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SMART: simulation model for activities, resources and travel

PETER R. STOPHER[1], DAVID T. HARTGEN[2] & YUANJUN LI[3]
[1] *Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA*; [2] *Center for Interdisciplinary Transportation Studies, The University of North Carolina at Charlotte, Charlotte, NC 28223, USA*; [3] *Lane Council of Governments, Eugene, OR 97401, USA*

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Abstract. This paper proposes the development of an activity-based model of travel that integrates household activities, land use patterns, traffic flows, and regional demographics. The model is intended as a replacement of the traditional Urban Transportation Planning System (UTPS) modeling system now in common use. Operating in a geographic-information system (GIS) environment, the model's heart is a Household Activity Simulator that determines the locations and travel patterns of household members daily activities in 3 categories: mandatory, flexible, and optional. The system produces traffic volumes on streets and land use intensity patterns, as well as typical travel outputs. The model is particularly well suited to analyzing issues related to the Clean Air Act and the Intermodal Surface Transportation Efficiency Act (ISTEA). Implementation would, ideally, require an activity-based travel diary, but can be done with standard house-interview travel surveys. An implementation effort consisting of validation research in parallel with concurrent model programming is recommended.

Introduction

The vast majority of transportation planning in urban areas, both in the US and throughout the world, is done with a four-step procedure known as the Urban Transportation Planning System (UTPS). Developed in the late 1950s and subsequently refined incrementally, this procedure uses aggregate data about sub-regional areas, called zones, to estimate travel on present and proposed networks. It is shown in Fig. 1.

In Fig. 1, the steps of Trip Generation, Distribution, Mode Choice, and Assignment (both transit and auto) constitute the standard four-step process. Land Use should be the first step in the process (thereby creating a five-step process), but is often either omitted or is conducted completely in isolation from the rest of the process. The four-step process is, effectively, contained within the solid-lined box in the figure. A brief description of the process would be as follows.

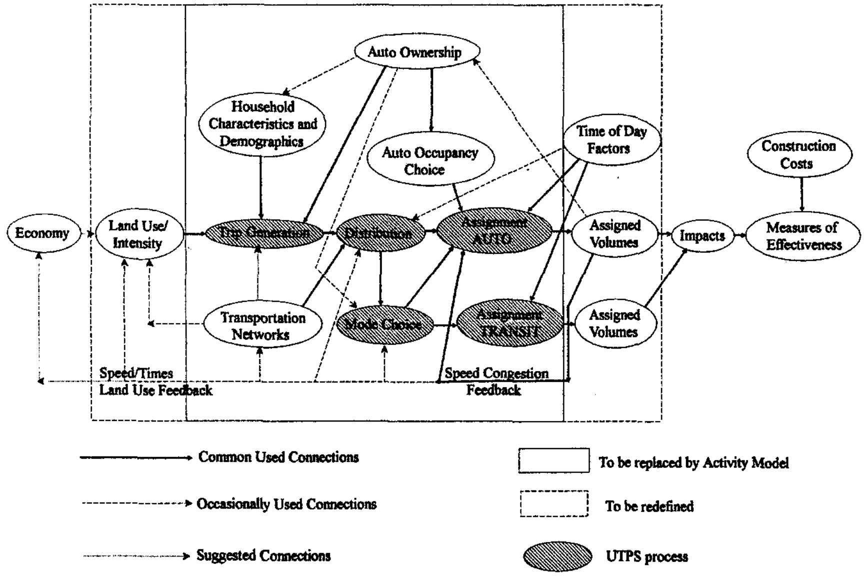

Fig. 1. Present travel demand forecasting model.

The process begins with exogenous forecasts (usually made at the level of the state) of economic growth that lead to projections of population and employment growth. These are input to the land-use model, which predicts the allocation of land uses within the region, based on the total levels of population and employment, and on the available space in the region. The outputs of land-use modeling feed into the trip-generation model, which is the first step of the four-step process. This model is also fed by household characteristics and demographics, such as household-size distributions, auto ownership distributions, and possibly other measures such as income and workers. The trip-generation model produces estimates of trip ends by traffic analysis zone (TAZ), which are then fed into the trip distribution model. This model estimates the origin-destination pairing of the trip ends to produce the overall trip patterns of the region. This is done usually based on the estimates of trip ends in a zone from trip generation and estimates of travel times developed from the highway network. In larger regions, the trip distribution step is followed by mode choice, which splits the trips between each origin and destination by mode of travel. In smaller regions, this step is often omitted because transit ridership represents such an insignificant element of total travel. The mode-choice model is driven by network data, similar to the trip-distribution model, and may also include some household demographics. The output of the model is origin-destination movements by mode for the entire region, with the origins and destinations being the TAZs.

