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Publication Date
1997

UCI-ITS-AS-WP-97-1

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January 1997

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An Activity-Based Approach to Accessibility

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ABSTRACT

This paper presents the initial formulation of an activity-based model structure to address deficiencies in traditional measures of individual accessibility and which incorporates temporal transference effects of alternative travel behaviors within a household to form an index sensitive to such effects. A network-based activity assignment protocol is developed for complex travel activity decisions within a household. The research incorporates routing, scheduling, household activity assignment, and ride-sharing components into a hybrid model that explicitly captures the interactions between household members and integrates mode availability, ride-sharing behavior, and time window constraints. In this approach, individual accessibility can be estimated and aggregated to reflect accessibility within a household under alternative transportation supply environments. Prior research on such accessibility approaches suggests that the proposed extensions can be applied to estimate the impacts of changes in transportation and land development policies; the usefulness of this approach in such analysis is demonstrated by its application to selected case studies based on data derived from the Portland, Oregon Activity and Travel Behavior Survey.

1. INTRODUCTION

Traditional accessibility studies are almost exclusively concerned with the spatial aspects of travel decisions (Ingram, 1971; Dalvi and Martin, 1976). Limitations on the definition and estimation of traditional accessibility measures in transportation planning have restricted applications to the use of simple aggregate indices, temporally independent, which can not reflect the potential for connectivity between activities. Applications of accessibility concepts have, therefore, been limited to such aggregate analyses as land use and facility location studies (for example, see Hansen, 1959). Consequently, the impacts of changes of transportation policy cannot be expressed easily in terms of accessibility-related effects, although the provision of accessibility is typically an important goal in the implementation of new transportation policy options. This deficiency is particularly acute when accounting for the effects of accessibility transference both among household members (e.g., through ride-sharing) and between different time periods (e.g., through trip-chaining).

With the accepted notion that the demand for transportation is derived from the demand for activity participation, the collection of travel decisions embodied in travel-activity patterns result from a complex decision process that incorporates interactions among household members as well as constraints on time and mode availability under limited resources (Recker *et al.*, 1986a, 1986b, 1987; Garling *et al.*, 1989; Golob, 1990; Van Wissen, 1989). An extension of traditional aggregate accessibility concepts to the level of the household is needed to properly reflect these temporal and activity-based aspects of accessibility.

2. REVIEW OF ACCESSIBILITY CONCEPTS

Traditional measures of accessibility, such as those developed during the 1960's, are based on an aggregate foundation; they can be operationalized only on an average and aggregated basis void of information on individual behavior. Traditional accessibility can be defined loosely as an interaction of activity location with the provision of transport services. Operational definitions of aggregate accessibility measures have been offered by a number of researchers (Hansen, 1959; Ingram, 1971; Dunphy, 1973; Sherman *et al.*, 1974; Williams and Senior, 1978; Wachs and

Koenig, 1979). Dalvi and Martin (1976) and Dalvi (1979) provide a systematic review of different indices, comparing and contrasting accessibility measures based on different types of distance metrics and functional forms. Despite any general usefulness, traditional measures of accessibility are characterized by a number of shortcomings; these traditional measures:

(1) employ home-based measurements only
(2) utilize distance based on average or zonal measures.
(3) reflect little or no individual behavior aspect in the measurement.
(4) provide little or no recognition of complex travel behavior (such as trip chaining).

Some of these limitations have been addressed by research that has expanded the previous studies by considering temporal (Burns, 1979) and microscopic aspects (Ben-Akiva and Lerman, 1979). In particular, Burns (1979) proposed a temporal component of accessibility based on Hagerstrand's (1970) concept of the space-time prism and has shown that, in general, a person's accessibility can be increased more by relaxing timing constraints on activity participation than by increasing the average speed of travel. Hagerstrand viewed accessibility as the freedom of individuals to participate in different activities and, with the use of time-space prisms, investigated the dependence of accessibility on its transportation, temporal, and spatial dimensions. Accessibility benefit measures were constructed based on different assumptions about how individuals value the opportunities available to them, and these were used to analyze and compare the accessibility implications of a variety of transportation policy options.

The time-space geography framework originated by Hagerstrand (1970) and used by Burns (1979) has had fairly wide application as a basis for deductive accessibility measurement and as one of the foundations for inductive diary analysis. It is commonly referred to as the "constraint-based approach" given the defining role that spatial and temporal constraints in the formulation. In this framework, space is typically expressed as a two-dimension plane, while time is depicted via a third, vertical axis. Within this three-dimensional space, so-called time-space prisms define the limits of what is accessible.

Extensions and applications of this approach are numerous, however, operationization of Hagerstrand's framework to meaningful policy evaluation has proven extremely difficult, principally because of the complexity of the analytics embedded in the time-space approach. Most often, studies have either been restricted to descriptive analysis or have involved computer-oriented model systems that produce the enumeration of feasible time-space paths. Because of the complicated dimensionality of the problem, these latter efforts have relied principally on exhaustive enumeration or the application of sequential procedures to reduce the complexity in forming the activity pattern (Kitamura and Kermanshah, 1983, 1984; Recker et al., 1986a, 1986b). In a few cases, structural equation systems and simple multivariate data analysis techniques have been employed to determine the relationship between activity patterns and socio-demographic attributes (Golob, 1985, 1986; Golob and Meurs, 1987). With few exceptions (Koppelman and Townsend, 1987; Golob and McNally, 1997), prior research has focused on the activity patterns of individual members of households; work addressing the collective travel behavior by household members is quite limited.

Activity-based models are being combined with, or are replacing, the traditional four-step forecasting process and associated land use models to explore new planning modeling systems reflecting tenets on the activity-based approach. Two such model systems under development are AMOS (**A**ctivity **MO**bility **S**imulator) (Kitamura *et al.*, 1994) and TRANSIMS, each offered as an alternative planning system to replace the conventional forecasting model system. SAMS (**S**equenced **A**ctivity-**M**obility **S**ystem), a core component of AMOS, is activity-based and incorporates explicit modeling of adaptation behavior, forecasting by micro simulation, GIS-based data structures, and endogenous forecasting of socio-demographics, land use, and travel. The federally-sponsored Transportation Model Improvement Program (TMIP) has as one of its thrusts the design and development of a new model system to replace the current forecasting system. TRANSIMS (Barrett *et al.*, 1995), under development at Los Alamos National Labs, provides a micro-simulation environment designed to reflect an activity-based approach and to provide more accurate estimates of system performance as required under recent federal legislation.

With a similar goal of explicitly extending activity-based approaches for application in policy analysis, Recker (1995) has advanced a theoretically elegant mathematical programming framework that holds potential to operationalize activity-based travel demand methodologies. The Household Activity Pattern Problem (HAPP) is posed as a variant of the pick up and delivery problem with time windows (PDPTW). The model addresses optimization relative to the household's utility function which reflects the interrelated paths of household members, each with a prescribed activity agenda, and a stable of vehicles and ride-sharing options available.

3. A REFINED DEFINITION OF HOUSEHOLD ACCESSIBILITY

Despite noted advances, a modification of the accessibility concept is necessary to accommodate policy dimensions that result in redistribution of accessibility across individuals in the same household and over time periods for a given individual. This reformulated concept should be related not only to transportation system and land use characteristics but also to individual demographic characteristics and to measures that define the household transportation supply environment. The resultant measure should be both general and operational and also should reflect individual person and household differences. Given the identified limitations associated with traditional accessibility measures, new measures of accessibility should:

(1) be policy sensitive,
(2) reflect differences in personal and household characteristics,
(3) reflect temporal aspects in measurement, and
(4) reveal an accessibility transference effect.

The basic motivation of this conceptual framework stems from the idea that, by combining the trip chaining problem, activity participation problem, activity scheduling problem, and household interaction problem, both spatio-temporal constraints and household interaction effects can be incorporated into a more meaningful measure of the potential of a household to interact with the built environment. Taken together, the components of the proposed framework can be described by the Household Activity Pattern Problem, or HAPP (Recker, 1995); the solution patterns reveal personal travel behavior and activity participation within a household context, while preserving the concept that accessibility originates from participation in activities, that travel constitutes the linkage between activities, and in which all of the required components are contained in the activity scheduling problem.

The proposed modification to the measurement of accessibility is based on the aggregation of a microscopic accessibility index which measures individual accessibility within a constrained transportation environment. Within this context, personal accessibility is described as a measure of the *potential ability of individuals within a household to reach activity opportunities, subject to the spatio-temporal constraints imposed by their daily obligations and transportation supply environment.* The intent is to identify and measure the potential for interaction that remains after accounting for the consumption of time-space needed to accomplish an individual's daily demand for in- and out-of-home activities. Redefinition of individual accessibility by considering not only average spatial aspects but also temporal and activity-based aspects can provide the capability to account for the effect of accessibility transference, over time, between household members, and within the population.

The proposed accessibility index is based on Hagerstrand's space-time prisms, by which accessibility can be defined as the potential "reachability" of specific members in the household.. The spatial location and temporal availability of activity sites, together with the maximum speed an individual can travel between sites, establishes the individual's space-time prism; the volume of this prism represents the full range of possible locations at which an individual can participate. Once an individual initiates a pattern, the potential action space for subsequent activities is reduced as a function of characteristics of prior activity (e.g., duration). The accessibility is measured by the volume of the time-space prism in Hagerstrand's 3-dimensional space for each individual. It is herein proposed that the aggregation of individual accessibilities, a microscopic measure, over all household members be interpreted as an assessment of macroscopic accessibility accruing to the household. Figure 1 provides an example to illustrate the calculation of the proposed accessibility measurement for a hypothetical member of a household, if the associated activity diary is known. In the case illustrated, the individual has three out-of-home activities that are to be completed, as well as two scheduled activities to be completed in the home. The spatio-temporal path, reconstructed from the activity diary of this hypothetical individual, is shown by the solid line; its projection onto the spatial plane is represented by the directed line segments. In the figure, the shaded prisms encompass the physical space that can be reached during the periods for which no specific activities are scheduled. The volumes of these prisms thus offer a measure of the potential to engage in additional activities. The "packaging" of the activity/travel decisions obviously impact the nature of such prisms contained in any activity pattern; in general, efficient travel decisions (e.g., trip chaining) tend to increase the potential to engage in additional activities should either the need or desire arise. An example of this is provided by the pattern shown in Figure 2, in which Activity 2 has been chained with Activity 1 rather than with Activity 3. When compared to the original pattern, the pattern in this figure results in a net gain in accessibility (at the home location), as well as a "transference" of accessibility to a different spatio-temporal location centered about the spatial location of Activity 2. Although not shown in this example, it is easy to imagine a similar transference that could take place between individuals in a particular household if, for example, another member of this particular household assumed responsibility for completing Activity 3. It is precisely these sorts of considerations that the measure of accessibility proposed herein is designed to capture.

The approach illustrated above is of general use in the estimation of the transference of accessibility under a range of relevant policy scenarios. The addition of a temporal dimension provides the ability to measure the variation of accessibility by time-of-day, while the analysis of personal accessibility facilitates a better understanding of transference of accessibility among household members, both in terms of ride-sharing and trip-chaining behaviors. After a presentation of the overall model formulation, the potential utility of this approach in policy analysis is demonstrated using travel survey data.

