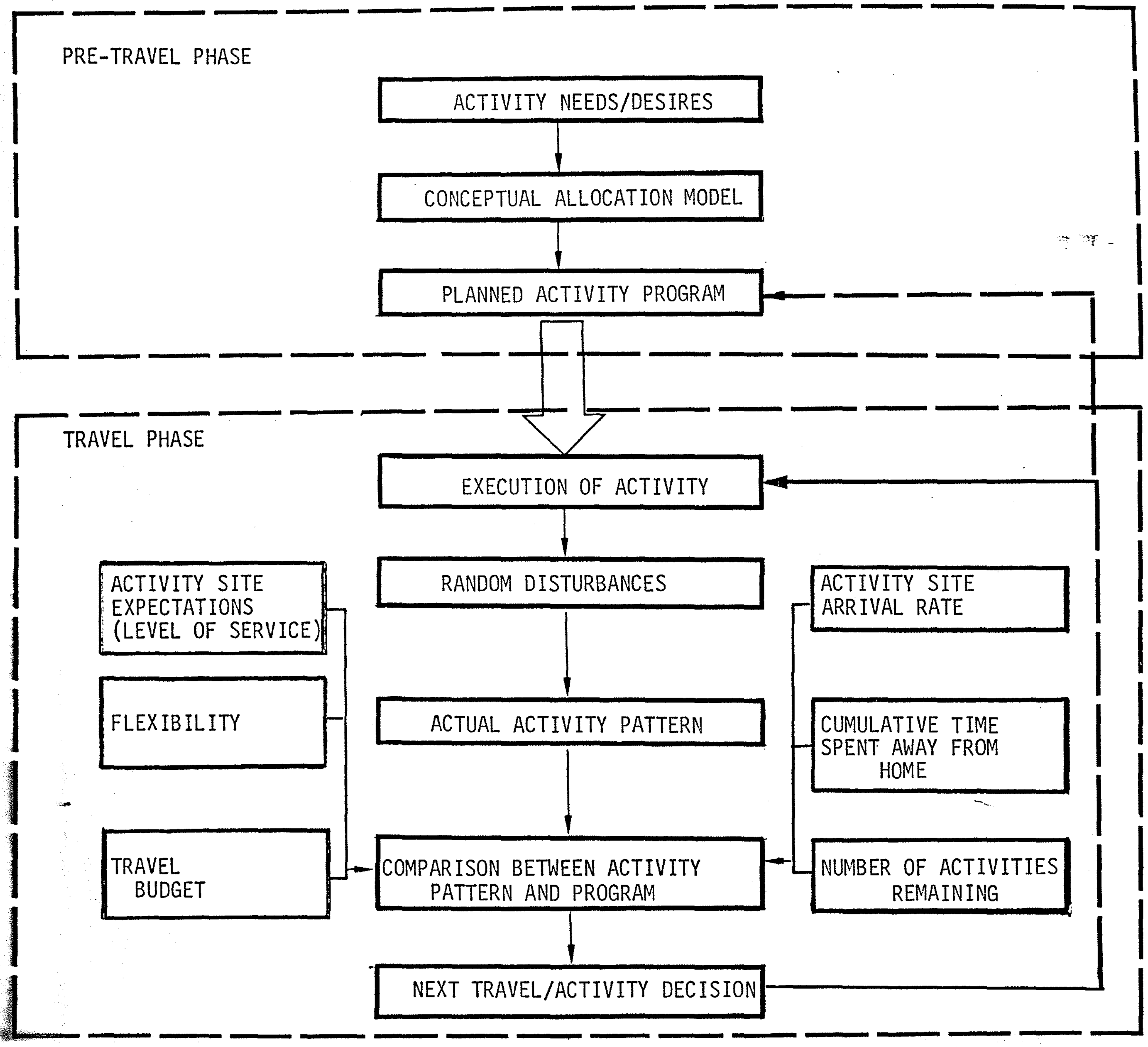

Figure 2. CONCEPTUAL MODEL OF THEORETICAL FRAMEWORK

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