The output of mode-choice then provides trip tables that are assigned to the relevant networks – auto trips to the highway network and transit trips to the transit network. Assignment is usually performed on the basis of minimizing travel times in the relevant network. Prior to auto assignment, person trips are converted to vehicle trips, based on auto occupancy. If assignments are to be done for different time periods, there will usually be a further preprocessing step to assignment where time-of-day factors are applied to the trip tables and assignments made for each time period (e.g. a.m. peak, midday, and p.m. peak). The product of this step is assigned volumes on the networks, from which impacts, in the form of adequacy of capacity and levels of service, can be estimated. From the impacts, and from input of construction costs for capital investment projects, measures of effectiveness are generated for the networks and proposed additions and changes to the networks. Highway assignments are usually iterated on the basis of output speeds and congestion, until an equilibrium result is achieved. This is shown by the speed/congestion feedback arrow to auto assignment in Fig. 1.

The figure also shows that some applications of this four-step process include a feedback of speeds and congestion to the trip-distribution step, and even to the land-use step. However, such feedback steps have largely been ignored until very recently. The need for them arises from the sequential nature of the process. When travel times or speeds are input to land-use models, trip-distribution models, or mode-choice models initially, they must be based on guesses at the actual times on the networks, because initially only the free-flow times are known. After assigning trips, estimates are now possible of the actual times, but these will be inconsistent with the original input values. By changing the values input to land use, trip distribution, or mode choice, the results of these steps will change. There is, therefore, a need to feed back these values through a number of iterations that, it is hoped, converge to a stable result.

Figure 1 also shows some linkages that have been proposed or suggested and that should be implemented in the process, but currently are not. These include a feedback of land-use data to the economic model for the state and region, a feedback of travel times to trip generation (requiring that the trip-generation model be redefined to include travel-time sensitivity), and a feedback of assigned volumes to auto ownership and of auto ownership to household characteristics. Finally, Fig. 1 shows that the system of the four-step process, enclosed in the solid box, is to be replaced by the Activity Model described in this paper, and those steps outside the solid box, but inside the dashed box, are to be redefined by the Activity Model.

While the UTPS process is widely used – indeed, even institutionalized – in literally thousands of applications, and contains many attractive features, it has also generated much criticism and controversy. Reviews and criticism of the UTPS process are widely available, and generally make points not in substantial disagreement. For instance, in reviewing the system, Supernak (1983) notes that with the exception of disaggregate mode-choice models, very little progress has been made in travel-demand modeling in the past thirty years. Specifically, UTPS continues to exhibit a lack of behavioral content that prevents the analyst from evaluating alternative policies that are unrelated to investment proposals for major facilities. These problems, always apparent and annoying, have taken on new significance as the Clean Air Act Amendments (CAAA) of 1990 and the Intermodal Surface Transportation Efficiency Acts (ISTEA) of 1991 place greater modeling and analysis burdens on states and Metropolitan Planning Organizations (MPOs), and require more and more emphasis on non-capital investments and scenarios that are conditioned on changing travel behavior. Another increasingly problematical aspect of the UTPS process is its focus on a one-way trip as the unit of analysis, with the heroic assumption that each such trip is totally independent of those made before and after it. Much research has focused on trying to change the unit of analysis to a trip chain or trip tour, but the real problem is that the unit of a trip is a concept that simply does not work in today's more complex society. Use of this concept as the fundamental modeling unit is a major problem with the current travel-forecasting paradigms.

The UTPS models are primarily based on aggregate relationships that exhibit ecological correlations and mask underlying causal patterns. The aggregate nature of the models tends to make the results descriptively reasonable, but predictively barren. That is, there is little causality embodied in the relationships, and models are primarily structured on the basis of high cross-sectional correlations between observed behaviors and observed household and system characteristics, all analyzed at an aggregate level. Information about the dynamics of behavior, interrelationships within the household and among different trip makers, and relationships to other quality of life aspects are all absent from the models.

A further substantive issue relates to the general lack of feedback (in practice and use) between model elements, which prevents the system from reaching full equilibrium in forecasting environments. As is shown in Fig. 1, feedback within assignment is the only feedback loop that is customarily applied, while feedback to prior steps is an infrequent occurrence. In fact, where feedback has been preformed lately, it often constitutes a single iteration with no attempt to reach equilibrium or stability of estimates. Typically, output speeds are lower than those assumed in shaping the region or in distributing travel. This encourages the overestimation of travel demand for new transportation proposals. Goodwin (1992) expresses the issue in terms of adaptation, noting that consumers in the greater London area have been observed to be considerably more flexible in response to increasing congestion than was originally hypothesized. His explanation is that the range of adaptations consumers have available is far greater than what can be modeled easily, and therefore the analyst errs by concluding that, if major transportation investments are not made, congestion will overwhelm the city.

Supernak (1983) calls for the development of ". . . simple, yet not primitive, easily applicable models . . ." for urbanized areas. Among the characteristics such models should contain are the following:

- Modified behavioral structure, and focus on subsystems
- Definition and stratification of the analysis units
- Dynamic rather than static
- Feedbacks to land use and supply
- Interrelationships between submodels, particularly car availability and trip generation
- Policy sensitivity

It is clearly a tall order, probably impossible, to achieve these goals with a "simple, yet not primitive" model structure. What follows is an attempt to describe the outlines of a working tool that could, if further developed, form the basis of a partial solution.