4. ACTIVITY PATTERN REPRESENTATION

The household travel-activity decision-making process underlying the proposed activity-based approach to accessibility is formulated as a network-based routing model incorporating vehicle assignment, ride-sharing behavior, activity assignment and scheduling, and time window constraints. The general approach involves treating the HAPP as an analogy to the Pickup and Delivery Problem with Time Windows (PDPTW). Details of this formulation can be found in Recker (1995) and, although the results quoted in this paper are based on a modified version of the mathematical program developed in that work (in terms of both the definition of variables and specification of problem constraints), the same general considerations apply.

In analogy to the PDPTW, activities are viewed as being "picked up" by a particular household member at the location where performed and, once completed (requiring a specified service time), are "logged in" or "delivered" on the return trip home. Multiple "pickups" are synonymous with multiple sojourns on any given tour. The scheduling and routing protocol relative to some household objectives produces the travel/activity pattern.

The problem is defined by a network graph **G=(V,A)**, where **V** is the set of all vertices, and **A** is the set of all arcs in the network. Physically, **V** can be a set of demand nodes, and **A** can be explained as the connections between these demand nodes. The standard Vehicle Routing Problem (VRP), that has been applied in numerous studies (Golden, 1984; Desrochers, *et al.*, 1988; Solomon and Desrosiers, 1988) is defined on this graph as the visit to each node once and only once by a stable of vehicles with specific capacity constraints. The goal of HAPP may be described as: *Minimize a hypothetical objective function*, a function which generally expresses the cost incurred by a household in completing all of the activities needed to be performed by household members) *subject to constraints related to transportation supply, time windows, vehicle capacity, and logical connection between activity nodes*. The HAPP, which is more complex than a generic VRP, can be defined on an expanded graph with the addition of temporary returning home nodes, and the replacement of the activity nodes with drop-off and pick-up function nodes, which physically represent the same locations as those of the activity nodes and logically are used to explain different purposes of that trip. The requirements for the household members to complete all scheduled activities (visiting all activity nodes), which could be performed either by some specific person or by anyone available, are maintained within this model. Each activity in the HAPP must be performed once and only once (equivalent to the definition that each vertex of the network in the VRP should be visited once and only once), and there is a limitation (a time window) on the period for performing the activity.

The resulting HAPP formulation is in the form of a Mixed Integer Linear Programming (MILP) model. The equations describing the problem are extensive (see Chen, 1996, for the actual mathematical program or Recker, 1995, for an equivalent formulation), and are omitted from this exposition in the interest of both brevity and focus. The minimization of some pre-specified weighted combination of total travel time, waiting time and out-of-home cost for each member of the household form the class of objective functions easily incorporated in this formulation. The constraints for this MILP are classified into six groups:

(1) routing for vehicle and household member
(2) scheduling for vehicle and household member
(3) assignment for vehicle and household member
(4) time window constraints
(5) coupling constraints of routing variable for household member and vehicle
(6) side constraints including budget, capacity, and rules for ride-sharing behavior.

Routing constraints define the allowable spatial movement of vehicles and household members; they include those constraints that guide flow conservation and the origination and termination conditions of each movement. The set of scheduling constraints specify the relationship of arrival time, activity start time, and waiting time, and temporal continuity conditions. Assignment constraints are applied to match the relations between activity participation, vehicle usage, and activity performers (household members). In conjunction with scheduling constraints, time window constraints are used to specify available schedules for activity participation. Coupling constraints define the relations between vehicle-related variables and member-related variables. Lastly, a series of side constraints are used to eliminate illogical connections between activity nodes.

5. SOLUTION PROCESS

The use of a mathematical programming approach offers some distinct advantages to activity-based analyses. In addition to its ability to verify the existence and correctness of the complex solutions arising from activity-travel path formulations, it is arguably the only approach that inherently accommodates the continuity and consistency requirements governing the series of activities and travel links that comprise a traveler's movement through the time and space continuum during a given period of analysis. Despite these strong conceptual advantages, the approach offers some serious challenges that must be overcome to enable its practical implementation as a tool for policy analysis. Such formulations typically contain a large number of constraints and variables, and the corresponding computational effort increases exponentially with the number of constraints and variables. In general, it is extremely cumbersome to solve large-scale problems.

Such problems arise principally from the feature that the formulation is of the mixed integer programming type, which belongs to the so-called NP-Hard (non-deterministic polynomial time) class of problem; the number of fundamental computations increases exponentially with the size of the problem. Consequently, it is practically impossible to solve a large-scale problem in a limited amount of time, using formal solution algorithms. Most often, heuristic algorithms that use "common sense" rules to limit the number of alternatives examined (and thereby reducing the time required) are employed to solve such problems.

In the formulation of the HAPP originating from the vehicle routing problem, an augmented network is constructed with nodes that number four times that of the original related vehicle routing problem. Moreover, additional complexity is associated with the included indices representing both the vehicles and persons as well as additional constraints on temporal feasibility and resource budgets. Because of these factors, a heuristic method was developed specifically to solve the HAPP.

The models with and without ride-sharing options have different model structures; the former can be treated by enumerating all possible ride-sharing options of the latter, which is a VRPTW-based problem with budget constraints. Employing a relaxation on the number of available vehicles within a household, the problem with ride-sharing can be reduced to a VRPTW. Furthermore, assuming that the triangle inequality is satisfied, the solution of VRPTW can be shown to be a lower bound to the original problem. The solution procedure can be divided into a two-stage process. At the first stage, a VRPTW is solved to generate initial feasible solutions; at the second stage, enumerations of tours with the ride-sharing option are generated subject both to the number of available vehicles and to a series of filters to screen out all illogical connections between activities. Since the feasible solution space of the first stage is larger than that of the second stage and the objective functions are the same, the solution generated from the first stage is feasible if any solution of the second stage is feasible. This offers a way of reducing enumerations by eliminating all infeasible initial solutions.

5.1 "Savings" Estimation

In the first stage of the solution procedure, a VRPTW-based problem with resource constraints is constructed with the introduction of a vehicle relaxation concept. The solution procedure for the first stage is derived from an analysis of constrained shortest path problems and the concept of opportunities from travel time savings. By adopting a shortest path algorithm, it is possible to find the locally least-cost tours. Application of relative savings information enables efficient comparisons among the possible candidate links to be inserted in the least cost tours. The combination of a constrained shortest path algorithm and the "savings method" produces a hybrid heuristic that integrates tour construction and tour improvement. Given a multipartite network with N x N nodes, the algorithm is:

Step 0: Set: k = 0

Step 1: Calculate the savings matrix S:

$$S = [s_{ij}],\ s_{ij} = (t_{oi} + t_{oj} - t_{ij}) - w_{ij}$$

where:

$$w_{ij} = \max\{a_j - (T_i + s_i + t_{ij}),\ 0\}$$

and:

w_{ij}	= the minimal required waiting time to go from node i to j
t_{ij}	= travel time from node i to node j (o = current location)
a_j	= the early time window at node j
T_i	= activity begin time at node i
s_i	= activity duration at node i

Step 2: Calculate opportunity cost matrix O:

$$O = [o_{ij}]\ ;\ o_{ij} = \max_{m,n}\{s_{mn}\} - s_{ij}$$

Step 3: Define the initial condition and the recurrence equations:

$$f_0(\mathrm{o}) = 0$$

$$f_{k+1}(j) = \min\{f_k(i) + \mathrm{o}_{ij} + t_{ij} + w_{ij}\}, \ \forall j \in \mathbf{V}$$

Step 4: Check feasibility of including the next node; if yes, go to 5; otherwise, go to 6

Step 5: Set k=k+1; calculate $f_k(n)$ for each node n until all stages are finished

Step 6: Calculate the cost for the whole network based on the sum of the constructed tours and all remaining single vertex tours

Step 7: If no nodes remain, then terminate; otherwise, extract the selected tour from the network and go back to step 0 with the remaining network.

The algorithm begins with the initialization of stage 0, and then calculates the general savings matrix from spatial and temporal variables. The opportunity cost is defined as the cost of not utilizing least-cost links. As a basis for dynamic programming, the recurrence equation is defined from opportunity cost. The feasibility of connecting the next node into the tour is tested for adherence to time window constraints, and compliance to person-node pairs (which mate an activity node with the person to perform that activity). The scheduling is handled by "moving forward", in which the arrival time at the activity node and the activity begin time are adjusted by advancing the time frame to find the first available time point for node insertion. The maximum time to shift forward and backward are stored for subsequent manipulation of the time window for the next node. If inserting the next node into the tour is infeasible or if the resulting savings is negative, a new defined cost is calculated that accounts for the spatial and temporal cost of the current and all other single-node tours. Otherwise, combination of nodes continues until the end of the stage.

5.2 "Wasting" Estimation

In the second stage, the heuristic method described above is modified by an insertion algorithm designed to deal with the large dimensionality of the problem. A new term, "wasting", is introduced with a meaning similar to the "savings" term. Wasting is defined as the additional travel time needed to utilize ride-sharing. The algorithm is a modification of the savings method and can be described as follows:

Step 1: Calculate the "wasting" of ride-sharing and "savings" of trip chaining

Step 2: Sort the wasting and savings of each node-pair in ascending order

Step 3: Select the minimal wasting node-pair to be the ride-sharing option and then apply the savings method to insert the other nodes into the first node-pair

Step 4: Check the side constraints regarding the time window, budget, load, and vehicle-node-pair constraints. If violation of the side constraints is detected, select the node-pair with the next minimal wasting and go to step 3

Step 5: Repeat until all of the nodes are exhausted

These two algorithms take particular advantage of the characteristic that available matching patterns are quite selective and regular, which greatly simplifies the ride-sharing matching process through a combination of wasting and savings for all available nodes.

6. EMPIRICAL APPLICATION

Observed activity patterns are the result of decisions made by household members subject to restrictions placed either by transportation supply or resulting from a variety of unobserved factors which influence travel behavior. The collection of individual travel/activity patterns provides a description of revealed household travel demand. Optimal travel/activity patterns represent normative behavior that is expected to exist under conditions constrained *only* by the spatio-temporal conditions described in the HAPP formulation. The gap between these two definitions, observed and optimal, can be taken as the potential benefit that may be achieved through elimination of these unobserved restrictions. As such, it becomes a performance measure that is potentially beneficial in evaluating the limits of the potential of policy alternatives on daily activity patterns.

The optimal activity pattern used in this analysis is based on a simplified objective that minimizes the sum of travel times and waiting times in a daily household activity diary, while discouraging people from making unnecessary out-of-home trips through use of a constant penalty function for having to leave home. Accessibility is measured by the volume of the space-time prism. Results of the calculation of potential improvement through optimal behavior are illustrated by measurement of both absolute and relative improved accessibility and travel time. The measurements are defined as:

$$ACC_r = \frac{acc_{opt} - acc_{obs}}{acc_{obs}} \cdot 100$$

$$TT_r = \frac{tt_{opt} - tt_{obs}}{tt_{obs}} \cdot 100$$

$$ACC_a = acc_{opt} - acc_{obs}$$

$$TT_a = tt_{obs} - tt_{opt}$$

where:

ACC_r	= relative percentage change in accessibility with respect to that observed
acc_{obs}	= observed accessibility measure
acc_{opt}	= optimized accessibility measure
TT_r	= relative percentage change in travel time with respect to that observed
tt_{obs}	= observed travel time measure
tt_{opt}	= optimized travel time measure
ACC_a	= absolute change in accessibility
TT_a	= absolute change in travel time

The HAPP model system is applied as a means to evaluate the potential improvement in household accessibility resulting from optimal activity scheduling, trip chaining, and ride-sharing. Distributions are computed of potential travel time savings and of changes in a accessibility measure defined by space-time prisms. The factors that underlie these improvements are investigated by performing ordinary least squares regression analyses between the potential reduction in travel time (increased accessibility) and a variety of life-style, socio-demographic, and activity diary variables.