Model description

Overview

In this section, we develop the outlines of an activity-based simulation model that integrates land use, traffic, and household activities and resources. The model, termed SMART (Simulation Model for Activities, Resources and Travel) is a substantial revision of the familiar UTPS process shown in Fig. 1. It was developed as part of a Federal Highway Administration (FHWA) initiative to consolidate knowledge on new approaches to travel demand modeling (Weiner 1993).

In essence, SMART replaces the four-step UTPS model structure with one based on the activity patterns of households and their outputs: resource use, activities and travel. In this sense, it replicates much more closely how decisions about travel are actually made, and how these actions affect the growth of the region. It is an integrated model that ties together the major dimensions of the problem (households, resources, and decisions; transportation systems; and land uses) in a behavioral way, while still providing the key output requirement: link volumes and flows on transportation systems. Importantly, while the four-step process does not include land-use modeling, which is usually performed as a separate and often unrelated modeling activity (even by a different agency), this modeling process brings land-use modeling firmly into the basic paradigm.

The SMART structure is based on an integration and synthesis of ideas in the transportation literature that deal with household activities and roles. Of particular relevance are the work of Jones (1979a, 1979b, 1980), Recker (1986a, 1986b), and Axhausen (1991) on activity simulation; Knippenburg (1987), on ranges and closure; Hagerstrand (1970), Lenntorp (1976), and Kitamura & Kostyniuk (1981) on time-space paths; Fried & Havens (1977) on role allocation and adaptation and Goodwin (1992) on adaptation; Hemmens (1970), Hartgen & Tanner (1970) on activity structure and household decision-making; and Stopher (1992) and Jones (1986) on diaries and activity surveys. The reader familiar with these authors will see variants of their ideas in the SMART structure.

Modern geographic-information systems (GIS) are viewed as central to the successful development of an activity-based modeling system. These systems allow for the joint layering of regional land uses, transportation, available land, household locations, and household activity patterns. This provides a means to model the geography of the region the same way that travelers do: as partial spatial maps. Indeed, the entire SMART model could be developed within a GIS framework, functioning as a spatial decision support system operating on existing and projected future land use.

The SMART model is flexible with respect to the level of aggregation. Ideally, we believe that it would operate in a fully-disaggregate mode, probably using sample enumeration or micro-simulation procedures to develop estimates that would provide volumes on transportation facilities. However, it is also possible for the model to be operated at varying levels of aggregation, including being operated within traditional traffic analysis zones (TAZs), although we do not recommend this. In such a case, the preferred operation would be to use market segmentation as the underlying basis of estimation and aggregate to the TAZ by determining the fractions of population in the TAZ in different market segments. In whatever manner the model is applied, there will, of course, be a necessity to forecast the input variables, which, as is discussed later, are primarily ones that describe households in terms of life-cycle stage and resource availability. Methods to forecast these variables are not discussed in this paper, but are a matter of concern for the implementation of the proposed paradigm.

An overview of the SMART system is shown in Fig. 2. The model focuses on interaction between four key features of regions. The major elements of the system are:

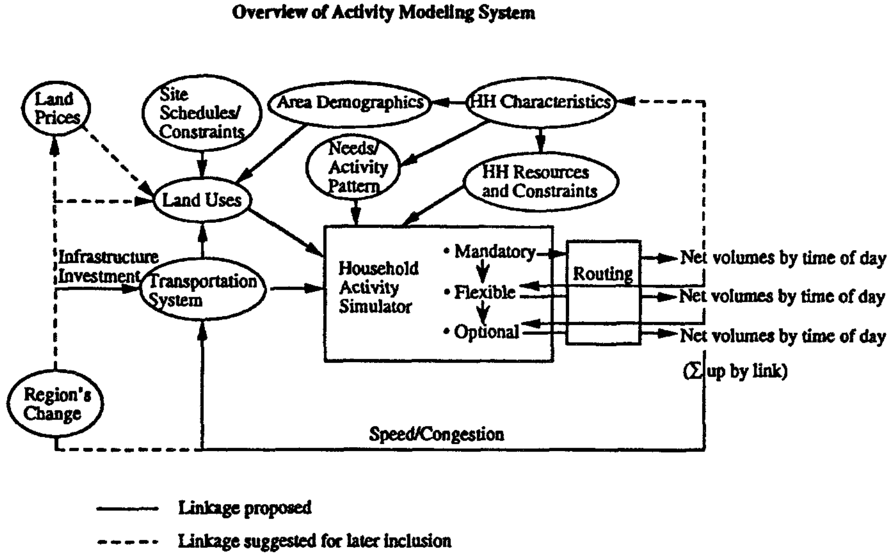

Fig. 2. Overview of the SMART model structure.

- Households, the primary activity and travel consumers.
- Land uses, that is sites where activities can be engaged in
- Transportation systems, connecting sites and residences

Each of these is described further by its key elements:

Households

Characteristics, resources, and constraints. These consist of household attributes and capabilities that permit it to engage in daily activities. Examples include vehicles, drivers, access to transportation systems. Constraints include physical and temporal limitations, particularly time available and money.

Needs and activity patterns. To sustain themselves and provide for the growth and satisfaction of members, households must identify and meet needs. These include basic needs such as shelter and food, money and resource gathering, and also other needs for interaction, and personal growth. Activities are the assigned set of behaviors that household members engage in to satisfy needs. Activity patterns are the structured set of activities by individual, resources, schedule, and location.

Land uses

Activity sites, locations where activities are permissible and can take place. Common examples would be employment sites, residences, commercial, parks.

Most activity sites have associated schedules of operation, that is times and days when activities are engagable.

Area demographics. The aggregate characteristics of land areas, describing the traits of households and other activities sited there.

Land prices, the market values of land parcels, both occupied (in use) and vacant.

Transportation systems
Transportation systems access, the specific elements of transportation systems that tie land uses and activity sites together and make sites accessible.

Routing, the specific sequence of links and terminals forming a minimum cost path between two activity sites.

The SMART modeling system is based on a number of tenets that describe the underlying structure of travel, activities, and urban form. These are:

1. The household, acting through its individual members, is the primary decision-making unit. Individuals, by engaging in assigned activities, carry out these decisions.
2. The need to engage in activities that satisfy household requirements is the driving force behind decisions that result in travel.
3. The decisions to participate in activities (and who will participate) result from negotiation and role allocation within households.
4. Most activity engagement, and hence most travel, is habitual and repetitive on cycles. Household travel patterns do not shift frequently.
5. Travel is generated incidentally from the activity allocation process. After initial assignment of activities, household members do not consider travel features extensively. With few exceptions, travel is not the focus of activity behavior. Therefore, a successful travel model must focus not on travel but on activities.
6. Time and cost constraints limit the choices of activities and locations available to households, and hence limit the travel options.
7. Households adapt activity and travel patterns incrementally, in response to changes in household needs, land uses, and transportation services.
8. Over time, land owners and agencies adapt activity sites and transportation systems to meet evolving aggregate demands from households. Congestion and accessibility serve as two, but not the only or the most important, factors in changes in activity sites and transportation systems.

These concepts are explained in more detail below.

The basic concept of activities

The basic concept underlying the SMART model is that a household consists of individuals who operate part of the time as a group entity (the household) and part of the time as independent individuals. As an initial simplifying assumption, it is postulated that household needs are determined first; next, roles in meeting these needs are assigned to eligible members of the household; and, finally, the household resources required for meeting these needs are committed to them. Individual needs can then be met to the extent that time, money, and other resources permit, after the needs of the household as an entity have been met.

It has long been held by transportation planners that travel is a "derived demand" (Stopher & Meyburg 1976; Oi & Shuldiner 1965), in other words, that travel is demanded not for its own sake, but rather as a means to undertake an activity that produces utility for the individual or household. It is implicit in this assumption that each such activity is either not available within the household (i.e. without traveling), or that it is available but with a sufficiently smaller utility that travel is still desirable to obtain much greater utility from performing the activity at a location outside the home. Two notions embodied in traditional travel-forecasting procedures attempt to acknowledge this: first, trip purpose is used as a surrogate for the value or utility of the activity enabled by travel; and second, travel, whether for home-based or non-home-based purposes, is produced by households and attracted to other locations. Unfortunately, these constructs mask extremely large variations in utility between activities, and fail, as a result, to provide adequate distinction as to the utility of different activities and, therefore, to permit some assessment to be made of the trade-off between travel disutility and activity utility.

It is also important to note here that we use the term "utility" in its broadest sense, to mean the usefulness to be derived from an activity. This should not be taken to imply that the SMART paradigm is based on utility-maximization, however. While utility maximization could be used as a basis for developing models, other theories may be equally or more applicable and useful in developing this paradigm.

It is not unreasonable to conclude that some of the shortcomings of traditional travel-forecasting models arise because of the fact that the "trip-purpose" construct does not address the derived-demand nature of travel adequately. Nevertheless, individuals engage in such a variety of activities that some means to classify the activities is essential to any form of modeling. In the SMART model, it is first proposed that activities should be classified into three primary groupings, similar to those that have been proposed at various times by others. While some researchers have proposed subdividing trip purposes into discretionary and non-discretionary categories, we postulate that a further subdivision is appropriate, namely into mandatory, flexible, and optional activities. Mandatory activities include those activities for which the frequency of undertaking the activity is normally fixed, the locations where it is done is fixed over significant periods of time, and the scheduling and duration of it are also largely fixed. Mandatory activities include work and school, and often also day care for young children. For most of the population, sleep should be considered a mandatory activity, while for other subgroups, medical care may also be a mandatory activity. Mandatory activities largely, but not entirely, map into the non-discretionary category proposed by others.

At the other extreme are optional activities, for which all of the characteristics just mentioned may vary. In other words, the frequency is not fixed and may include a zero frequency in any selected time period, i.e. that undertaking the activity is optional; the location at which the activity may be undertaken is open to choice; and the length of time spent in the activity and the time at which the activity starts and ends is open to choice. These activities will include most social and recreational activities, cultural and community activities, etc. Generally, they map into the category of discretionary activities. However, more importantly, many of these activities can be done at home as well as in locations away from home, so that there is often a question as to whether travel will be required, even when such activities are engaged in.