6.1 Data Specification

An application of the HAPP model has significant data requirements. Since the model represents activity/travel behavior of the members of a household, detailed information is required on travel and activity participation for each member, as well as transportation supply information (including household vehicle holdings and network travel times). Constrained by these requirements, data sets suited to a demonstration of the potential usefulness of the HAPP model in a policy context are limited. At least one recently collected data set, the Southwest Washington and Oregon Area 1994 Activity and Travel Behavior Survey, contains sufficiently detailed information, including travel/activity diaries (with mode availability) and a regional transportation network model, for an application of the HAPP model.

6.1.1 Sampling Activity Data

A portion of this survey conducted in the Portland metropolitan area for a consecutive two-day period was selected; the initial sample included 2,232 households and 5,125 persons with a total number of 67,016 activities and 37,965 trips (each split fairly equally between the two survey days). All vehicles available to household members are recorded. Available household information includes: household size, household income, type of dwelling unit, and the number of available vehicles. The survey also provides person-level data including age, gender, employment status, occupation, student status, and driver license status.

In this initial application, some assumptions and simplifications associated with the Portland data set are made. First, the complete data set containing 2232 households is divided into seven groups classified by household size; 2-member, 3-member, and 4-member were selected for further analysis. From this sample, only households headed by adult male-female couples were selected. This stratification simplifies analysis and facilitates interpretation of results. In the current application, both in-home activities and non-auto related travel activities also are excluded. Based on these criteria, the resultant sample of 2-member, 3-member, and 4-member households comprise 402, 193, and 153 households, respectively. Summary statistics relating to household, person, activity, and travel characteristics are provided in Tables 1, 2, 3, and 4, respectively.

The summary presented in Table 1 shows the trends that are expected in demographic characteristics that are intrinsically related to household size (e.g., numbers of licensed drivers, vehicles). Also, there is a general trend toward younger adults as household size increases, an artifact most likely related to life-cycle stage. Although the mean number of employed persons in the household increases with household size, the results shown in Table 2 indicate that the household groups are remarkably similar with respect to employment characteristics once the "retired" household members are removed from consideration; 2-member, 3-member and 4-member households comprise 29.3, 6.3 and 1.5 percent of retired persons, respectively.

Table 3 presents the mean values of selected travel and activity participation characteristics for households in each of the three groups analyzed. The results again show the expected trends toward an increase in the total numbers of trips and activities for households as size increases. However, despite this increase in number, the averages both of total travel time per person (including those who make no trips) and of travel time per trip are quite similar across all groups. (Although not shown in the Table, the values of the average total travel time per person, conditioned on those who make at least one trip, are also similar across the groups.) The trip chaining characteristics of the three groups are also similar, with approximately sixty percent of chains being simple tours; however, we note that a substantial number of the tours are relatively complex – about one quarter involve three or more activities.

Table 4 presents a breakdown of the travel/activity behavior by purpose. These results are consistent with the similarities noted above. We conclude from these aggregate statistics that any differences that are uncovered from an analysis of potential gains in accessibility are not simple artifacts of household size, but rather are dependent on aspects of the activity/travel patterns not revealed in such coarse measures.

6.1.2 Specification of Supply Data

The travel time matrix, a key component of HAPP, is estimated by generating skim trees based on non-peak-hour travel times for all O-D pairs. In the Portland traffic model, there are 1,260 Traffic Analysis Zones, 21,868 links, and 9,703 nodes.

A comparison between network and survey travel times was made to estimate the difference between calculated and reported travel time. The comparison indicated tendencies of respondents to round off reported travel time (to 5 or 10 minute categories) and, in most cases, to report a substantially longer travel time for trips with network travel times less than 5 minutes. Some adjustment of network travel time was necessary to reconcile network times with times reported in the diaries (for a related adjustment, see McNally and Recker (1986)). A two-stage adjustment procedure was used to establish congruence between network and reported travel times. The first stage involves multiplying network times, categorized in discrete time intervals, by the ratio of the mean reported time to network time. The results of these calculation are provided in Table 5 for each of the three sub-samples analyzed. This global adjustment of network travel time is then further adjusted to account for any differences in perception of individual households by multiplying the adjusted network times associated with that household's activity patterns by the ratio between the household's total reported travel time and total adjusted network travel time for their patterns. Following this adjustment, the sum of the reported travel times will be equal to the sum of the corresponding network travel times for each household, providing a basis for comparison between revealed and normative behavior.

6.2 Potential Changes in Accessibility and Travel Time

Summary distributions of the potential savings in household travel time and changes in accessibility for each of the three household samples are provided in Figures 3 through 14. Figures 3, 7, and 11 describe the distributions of the relative and absolute difference in accessibility, as measured by the volume of the respective space-time prisms associated with the optimal and observed activity patterns. The distributions are seen to be similar for the three household groupings and generally resemble a negative exponential distributions. While a large portion of the households can be expected to have only minor relative improvement in accessibility with optimal behavior (e.g. less than a 20 percent increase), a substantial number of sampled households exhibit the potential for moderate-to-major gains in accessibility. For 2-member, 3-member, and 4-member households, improvements of 40, 55, and 60 percent, respectively, are possible. The general positive relationship between the percentage of households achieving moderate-to-major relative improvement and household size is speculated as an artifact of a similar general tendency between the size of the household and the complexity of the related activity pattern (i.e., greater household size leads to more activities and trips, which lead to more complex time-space paths, which lead to a greater opportunity for finding efficiencies). Distributions of potential improvements in absolute accessibility with optimal behavior (Figures 4, 8, and 12) generally follow the same tendencies noted for the corresponding relative values. Distributions of potential relative improvements in travel time for the three groups (Figures 5, 9, and 13) are distributed somewhat more flatly than are the distributions associated with the accessibility measure. Again, however, the results indicate that substantial segments of the sample population stand to gain at least moderate improvement (e.g., greater than a 20 percent increase) in overall travel time - approximately 60 percent of 2-member households and over 70 percent of both 3-member and 4-member households. Distributions of potential absolute improvements in travel time (Figures 6, 10, and 14) more closely resemble those associated with the improvements in accessibility.

To summarize the comparisons among these patterns for different household groups, it is concluded that there is a tendency in which larger household size results in a more pronounced "tail" to the savings distribution achieved with optimal travel behavior. One possible explanation is that the presence of more children (which accounts overwhelmingly for the size differential among the three groups), especially for those under age 12, leads to a more complex activity diary, and thus results in a more likely inefficient arrangement of trips and activities associated with this diary. Another is that "unaccounted for" constraints and objectives (i.e., those not included in HAPP formulation, which is constrained only by physical consistency of the time-space path) are more pronounced in families with children.

For all groups, the rearrangement of activity patterns through optimal behavior is shown to lead to potentially significant improvements in travel times and accessibility, and therefore, can be potentially beneficial in terms of reduction in fuel consumption, increase in the efficient use of household vehicles, and an overall reduction of automobile vehicle-miles traveled.

6.3 Modeling Changes in Accessibility and Travel Time

Demographic variables as the existence of children under 12 years of age, the number of driver's license holders, and other household socio-economic variables, and such instrumental variables as the presence of ride-sharing and trip chaining, were employed in regression analyses as a means of exploring their possible relationship to the potential improvements in the accessibility and travel time variables noted above. The notation and definition of the variables used in the regression analyses are listed in Table 6. The estimation results are provided in Tables 7 through 10 for relative and absolute accessibility and travel time improvements.

In Table 7, the regression results on relative accessibility with respect to 2, 3, 4-member households, and the combination of all three groups, are presented. The estimations are significant (F-test with $\alpha=0.05$). The difference in the number of trips within a trip chain for the optimal and observed patterns, TPDIFF, is significant in all three models. For 2-member households, the number of household vehicles (VEHS) is also significant, the number of HH licensed drivers (DRVRS) is also significant in the 3-member household model, and FLEXTIME, VEHS, TRIPS, and RIDESHARE are all significant in the 4-member household model. The trip difference variable (TPDIFF) has an important role in each estimated model, and it is concluded to have a major positive effect on increasing accessibility. For the combined household sample, all of the variables are highly significant in terms of T statistics and all of the signs of these variables are as expected. To summarize, the estimation results suggests that ride-sharing behavior, the presence of more trips and more vehicles, and an increase in trip chaining (TPDIFF) all have positive effects on accessibility. The magnitude of the ride-sharing effect is greater than that of the trip chaining variable. In the case of absolute accessibility (Table 8), TPDIFF still plays an important role. In addition, such socio-demographic variables as MULTIJOB, FTSTUD, and LATE are also critical.

The F-statistic for each model is better than that for the relative accessibility model, and all of the variables are significant.

In terms of relative travel time improvement (Table 9), the trip chaining variable (TPDIFF) as well as ride-sharing variable (RIDESHARE), as expected, always have a positive effect. Other variables, including INCOME, LATE, MULTIJOB, and ACTS, all have negative effects. Confirming the results of the previous section, the HHSIZE variable is significant in the case of all households, an indication that the presence of a greater number of household members may involve resource allocation constraints that result in inefficient arrangements of activities within the household. The estimations for absolute improvement (Table 10) are both significant (t- and F-statistics) and are somewhat self-explanatory. HHSIZE, as in the case of relative travel time measurement, has a positive effect. FLEXTIME, INCOME, LATE, and VEHS variables all have positive effects. The same result is found for the RIDESHARE and TPDIFF variables. The OLS estimation results indicate that some socio-demographic variables and activity pattern-related variables (e.g., ACTS, LATE, FLEXTIME) do affect the potential for improvement in accessibility and travel time. The household size variable (HHSIZE), also effects the travel time measurement. However, the most important variables are the ride-sharing and trip chaining variables that are present in almost every estimation. These two variables have positive signs in every case, and the magnitude of the coefficient for the ride-sharing variable is greater than that of the trip chaining variable. It is conjectured that in the case of ride-sharing behavior, better trip chaining results in an efficient arrangement.

7. SUMMARY AND CONCLUSIONS

Although accessibility measures have played an important role in transportation planning since the 1960's, their application is still largely confined to the use of aggregate data and average spatial distance to construct home-based measurements. Such measurements exclude activity-based constructs such as trip chaining and the role of temporal and spatial constraints on accessibility. As such, existing measures are responsive principally to changes in land use and transportation infrastructure. Activity-based analyses provide a framework with which to explore alternative structures for accessibility measurements that ameliorates these deficiencies.

The incorporation of activity-based concepts in the measurement of accessibility not only explicitly acknowledges a temporal dimension in assessing the potential for spatial interaction but also expands the applicability of accessibility consideration to a variety of real-world policy options. For example, increased accessibility resulting from trip chaining behavior and effects on accessibility transference can be easily accounted for in this context; such results can not be achieved with traditional accessibility measurements.

The empirical application of the HAPP model system provides an indication of the potential of activity-based modeling approaches to assess the bounds on achievable improvements in accessibility and travel time based on daily household activity patterns. It also provides an assessment of roles for trip chaining and ride-sharing as potentially effective method to facilitate policy improvements. The core element of HAPP is extremely complex. Standard mathematical programming methods do not take advantage of the characteristics of the problem, thus, solution methods are both cumbersome and impractical. A new solution process is proposed based on dynamic programming methods and modified by developing opportunity costs from the matrix of potential savings in travel and waiting time. The solution process not only simplifies the complex formulation, it also accelerates solution time.