The third category we propose is that of flexible activities. These are activities for which some of the primary characteristics are fixed, while at least one is optional, or rather, flexible. For example, grocery shopping may be done at various frequencies, although performing grocery shopping is necessary at a frequency at least equal to once in some time period. Locations for this activity are largely optional for any given household, and the duration and timing are also open to considerable choice. Other activities, such as banking, use of various services, major shopping (for clothing, furniture, and other similar items), some work-related activities, medical care, etc. are all flexible activities. Included in this category is also the activity of eating a meal, because while many people choose to eat three meals a day, others do not, so that there is no fixed frequency, no fixed location, and no fixed schedule or duration for this activity.

Each activity also has a duration that is required to perform it, and a beginning or ending time, scheduling its beginning or end. Mandatory activities will typically have fixed start (and often end) times, with small ranges allowable, while flexible and optional activities will have typically shorter durations and larger allowable ranges and scheduled times.

Activity categories and life-cycle stage

The second element of the SMART model structure is the postulate that the specific activities engaged in by primary category, and much of the variability that will be seen to surround the flexible and optional activities, is a function of the life-cycle stage of the household. Table 1 shows some preliminary ideas about important differences among the mandatory, and flexible activities that we believe relate to life-cycle stages.

Table 1. Variation in mandatory activities for different household groups.

Group	Work	Work-Related	School*	Medical	Sleep
1. Single Working Adult	Mandatory	Mandatory	Optional	Optional	Mandatory
2. Multiple Adults	Mandatory	Mandatory	Optional	Optional	Mandatory
3. Young Families	Mandatory	Mandatory	Optional	Flexible	Mandatory
4. Older Families	Mandatory	Mandatory	Mandatory	Optional	Mandatory
5. Nonworking Adults	N/A	N/A	Optional	Mandatory	Mandatory

* Because some adults may also be in school, the definition of school in this column should be considered primarily to refer to K-12 schooling. It also excludes pre-school, which is an optional activity.

In Table 1, we have shown primarily those activities that are considered to be mandatory for at least one life-cycle group. The reason for indicating mandatory for medical care for life-cycle group 5 is that this is primarily considered to be a life-cycle group of retired people, for whom, with aging, medical care tends to become more a mandatory than a flexible activity. However, this point is arguable and needs testing from empirical data. We can also add to the table that shopping and personal business/banking would be considered flexible activities for all life-cycle groups, and that remaining activities, such as social, recreational, and similar activities, are optional for all life-cycle groups.

The list of life-cycle categories is less extensive than those frequently used. Our intention here is to attempt to be as parsimonious as possible in defining life-cycle groups for the purposes of recognizing variations in the underlying definitions of mandatory and flexible activities, as well as in defining the possible alternative allocations of activities among household members.

Allocation of roles

The third element of the proposed SMART model is that the decisions to participate in activities are made on two levels. First, for activities required for the satisfaction of household needs, the decisions are made by the household as an entity. We also postulate that these decisions are the ones that utilize available resources and the time of individuals first, and that decisions to engage in other activities, either those that satisfy desires (but not needs) of the household, or those that satisfy the needs and desires of the individual, are made after first satisfying the households needs. The household, through its individual members, is the primary decision-making unit. Individuals, by engaging in activities, carry out these decisions. Second are those activities that serve the needs or desires of individual members of the household. (In the event that a household consists of only one person, these two become indistinguishable.) Utilizing the balance of time and resources that remain to each individual, these activities will be selected, together with durations and schedules, based on the time of day that is available and the amounts of time available. Of course, the option will often exist for some household members to combine personal and household activities, so that the total resources devoted to the combined activities is less than the sum of the resources required for the two separate activities. Such combinations may be achieved by chaining the activities so that intermediate trips home are not necessary, by selecting the locations for activities so that they are proximate, or by selecting the times of day and the duration to be spent in the activities so as to allow them to take place in combination.

The requirement to engage in activities that satisfy household needs is the driving force behind decisions that result in travel. The decisions to participate in activities (and who will participate) are the result of negotiation and role allocation within households. Thus, understanding the structure of households and how different stages in the life cycle affect the allocation of roles is fundamental to understanding the activities in which the household participates and the allocation of those activities to different members of the household.

Two basic types of household data are required: characteristics and resource data for each person, and needs (activity) patterns for the household. The characteristics data consists of information, for each person, about such items as:

- Age
- Cars/vehicles assigned or owned
- Driver's license status
- Gender

- Relationship
- Activities required (mandatory)
- Frequency of engagement in mandatory activities (not initially necessary)
- Hours required and locations for mandatory activities
- Activities that are flexible or optional
- Limitations on the flexibility of flexible activities
- Frequency of engagement in each optional or flexible activity
- Total household income
- Life-cycle stage
- Travel-time budget
- Total-cost budget.

Resource data for the household are a function of its characteristics, particularly income, life cycle, and location. "Activity-needs" data for the household show what activities are assigned or optional for each person.

The nature of travel and activities

The fourth element of the proposed approach has to do with our understanding of the nature of travel and its relationship to activities. First, we assume that most travel is habitual, depending for form on infrequently-made decisions. Commonly, travel patterns do not shift. This is a fundamental difference from current approaches to travel-demand modeling, that assume that travel patterns will adjust instantly to quite small changes in transportation-system characteristics. Second, we postulate that travel is, generally, an incidental item to the decision process that results from the requirement for activities outside the home. Modeling the travel process correctly and realistically requires that activities, not travel, be the center of attention. Again, this is a return to the fundamental philosophy that travel is a derived demand. In response to sufficient large external or internal stimuli, such as changes in household structure, resources, job change, loss, or addition, transportation investment, or land-use change, households adapt incrementally by changing activity patterns and hence travel, within time and budget constraints. The emphasis here, however, is on changes in activities or the resources of the household as the primary driving force behind changes in travel. It is only when a transportation-system change occurs that is of sufficient magnitude to impact the time or budget constraints of the household or individual that the transportation-system change can generate a change in travel. Even then, such changes will normally need to be for the mode of travel currently being used, rather than to alternative modes that are not currently used. This may not hold, however, when a completely new alternative, such as a rapid-rail system, is first opened to service.

There may be two exceptions to this concept that transportation system changes have limited ability to cause changes in travel patterns of the household. First, if a household or individual is currently devoting more resources to the travel involved for a specific activity (particularly mandatory activities) than is desired, a change in the transportation system that provides a new alternative that consumes less resources may be selected as a means to establish a more desirable resource allocation. Second, there may be changes in tastes and preferences of households and individuals that generate a desire to look at alternative transportation modes and to select a different mode on the grounds that it matches better the new tastes and preferences of the household or individual.

Allocation of household resources

The fifth element of the SMART approach is that the allocation of household and individual resources to activities and travel is made consistent with the mandatory, flexible, or optional nature of the activities. In other words, we postulate that households initially allocate resources to the mandatory activities, particularly in terms of time for the activity, time to travel to and from it, and such resources as household vehicles. The allocation of time to flexible activities comes next, with some trade-offs being possible between the frequency, duration, or amount of travel time required for flexible activities, in order to free up some resources for desired optional activities.

Consistent with this notion, it follows that households will generally allocate time out of each day to work, sleep, school, and any other mandatory activities for the specific household in question, together with the needed travel times to reach those activities that are not conducted in the home. It also follows that most households will allocate household vehicles to the travel required for these mandatory activities, essentially tying up these resources for the duration of the out-of-home mandatory activities. We postulate that there are primarily three circumstances in which household vehicles are not allocated to travel for mandatory activities:

1. When a non-household vehicle is available for a non-driving member of the household (e.g. a school bus), this will usually be selected as the travel means, except in cases where a household's tastes and preferences are in conflict with such a choice, or where another household member will travel past the activity location at a time that is consistent with the mandatory time to be at the activity, and therefore is able to provide a ride in a household vehicle.
2. When the activity is located in an area that has high parking prices, such that more money budget would be consumed than the household desires,

and when there are reasonable options (e.g. transit, carpools, vanpools) to travel without using a household vehicle, a household vehicle may not be allocated to this travel and activity.

3. When a household, because of tastes and preferences, opts to live close to a transit line that provides service to the location of a mandatory activity (such as work), a household vehicle will not be allocated to this travel and activity.

In the third case, the household may decide not to acquire a household vehicle, or an additional one, or may decide to get rid of a household vehicle, because the vehicle is unnecessary for travel to a mandatory activity. In these instances, the household may be seen to have made the decision effectively to become "captive" to the transit option. Whether captivity is by choice or necessity is likely to be difficult to determine, but needs to be borne in mind when examining the behavior of households and the allocation of resources.

Once these allocations have been made, the household allocates additional time and vehicle resources, together with monetary resources required, to serving those flexible activities that have been selected to satisfy household and individual needs. Choices of location and frequency are likely to be made on the basis of remaining time budget, money budget, and other resource budgets that are left after serving the mandatory activities. Finally, the household and the individuals in the household consider optional activities that it is desired to undertake. If resources exist to permit such activities to occur (and these resources will have to include, at a minimum, the time at an appropriate time of day, vehicle availability, and monetary resources), then the decision is made to engage in the activity. This is the point at which some trade-offs may be made. Among the possible trade-offs may be to change the frequency, location, or time of day for one or more of the flexible activities, in order to free up some resources for the optional activity; or to alter travel patterns from direct travel between home and an activity location and build activity chains that result in multiple activities being undertaken between leaving and returning to home. Such activity chains may require a reallocation of the individual in the household who performs a particular activity. They also require that the activities, as sequenced, are consistent with each other. For example, following grocery shopping that includes perishable, refrigerated, and frozen items, it is unlikely that a visit to a movie theater will follow, without a trip to home to unload the groceries.

Again, the focus in this paradigm has changed, so that we talk of activity chains, rather than trip chains, because it is, indeed, a decision to chain activities that is made by household members, and not a decision to chain trips. The so-called trip chain is the result of a decision to chain activities, and can be understood and modeled only when the correct view of it is taken.

Within this entire complex of the allocation of resources to activities, there is the additional constraint of the schedule of the household's vehicles. In many instances, the availability of a vehicle at a particular time for travel to a specific activity, or the requirement for a vehicle to be available for a higher-priority activity of another household member may be more limiting than the availability of time of the individuals in the household for a specific activity. Certainly, this concept would help explain the current trends in vehicle ownership, in which we appear to be moving to have at least one vehicle for each licensed driver in a household. By so doing, the constraint on vehicle availability is effectively removed.