There is room for substantial improvement in the scope of application of the modeling approach. Some strict assumptions made in the analysis, if relaxed, would make the approach more useful in general. In the future, the modeling process should more properly reflect behavioral aspects, uncertainty aspects, and a full GIS-based environment. The first aspect is imperative to fully reflect real activity interaction situations, the second is necessary to accommodate the inherent stochastic nature of activity participation and travel time variation, and the third would supply a better analysis environment. Herein, homogeneous behavior was assumed, however, the behavioral aspects which deal with user's response behavior and habit are probably quite different. Further research on user adaptation and habit would benefit the activity model. The stochastic nature of both activity participation and travel time should be considered. A full GIS environment would facilitate model application, in general, and would enable certain aspects such as destination choice to be more accurately specified.

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Table 1. Demographic Statistics for Selected Household Groups

Household Attribute	Household Size		
	2 Members (N=402)	3 Members (N=197)	4 Members (N=153)
Median Household Income	$40-$45K	$50-$55K	$40-$45K
Mean No. of Vehicles Owned	2.0	2.5	2.3
Mean No. of Licensed Drivers	1.9	2.3	2.2
Mean No. of Employed Persons	1.2	1.8	1.8
Mean Age of Adults in Household	53	42	39
Percent Single Family Dwelling Units	90	91	93
Percent Home Owners	85	89	84

Table 2. Employment Status for Non-Retired Adults in Selected Household Groups

Employment Status	Household Size		
	2 Members (N=402)	3 Members (N=197)	4 Members (N=153)
Percent Employed (Full-or Part Time)	87	86	83
Percent Unemployed	3	4	4
Percent Homemaker or Student	10	10	13

Table 3. Selected Mean Travel and Activity Characteristics

Characteristic	Household Size		
	2 Members	3 Members	4 Members
Number of In- & Out-of-Home Household Activities	13.9 (4.5)*	19.1 (5.4)	27.5 (6.8)
Number of Trips by Household Members	7.9 (3.9)	11.4 (5.0)	16.6 (6.7)
Travel Time per person for Out-of-Home Activities (Min.)	67.7	67.7	67.7
Travel Time per Trip (Min.)	19.1	19.5	18.0
Travel Time per Work or Work-Related Trip (Min.)	20.0	22.0	22.0
Number of Out-of-Home Activities per Trip Chain	1.88	1.86	1.79
Percent of Chains with One Activity	57.6	57.1	60.4
Percent of Chains with Two Activities	17.5	18.5	16.4
Percent of Chains with Three Activities	13.4	13.3	14.8
Percent of Chains with Four or More Activities	11.5	11.1	8.4

* Numbers in parentheses indicate standard deviation.

Table 4. Mean Number of Activities/Trips per Person by Trip Purpose

Activity/Trip Purpose	Household Size					
	2 Members		3 Members		4 Members	
	Activities	Trips	Activities	Trips	Activities	Trips
Out-of-Home Activities						
Work or Work-Related	0.7	0.6	0.7	0.6	0.5	0.4
Shopping	0.7	0.7	0.4	0.4	0.5	0.5
Maintenance	0.7	0.6	0.6	0.5	0.6	0.5
Discretionary	0.5	0.5	0.5	0.5	0.7	0.6
School	0.0	0.0	0.2	0.2	0.3	0.3
Travel-Related	0.1	0.1	0.3	0.3	0.4	0.4
Total Out-of-Home	2.8	2.5	2.7	2.4	2.9	2.6
In-Home Activities/Trips	4.2	1.5*	3.7	1.4*	4.0	1.5*
Total Activities/Trips	7.0	4.0	6.4	3.8	6.9	4.1

* Indicates Return-Home Trips for a specific In-Home Activity.

Table 5. Mean Adjustment Ratio for Travel Times

Network Travel Time (minutes)	Household Size								
	2 Members			3 Members			4 Members		
	ρ*	σ	N**	ρ*	σ	N**	ρ*	σ	N**
0- 5	2.88	2.63	766	2.75	2.33	418	2.58	2.62	721
6-10	1.72	1.12	806	1.54	0.88	545	1.71	0.96	600
11-15	1.37	0.71	534	1.44	0.73	316	1.23	0.64	378
16-20	1.29	0.80	264	1.24	0.72	210	1.07	0.47	196
21-25	1.10	0.57	182	1.12	0.60	118	1.04	0.46	124
26-30	0.97	0.44	92	1.19	0.51	63	1.03	0.46	66
31-40	0.91	0.47	70	0.88	0.46	64	0.96	0.35	35
41-50	0.62	0.41	17	0.89	0.30	17	0.97	0.46	16
51-60	0.36	0.30	9	0.87	0.29	5	1.38	0.01	2

* ρ = Mean Adjustment Ratio = (reported travel time)/(network travel time)
** Number of trips excludes non-automotive and those traveling out of the study area

Table 6. Definition of Variables Used in Regression Analyses

VARIABLE	DESCRIPTION
HHSIZE	Number of persons in household
INCOME	Annual household income
AGE<12	Number of children under 12 years of age
FLEXTIME	Presence of flexible work schedule
MULTIJOB	Holds more than one job
FTSTUD	Number of full-time students
LATE	Activities performed from 12am to 6am
DRVRS	Number of members with drivers license
VEHS	Number of household vehicles
ACTS	Total number of household activities
TRIPS	Total number of household trips
RIDESHARE	Ride-sharing present in activity diary
TPDIFF	Difference in trips per chain for optimal and observed patterns

Table 7. OLS Results: Relative Accessibility Improvement

Variables	2-member Households	3-member Households	4-member Households	All Households
FLEX TIME	27.91			
NO-DRV	-23.90	-15.98*		-13.48**
NO-VEH	8.83*		16.51**	6.90**
NO-TRIP			2.50**	
RIDE-SHARING			42.13**	
TP-DIF	16.11**	9.45*	12.46*	13.33**
(Constant)	57.29*	64.74**	-23.20	47.03**
Multiple R	0.30	0.24 0.39	0.24	
R Sqr.	0.09	0.06 0.15	0.06	
Adjusted R Sqr.	0.08	0.05 0.12	0.06	
F	9.62 **	5.75 **	5.06 **	15.51 **
N	402	193 153	748	

* α=10%
** α= 5%

Table 8. OLS Results: Absolute Accessibility Improvement

Variables	2-member Households	3-member Households	4-member Households	All Households
AGE<12		-971.50**		
LATE		1029.87*		
MULTI-JOB	-295.01**			-342.51**
FULL-STU			-442.72*	
NO-DRV	929.57**			
NO-VEH			709.40**	
NO-ACT			65.31*	
TP-DIF	769.86**	626.92*	745.89*	722.94**
(Constant)	-139.14*	1791.24**	-693.51	1880.77**
Multiple R	0.49	0.33 0.39	0.38	
R Sqr.	0.24	0.11 0.15	0.15	
Adjusted R Sqr.	0.24	0.09 0.13	0.15	
F	43.01**	7.59 **	5.06 **	64.17 **
N	402	193 153	748	

* α=10%
** α= 5%

Table 9. OLS Results: Relative Travel Time Improvement

Variables	2-member Households	3-member Households	4-member Households	All Households
HH-SIZE				4.32**
INCOME		-0.90*		-0.49**
LATE		-9.52**		
MULTI-JOB	-3.44**			
NO-ACT			-0.46	
RIDE-SHARING	16.77**	20.60**	6.99	16.58**
TP-DIF	2.37**	2.97**	2.50	2.97**
(Constant)	25.00**	34.99**	46.59**	18.90**
Multiple R	0.43	0.53	0.19	0.42
R Sqr.	0.18	0.28	0.04	0.18
Adjusted R Sqr.	0.18	0.26	0.02	0.17
F	29.62 **	18.19 **	1.81	39.50**
N	402	193	153	748

* α=10%
** α= 5%

Table 10. OLS Results: Absolute Travel Time Improvement

Variables	2-member Households	3-member Households	4-member Households	All Households
HH-SIZE				12.50**
FLEX-TIME		13.97*		
INCOME				9.42**
LATE	12.34*			
NO-VEH	3.69		15.97**	4.39**
RIDE-SHARING	35.14**	53.03**	27.42**	39.90*
TP-DIF	5.66**	9.38**		6.37**
(Constant)	14.34**	22.08**	22.61*	-13.39*
Multiple R	0.43	0.46	0.29	0.45
R Sqr.	0.19	0.21	0.08	0.20
Adjusted R Sqr.	0.18	0.20	0.07	0.19
F	22.77 **	16.85 **	6.60**	36.82**
N	402	193	153	748