Testable hypotheses

Successful implementation of the SMART model requires, initially, several steps grounded strongly in scientific method. This process proceeds from observation to hypothesis building, data collection, testing, and theory revision. While simplified versions of the SMART model could be developed without this structure, and indeed efforts such as TRANSIMS (TMIP 1995) are doing just that, we believe that confident progress requires a more methodical approach. Therefore, we have identified a number of key hypotheses concerning activities and travel that we believe can be tested and confirmed initially.

Hypothesis 1. Household needs and activity patterns can be grouped according to stage in household life cycle, particularly influenced by the presence and ages of children, and the presence or absence of workers.

Hypothesis 2. Mandatory activities, and the resources needed to accomplish them, are assigned to household members according to gender, relationship, age, and income-earning capability.

Hypothesis 3. The primary determinants of whether an activity is mandatory, flexible, or optional are: first, fixed location, and second, fixed frequency. The primary mandatory (fixed location and frequency) activities are: sleep, work, and school. Common flexible activities (frequency and location variable, but frequency is nonzero) are: grocery shopping, elective health, banking, major shopping, meal-eating, and some recreation. Common optional activities (non-fixed location and frequency) are: most social and recreation activities, cultural and community activities, and pleasure travel.

Hypothesis 4. Trade-offs between weekday and weekend activity are primarily a function of available time. Lower-priority activities are most likely to be scheduled off-time or on weekends.

Hypothesis 5. Vehicle and resource allocation to individuals is the primary factor in assigning flexible and optional activities to household members. Once assigned, activities are also provided with departure time, money for the activity, money for travel, accessing mode, destination, and travel companions.

Hypothesis 6. Households prioritize activities into mandatory, flexible and optional groups, if needed delaying the latter two.

Hypothesis 7. Households organize time and budgets around the need for mandatory activities, secondarily around other activities.

Hypothesis 8. Flexibility in the schedule of activities allows expansion of en-route geographies to include multi-stop chains.

Hypothesis 9. Departure times are an individual choice, made primarily to permit a high probability of arrival within the allowable schedule variance of mandatory activities. Transportation system features, including congestion, play a minor role in departure choice, particularly for mandatory activities.

Hypothesis 10. Most travel is habitual, as are the activity patterns that generate it.

Hypothesis 11. Choice of destination for most trips depends primarily on household decisions concerning activity allocation. Potential sites for activities are narrowly defined and limited to the geography immediately surrounding the axes formed by mandatory destinations and the home site.

Hypothesis 12. Choice of mode, for most purposes, is determined by vehicle allocation and prior mode choice, not by time and cost factors. It is essentially a household decision, not an individual decision.

Hypothesis 13. Route choice is primarily an individual decision, independent of other family members.

Hypothesis 14. Activity and travel decisions are essentially the same in urban, suburban and rural circumstances. It is primarily the opportunity space that differs, both in terms of the number and proximity of land uses that offer satisfying activities, and in terms of the transportation options to reach the activities. A model can be constructed that fits all environments equally well.

Hypothesis 15. The geographic area containing acceptable destinations for en-route stops between major activities is ellipse-shaped, with the major axis equal to the distance between the major destinations.

These hypotheses, and others, are fundamentally different from the driving structure of conventional travel-demand models. Therefore, thorough testing and verification should take place, in the process of model building.

Forecasts of travel using the SMART model would require land-use forecasts. We envision an interactive land-use model, in which land available would be used in a choice-based model that allocates activities to locations. Using a GIS-based land-use pattern, areas that contain acceptable sites for a household's activities are first drawn from the regional supply of sites. The chosen sites are those that fall within the "ellipse" areas formed by the household's major activity destinations (Li 1994).

Conclusion

This paper has outlined the structure and process for developing a new travel-demand paradigm based on household activities rather than person trips. A paradigm shift is called for, focusing not on travel but on the behaviors, needs, and roles that generate it. We recognize the difficulty of this shift: change is not easy, and the present paradigm, while widely viewed as unsatisfactory, is well-entrenched. However, it is also clear that progress in transportation modeling will not come if the discipline continues along the present path of pursuit. There are structural flaws in the present approach that are described in detail in the opening sections of this paper.

The options, unpleasant as they are, are to continue as is, to modify the present UTPS modeling structure by making incremental improvements, or to develop a consensus on how to proceed with a new paradigm. We believe that, in the long run, the latter course is preferable. To continue without change is almost prohibited by the nature of the planning changes required under the ISTEA and the CAAA. Change of some sort is required if the mandates of new legislation and rules are to be met. Incremental changes to the current paradigm are not capable of correcting fundamental flaws, such as the notion of the trip as the unit of interest and the assumption that a trip (defined as a one-way movement from an origin to a destination) is independent of any other trip. If such flaws in the paradigm are to be corrected, only a paradigm change can achieve this. The paradigm proposed in this paper has some important properties that should be kept in mind. Because the paradigm is based on analysis of the activities needed and desired by households and on the assumption that the selection of where, when, and how to do these is made based on resources available and constraints imposed on the household through allocation and negotiation, the paradigm is extremely robust and can evolve as society evolves. If role allocations should change in the future, the paradigm can change with those changes. Second, there is no requirement that the activities defined as mandatory, or flexible, or optional today must remain in those categories into the future. If certain types of occupations should be accomplished increasingly by telecommuting and flexible scheduling, the activity of work for some occupational categories could move into the flexible activity category, or even be moved into a newly-defined category in which location might still be fixed, but frequency, duration, and schedule are flexible.