* α=10%
** α= 5%

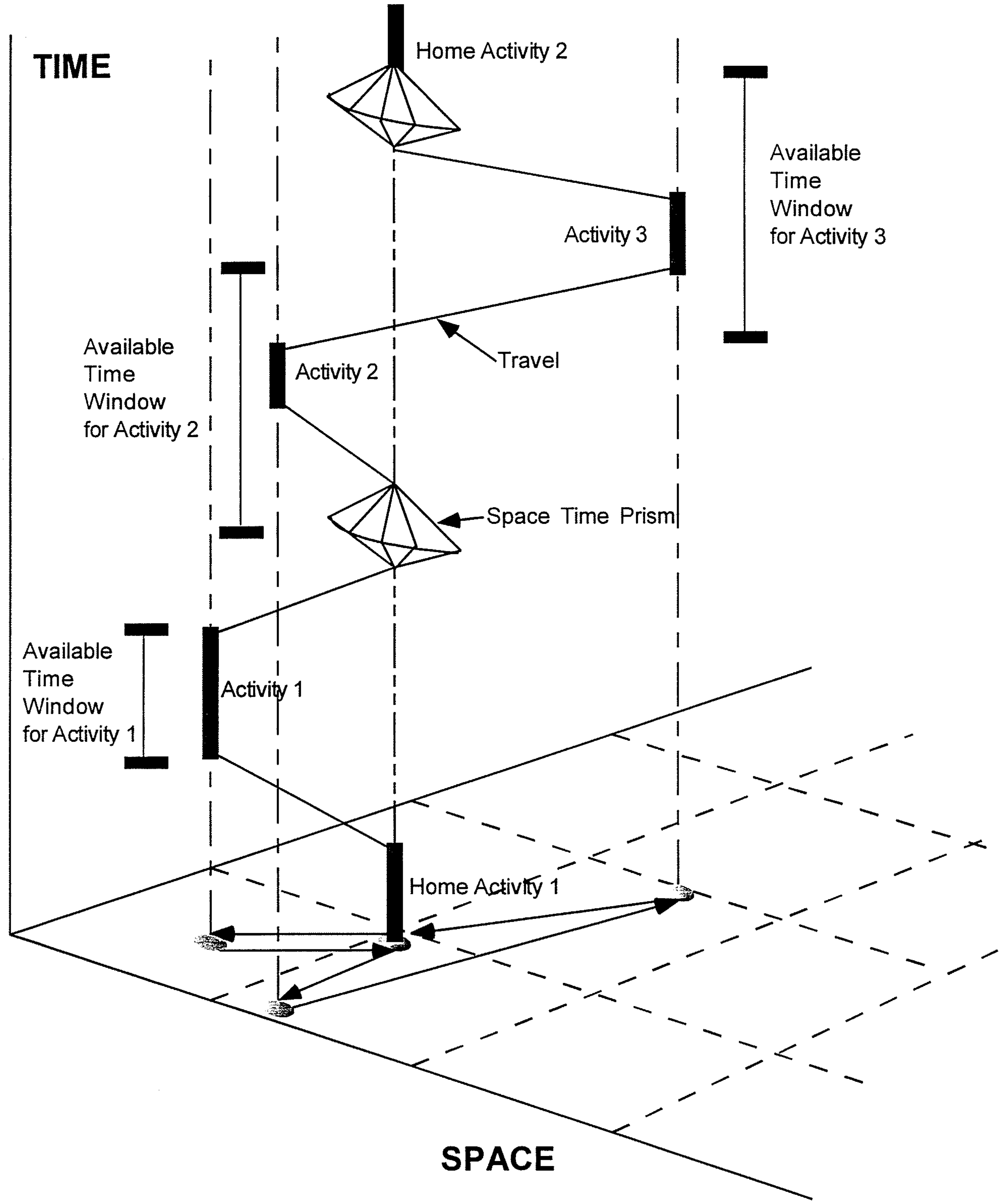

Figure 1. Example of Individual's Activity Pattern and Accessibility Prisms

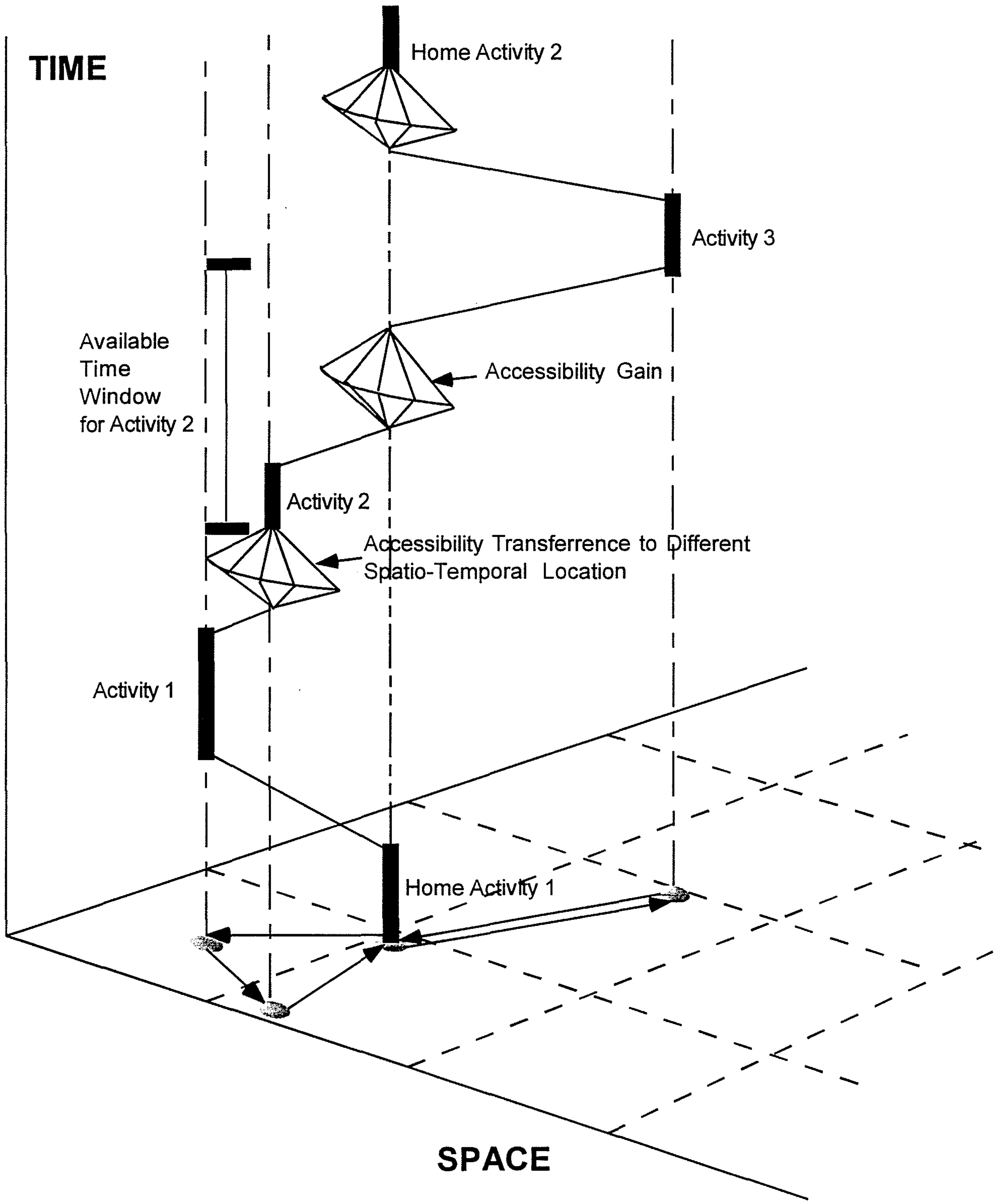

Figure 2. Example of Accessibility Gains and Transference with Efficient Travel Behavior

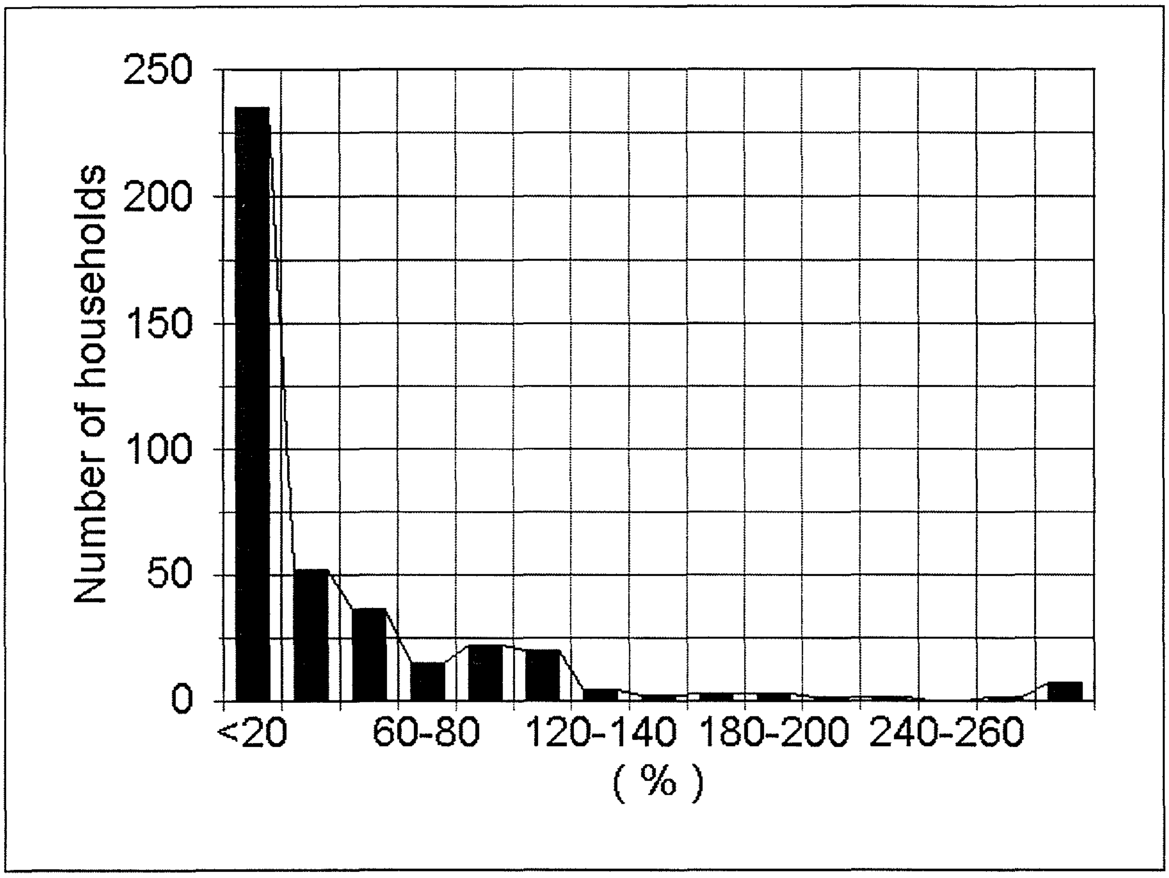

Figure 3. Distribution of Relative Accessibility Improvement (2-member Household)

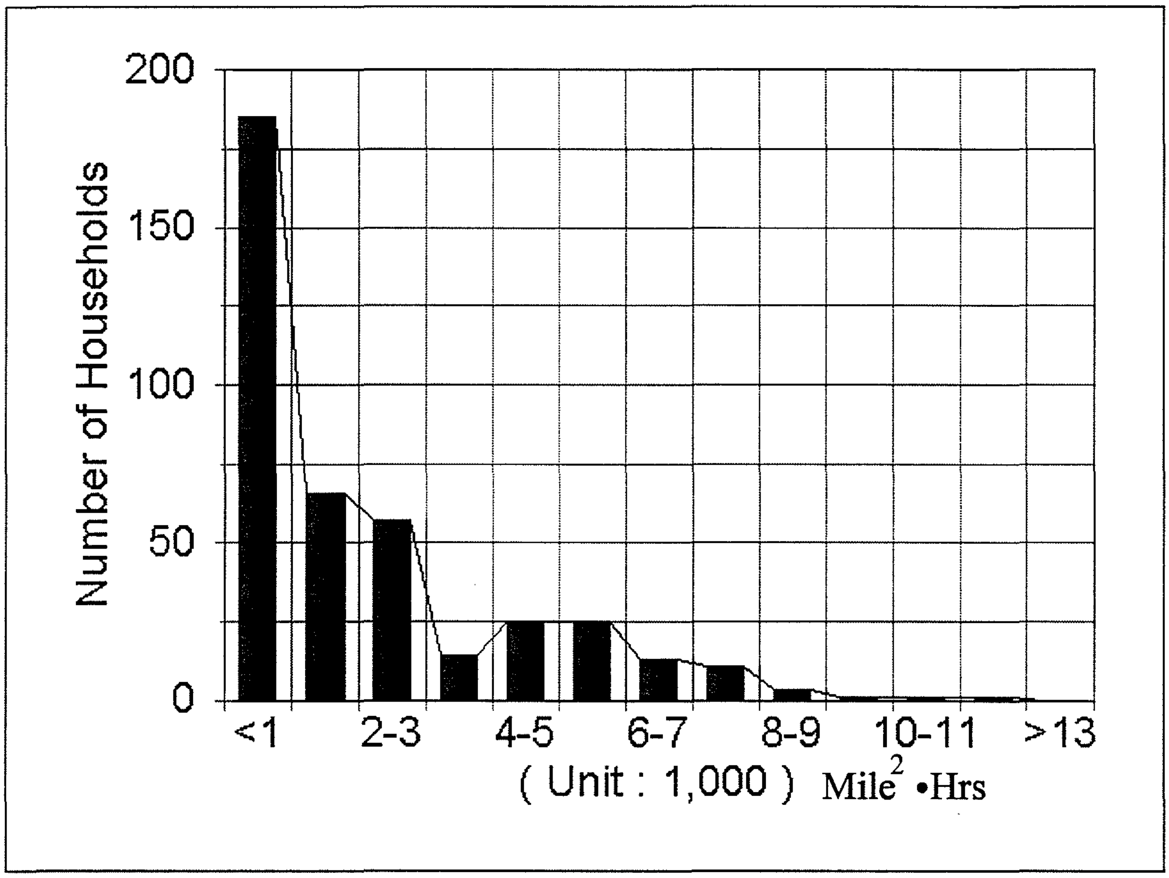

Figure 4. Distribution of Absolute Accessibility Improvement (2-member Household)

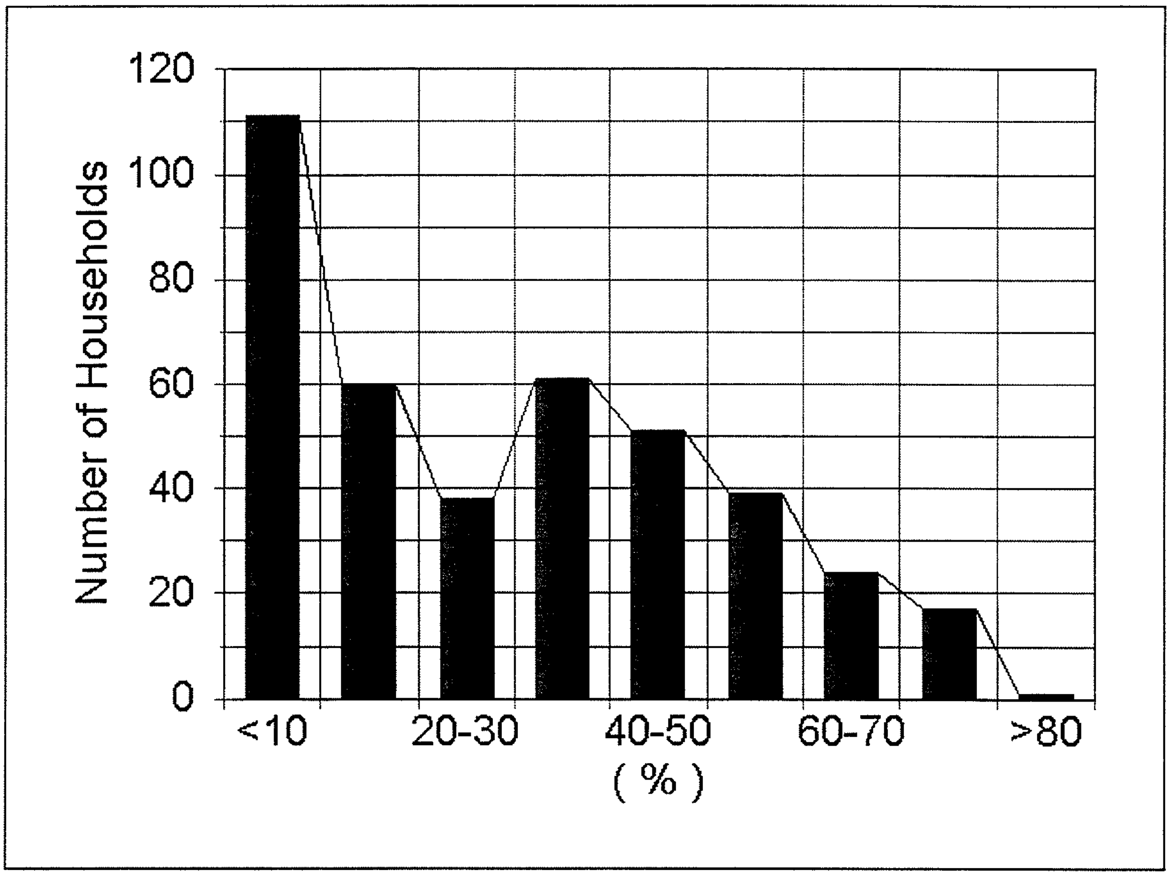

Figure 5. Distribution of Relative Travel Time Improvement (2-member Household)

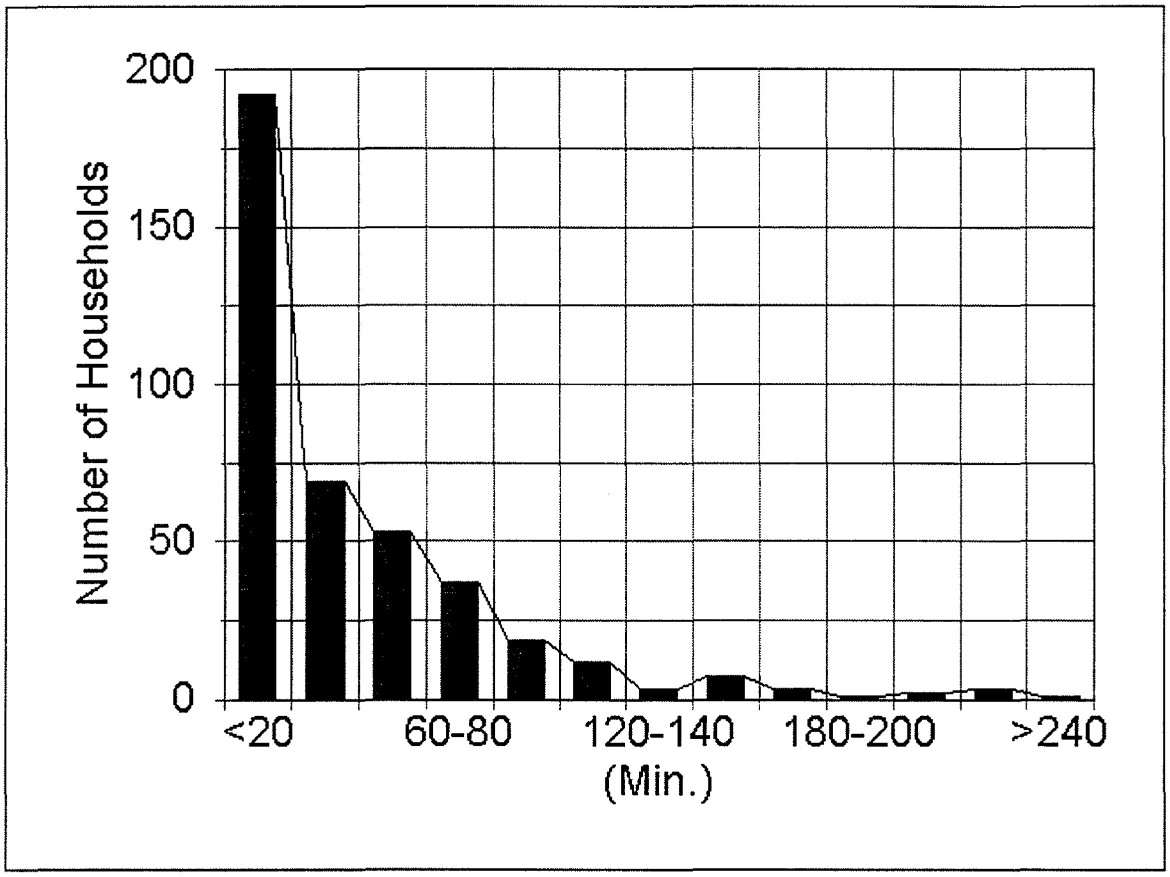

Figure 6. Distribution of Absolute Travel Time Improvement (2-member Household)

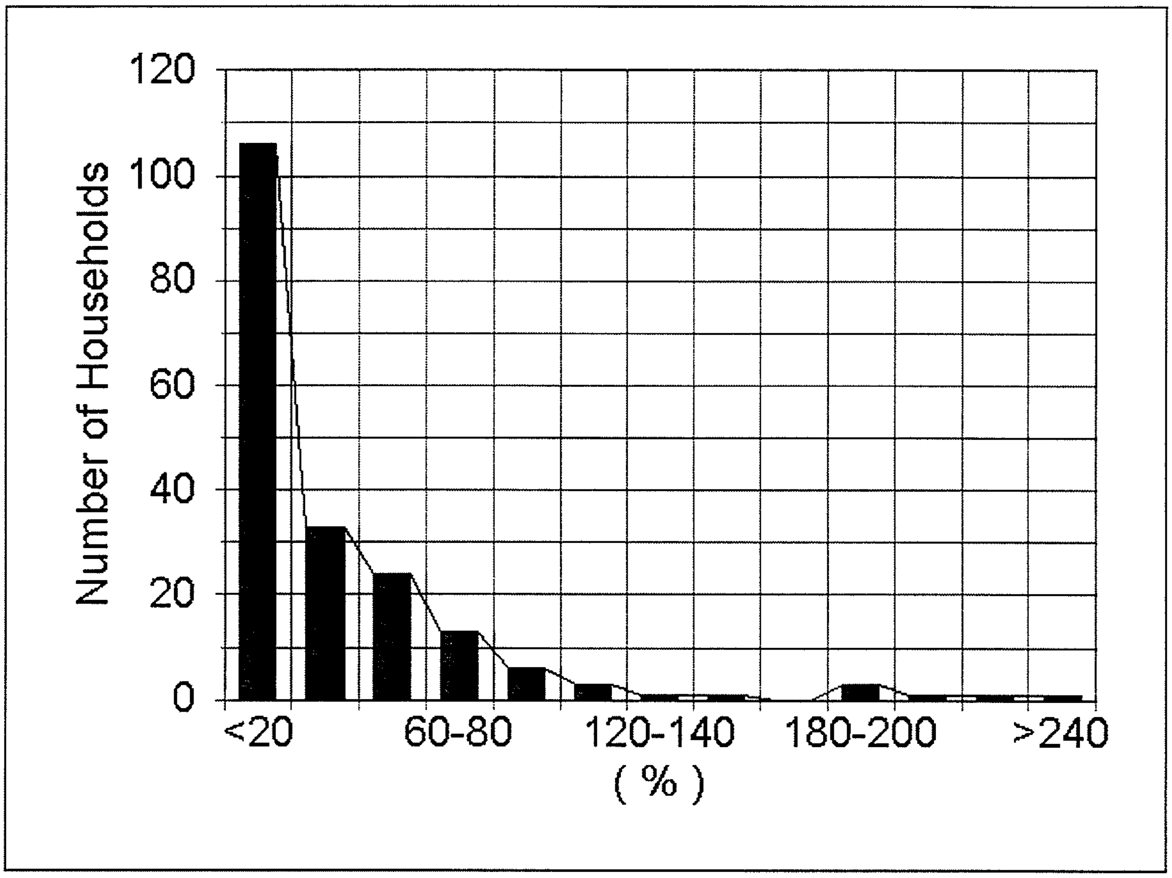

Figure 7. Distribution of Relative Accessibility Improvement (3-member Household)