Finally, it is appropriate to note that the potential to test the hypotheses and develop this approach into a practical travel-forecasting methodology is greatly increased by the recent trend in household travel-survey collection methods. Since 1991, a number of large urban areas have collected data using an activity diary, in place of the more conventional travel diary. The first of these was in Boston (Stopher 1992). Most recently, a two-day diary has been used in several urban areas of Oregon, in which both out-of-home and in-home activities have been recorded. The data sets resulting from these surveys (in such places as Boston, Southern California, Salt Lake City, Detroit, Portland, the Research Triangle Area of North Carolina, and North Central Texas, *inter alia*) provide an enormously rich resource for testing. Some preliminary work of this type has already been undertaken (Stopher & Vadarevu 1995), with tests performed of hypotheses 1, 2, and 3, from the earlier list. Initial results have been strongly supportive of this approach.

The authors hope that this paper has contributed to the dialogue and consensus-building on this direction, in which case we will have achieved our objectives. Clearly, the next steps are to proceed with testing the hypotheses, refining the concept, and developing some initial models.

References

Axhausen KW et al. (1991) Eurotopp – towards a dynamic and activity-based modeling framework. *Advanced Telematics in Road Transport*, Proceedings of DRIVE Conference, Feb. 1991, Elesevier Scientific Co.

Fried M, Havens J & Thall M (1977) *Travel Behavior – A Synthesized Theory*. Report to NCHRP.

Goodwin P (1992) *Adaptive Responses to Congestion*. Technical Monograph, Transportation Studies Unit, Oxford University, 11 Bevington Road, Oxford, England.

Hägerstrand T (1970) What about people in regional science? *Papers of the Regional Science Association* 24: 7–24.

Hartgen DT & Tanner GH (1970) Individual attitudes & family activities: A behavioral model of mode choice. *High Speed Ground Transportation Journal* 4(3): 439–467.

Hemmens GC (1970) Analysis and simulation of urban activity patterns. *Socio-economic Planning Sciences* 4(1): 53–66.

Jones PM (1979) HATS: A technique for investigating household decisions. *Environment & Planning A* 11: 59–70.

Jones PM (1979) Methodology for assessing transportation policy impacts. *Transportation Research Record Number 723*: 52–58.

Jones PM (1980) Experience with household activity-travel simulator (HATS). *Transportation Research Record Number 765*: 6–12, Fig. 2.

Jones P & Clarke M (1986) *Household Activity-Travel Patterns In Adelaide. Stage 1: Summary Report.* Oxford University, Transport Studies Unit, 11 Bevington Road, Oxford, England.

Kitamura R, Kostyniuk LP & Uyeno MJ (1981) Basic properties of time-space paths: Empirical tests. *Transportation Research Record Number 794*: 8–19.

Knippenburg CWF van (1987) Time in travel. Drukkerij van Denderen BV, Gronigen, Netherlands.

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

Li Y (1993) *GIS-based Spatial Representation and Travel Pattern Analysis: A Case Study in Activity-based Urban Transportation Planning.* Unpublished MS paper, Department of Geography, University of North Carolina-Charlotte, Charlotte, North Carolina, 28223.

Li Y (1994) GIS-based spatial representation and trip pattern analysis for the 1985 Charlotte household travel survey. Transportation Studies Center, UNC Charlotte, Charlotte, NC 28223.

Recker WW, McNally MG & Root GS (1986) A model of complex travel behavior: Part I – theoretical development. *Transportation Research A* 20A: 307–318.

Recker WW, McNally MG & Root GS (1986) A model of complex travel behavior: Part II – an operational model. *Transportation Research A* 20A: 319–330.

Stopher PR (1992) Use of an activity-based diary to collect household travel patterns. *Transportation* 19(2): 159–176.

Stopher PR & Hartgen DT (1993) *SMART: Simulation Model for Activities, Resources, and Travel.* Report prepared for Federal Highway Administration.

Stopher PR & Vadarevu R (1995) An investigation of the effect of life cycle on household travel behavior. Paper presented to the 8th Road Engineering Association of Asia and Australasia Conference, Taipei, Taiwan.

Supernak J (1983) Transportation modeling: Lessons from the past and tasks for the future. *Transportation* 12(1): 79–90.

TMIP (1995) *Travel Model Improvement Program Newsletter #2.* 1600 E. Lamar Blvd., Suite 112, Arlington, TX 76011.

Weiner E (1993) Upgrading US travel demand forecasting capabilities. Paper presented at the Fourth Conference on Transportation Planning Applications, Daytona Beach, Florida.