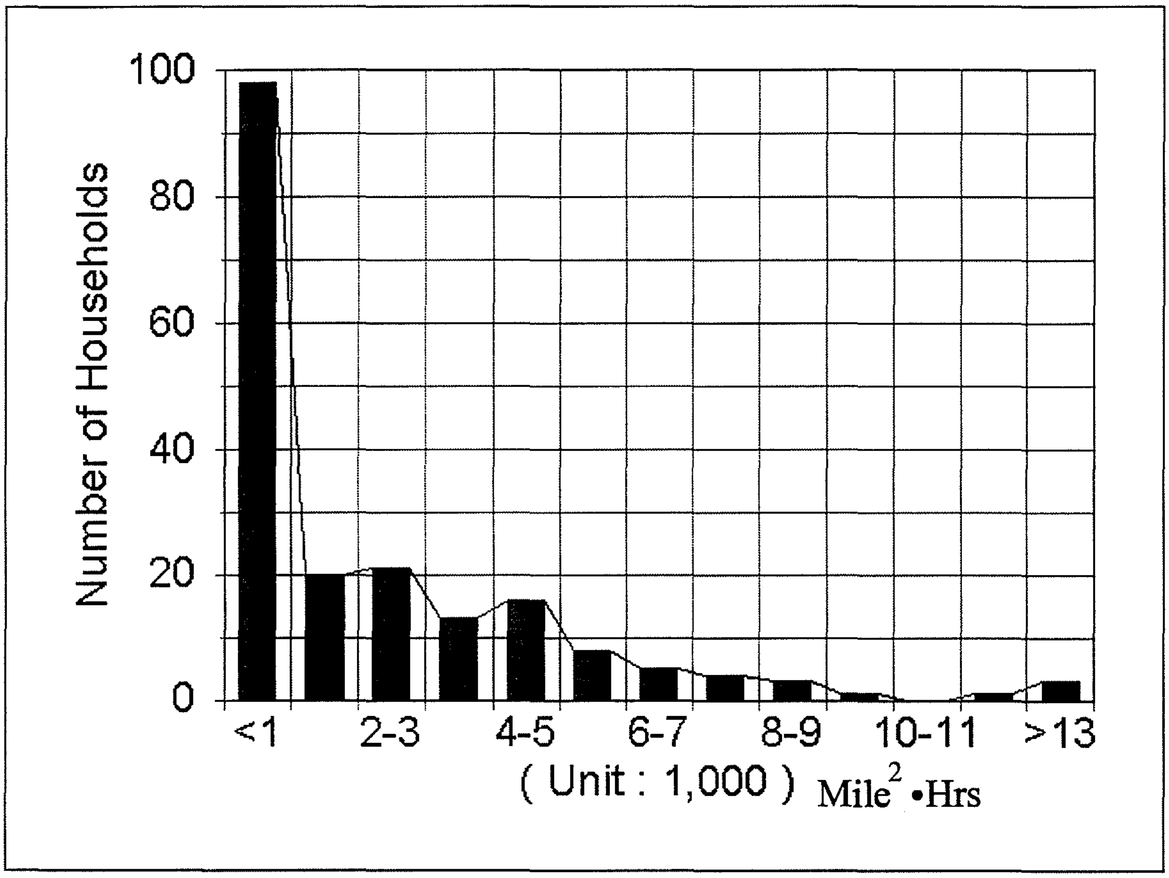

Figure 8. Distribution of Absolute Accessibility Improvement (3-member Household)

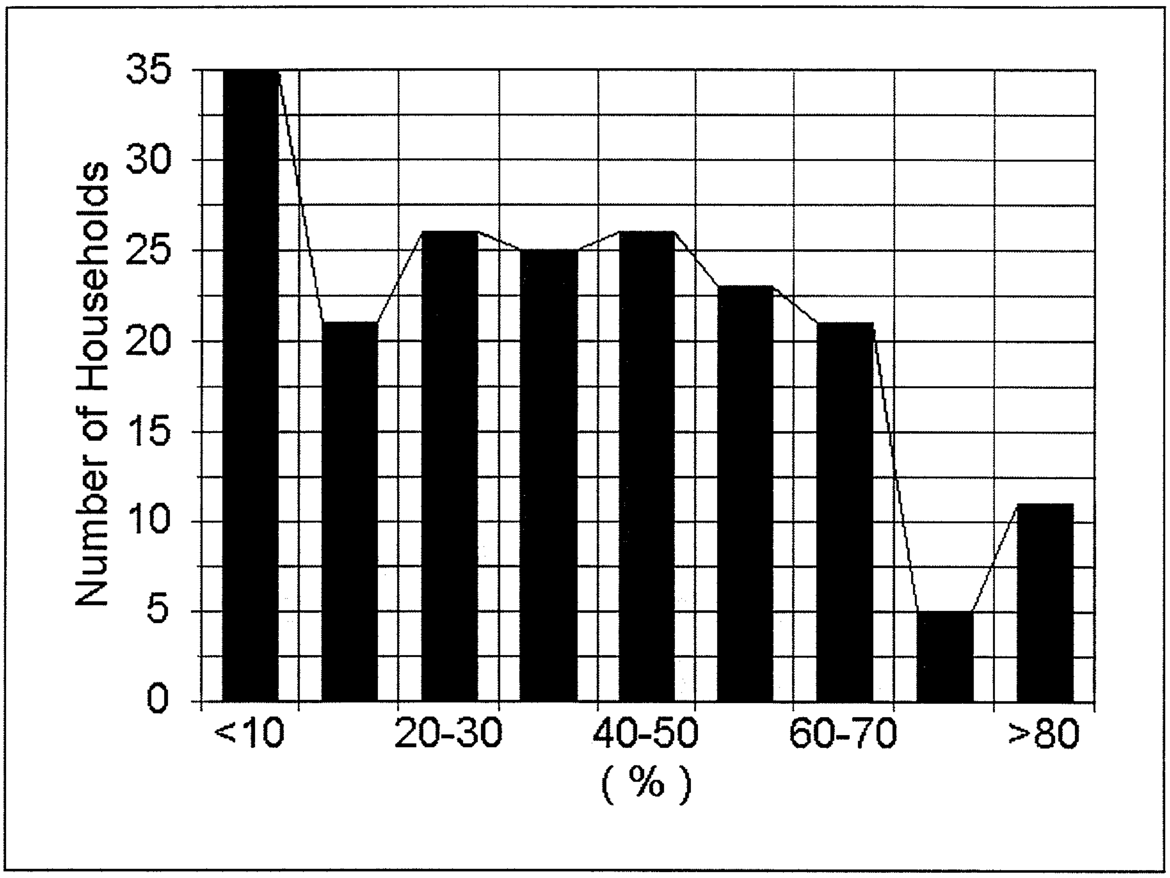

Figure 9. Distribution of Relative Travel Time Improvement (3-member Household)

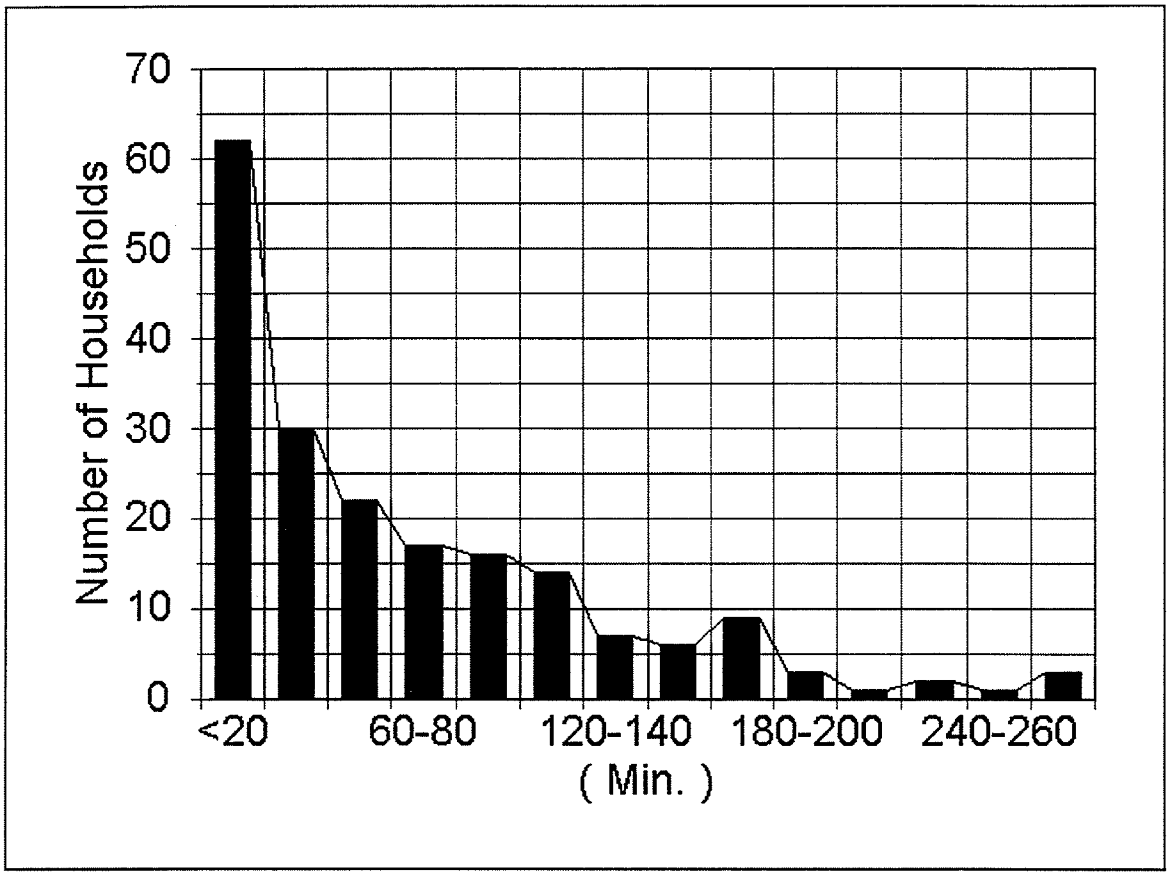

Figure 10. Distribution of Absolute Travel Time Improvement (3-member Household)

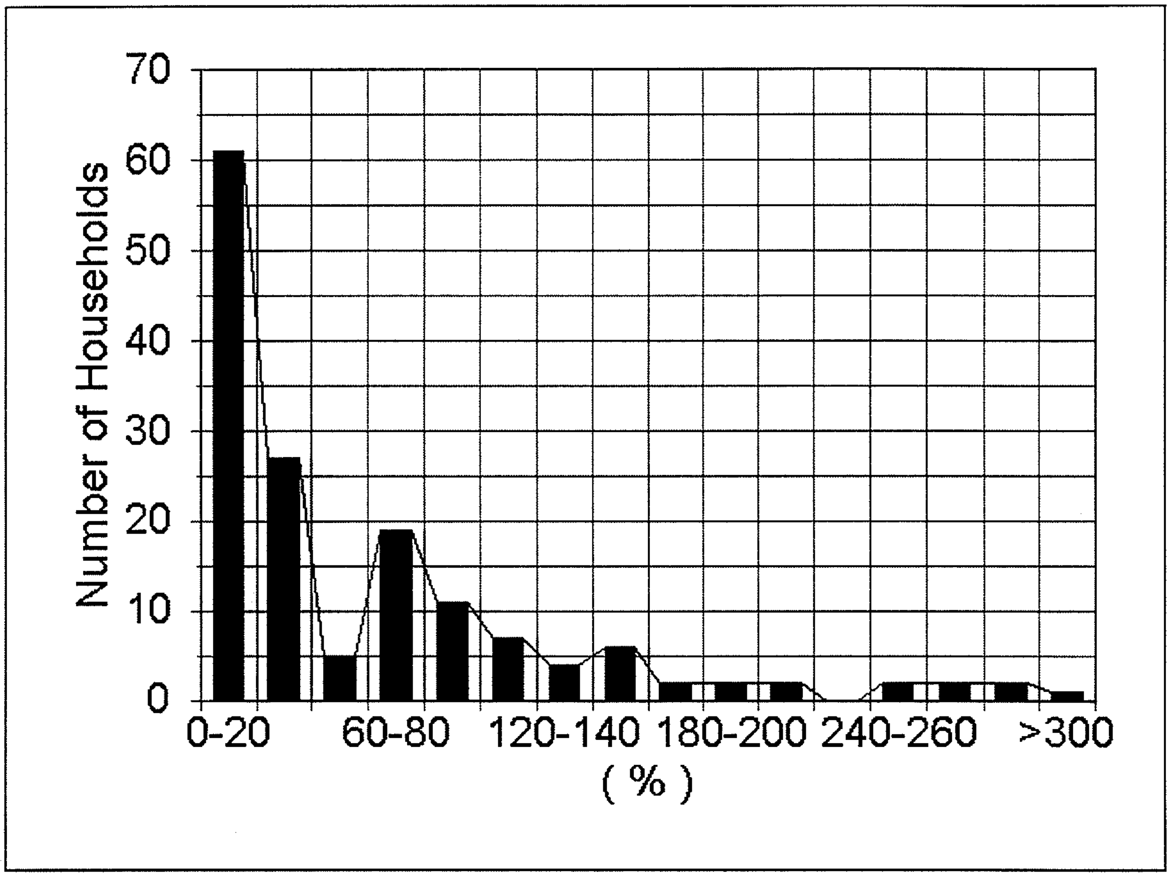

Figure 11. Distribution of Relative Accessibility Improvement (4-member Household)

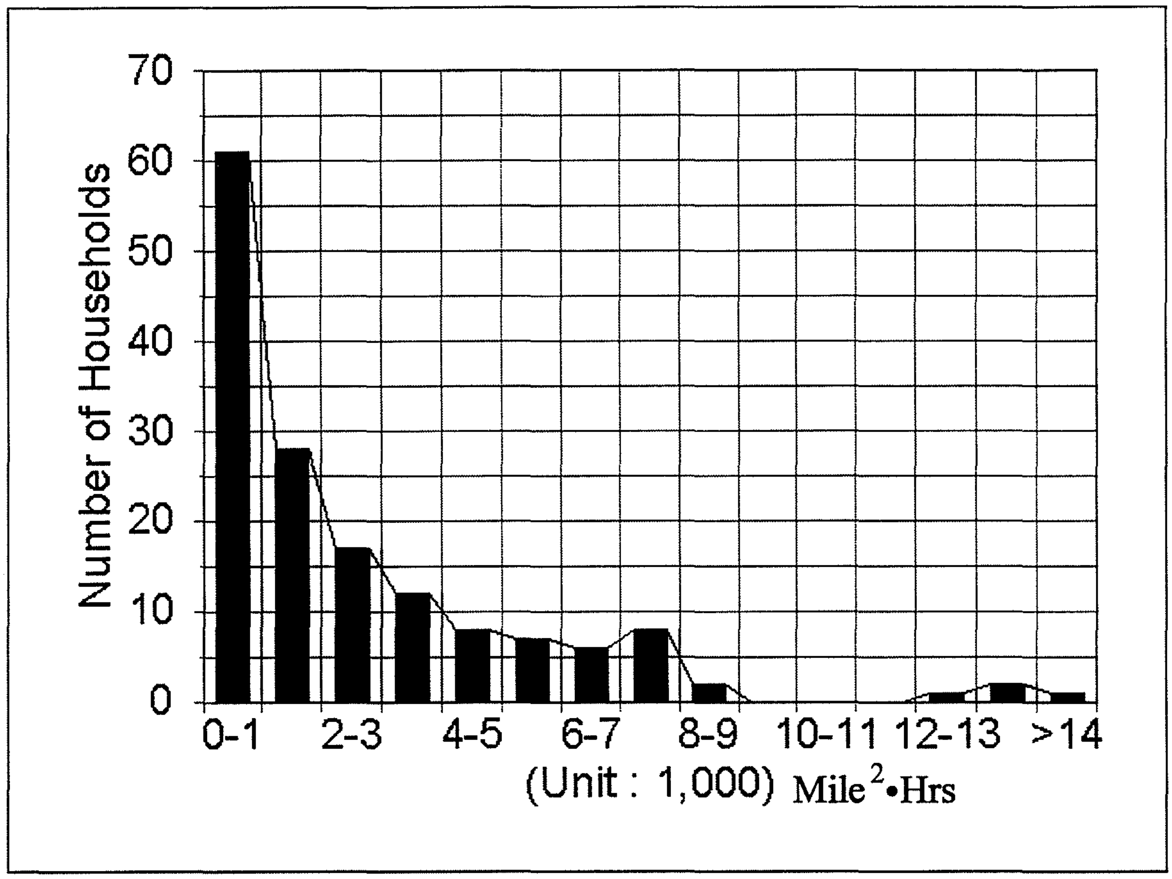

Figure 12. Distribution of Absolute Accessibility Improvement (4-member Household)

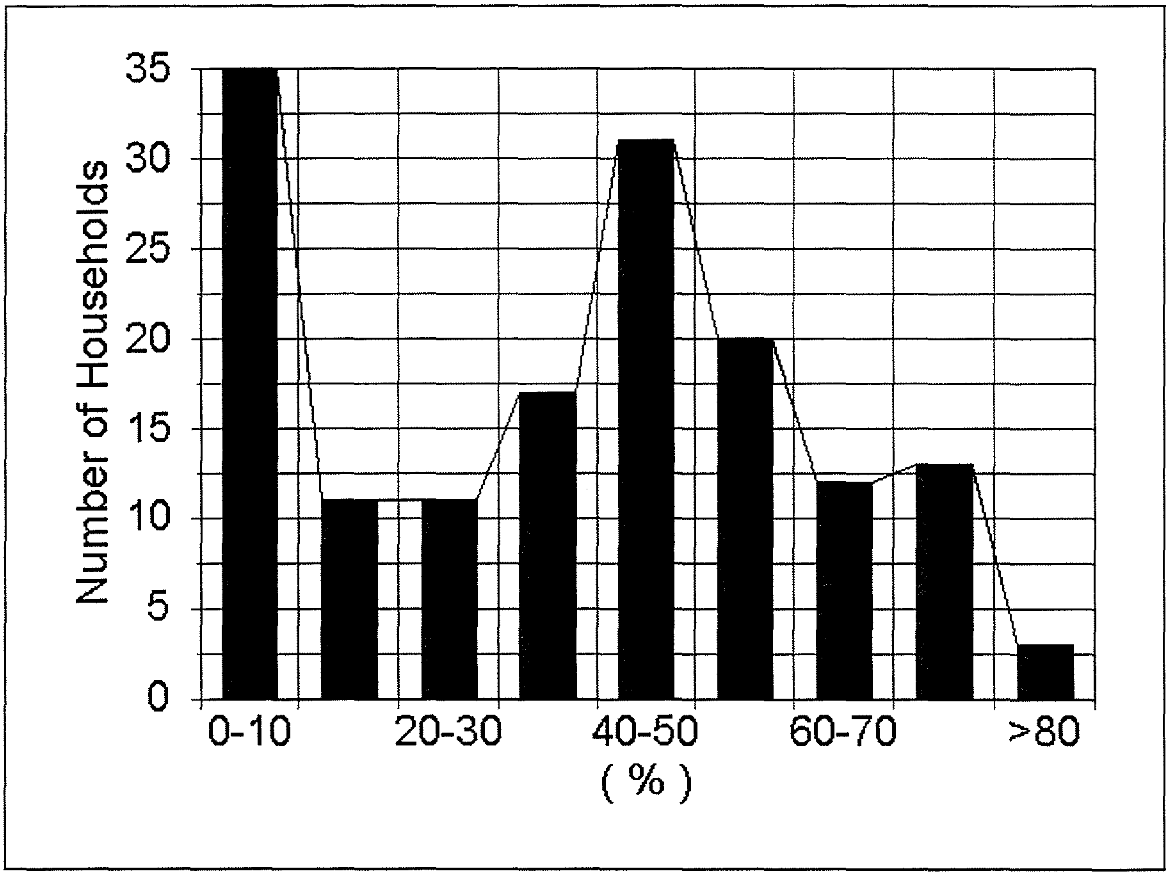

Figure 13. Distribution of Relative Travel Time Improvement (4-member Household)

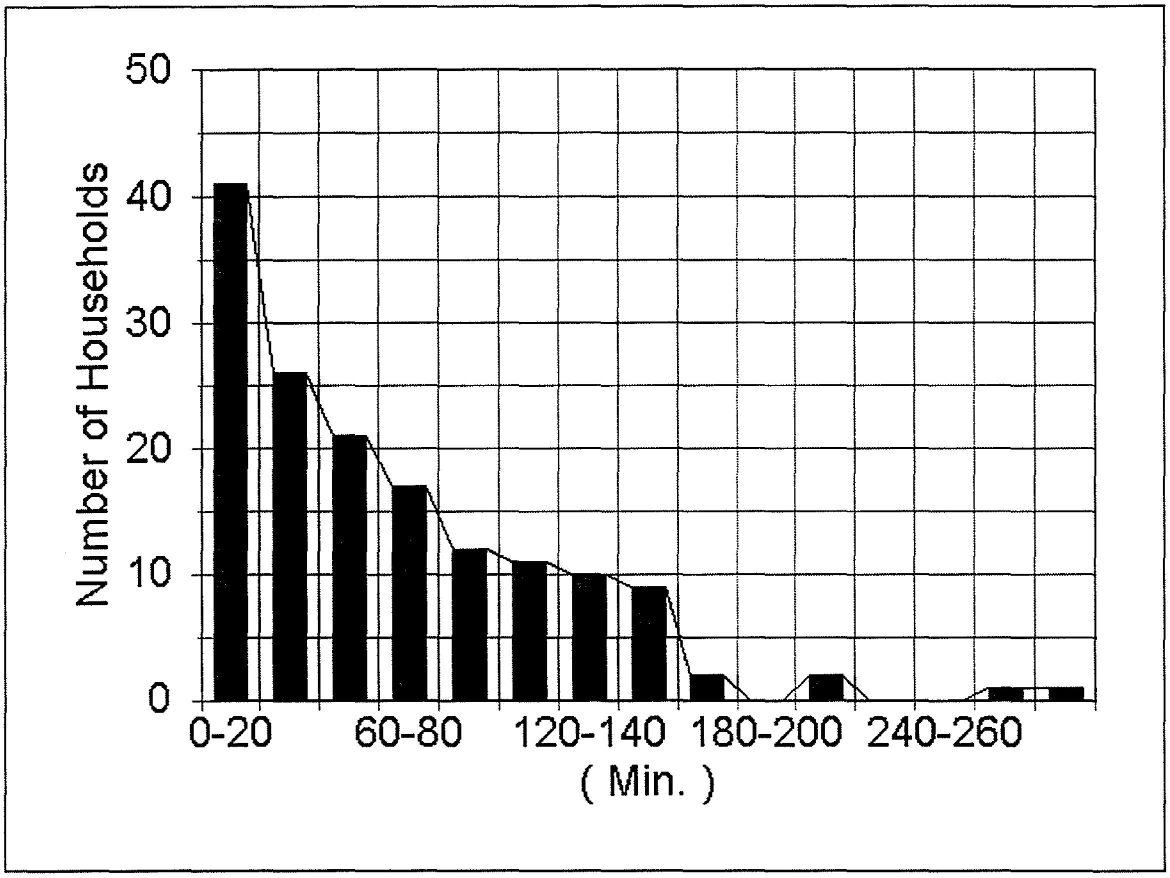

Figure 14. Distribution of Absolute Travel Time Improvement (4-member Household)