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**AN ACTIVITY-BASED APPROACH TO ACCESSIBILITY**

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**submitted in partial satisfaction of the requirements for the degree of**

**DOCTOR OF PHILOSOPHY**

**in Civil Engineering**

**by**

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This dissertation of Chienho Chen is approved  
and is acceptable in quality and form  
for publication on microfilm:

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1996

**DEDICATED TO**

**my parents**

**my wife, Hsinhsin**

**my son, Eric**

**my daughter, Vivian**

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An Activity-Based Approach to Accessibility

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In an effort to compensate for the deficiencies on traditional trip based approach, this dissertation focuses on the supplement in traditional measures of individual accessibility, and the incorporation of temporal transference effects and ride sharing behavior within a household to form a sensitive index. A network-based activity assignment protocol has been developed for complex travel activity decisions within a household. The proposed research incorporates routing, scheduling, and ride-sharing components into a hybrid model that explicitly captures the interactions between household members and integrates ride-sharing, and time window constraints. Under this approach, individual accessibility can be estimated and aggregated to reflect household accessibility. Prior research on such accessibility approaches strongly suggests that the proposed extensions can be employed to estimate the impacts of changes in different policy options. Results of this research will contribute to the state-of-the-art in complex travel behavior and validate a policy-sensitive forecasting model.

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## **CHAPTER 1**

### **MOTIVATION AND RESEARCH OBJECTIVES**

#### **1.1 INTRODUCTION**

The research in this dissertation focuses on the application of an activity-based model structure to help alleviate deficiencies in traditional measures of individual accessibility, and on the incorporation of temporal transference effects of ride-sharing and trip chaining behaviors within a household to form an index sensitive to such effects.

A network-based activity assignment protocol has been developed for complex travel activity decisions within a household. The research incorporates routing, scheduling, 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. Under this approach, individual accessibility can be estimated and aggregated to reflect accessibility within a household under restrictive transportation supply environments. Prior research on such accessibility approaches strongly suggests that the proposed extensions can be applied to estimate the impacts of changes in policies. Results of this research contribute to the state-of-the-art in complex travel behavior and validate the potential of activity-based frameworks in empirical applications.

## 1.2 MOTIVATION FOR THE RESEARCH

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 and between different time periods.

The decision-making behavior of trip-makers has been analyzed intensively, using both aggregate and disaggregate approaches (Ben-Akiva and Lerman, 1985; Wachs, 1989). With the accepted tenet that the demand for transportation is derived from demands for activity participation, research on complex travel behavior properly should commence with an investigation of the underlying behavior of trip-makers, including the initial choice of activities. 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; Recker *et*

*al.*, 1987; Garling *et al.*, 1989; Golob, 1990; Van Wissen, 1989). In this research, accessibility transference is purported to be a fundamental aspect of the travel-activity decision-making process in households explaining, for example, such behavior as ride-sharing and trip chaining. An extension of traditional aggregate accessibility concepts to this disaggregate level (i.e., household) is necessary to properly reflect the temporal and activity-based aspects of accessibility.

An activity-based approach to accessibility is proposed to capture the interactive behavior of individual trip-makers within the household. Specifically, the research attempts to formulate the household travel-activity decision-making process as a network-based routing model incorporating vehicle assignment, ride-sharing behavior, activity assignment and scheduling, and time window constraints. 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.

### **1.3 RESEARCH OBJECTIVES**

The long-term objective of this research is to provide the foundation for an activity-based transportation demand model system as an alternative to the conventional UTPS model system. Activity pattern analysis plays an important role in the development of such a system. Based on this long-term objective, the development of an

operational

activity pattern model as the core element in this general approach is advanced as a short-term objective.

The specific objective of the dissertation research is to develop an activity-based model that accounts for accessibility transference within a household, and to apply this model as a policy-sensitive, transportation planning tool in an investigation of commuting behavior. The dissertation research focuses on three distinct issues:

1. the complexity of travel-activity decision-making associated with accessibility transference and limited resources,
2. the algorithm to solve the proposed complex activity pattern model, and
3. the implications and applications of accessibility transference.

#### **1.4 RESEARCH APPROACH**

The research consists of several stages that build upon previous activity-based research completed by modelers at the University of California, Irvine (McNally and Recker, 1986; Recker, 1995). A comprehensive literature review is presented that provides a critical overview of the analysis of accessibility in transportation, and discusses the potential for the integration of decision-making behavior of household trip-makers within the activity-based paradigm. The development of a microscopic view of accessibility was accomplished as the first and most important research task. Issues of

constrained resources, household behavior, personal roles, and individual preferences are key aspects of this microscopic perspective. A network-based formulation has been developed, integrating routing and scheduling, activity assignment, vehicle assignment, and ride-sharing components into a comprehensive and complex model structure. This model provides the theoretical basis to investigate the dynamics of household accessibility transference.

Solution procedures are a critical element of the complicated routing-related model developed in this research. In particular, the addition of ride-sharing behavior makes the structure of the activity-based model extremely complex. Therefore, direct treatment of general exact methods is both impractical and ineffective. Rather, it is important to develop efficient solution strategies to overcome the increased complexity.

It is purported that aggregation of individual household accessibility as specified in the microscopic approach will result in an assessment of macroscopic accessibility. The aggregation is of particular use in the estimation of the transference of accessibility under a range of relevant policy scenarios. The resulting model is applied to selected case studies, focusing on applications based on data derived from the Southwest Washington area of the United States. The usefulness of this approach in policy analysis is assessed via a dynamic analysis of commuting behavior.

## **1.5 RESEARCH TASKS**

In accordance with the research objectives and approach, several tasks were

accomplished. The principal tasks are described as follows:

1. Review related references and modeling techniques;
2. Explore effective and efficient techniques to reduce the complexity of the proposed model to a reasonable computational and conceptual level;
3. Develop and synthesize methods of measuring individual accessibility;
4. Construct an operational model of travel-activity decision-making that incorporates accessibility transference effects, and
5. Test the proposed accessibility framework in a policy analysis context.

## **1.6 ORGANIZATION OF THE DISSERTATION**

The second chapter of this dissertation presents a review of the relevant literature on measurement of accessibility and different perspectives on activity-based model are also discussed. A conceptual framework is constructed based on the review of literature and the motivation of this research; a refined measurement of accessibility that is originated from time space prism is also created. The third chapter includes the formal formulation of the Household Activity Pattern Problem (HAPP) and some initial tests with the exploitation of ready-to-use commercial mathematical programming packages. By applying a resource relaxation concept, in which the original problem is reduced to a two-stage problem, a Vehicle Routing type Problem with Time Window constraints and a matching-and-permuting process, an effective and efficient solution procedures is

developed and discussed in Chapter 4. Chapter 5 describes the selection of suitable data sets and some summary statistics of the selected data set. The validation and application of the proposed model is illustrated in Chapter 6 by presenting results on measurements of potential travel time and accessibility improvements. Finally, some concluding remarks and directions for future research are presented in Chapter 7.

## CHAPTER 2

### LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

#### 2.1 INTRODUCTION

A review of prior research related to accessibility and activity-based analysis provides an understanding of the drawbacks and restrictions of traditional accessibility measures, and the underlying features of an activity-based approach. The review offers evidence that many of the shortcomings of the former could be overcome by the use of the latter, articulating the conceptual framework by which activity-based approaches can be incorporated into more appropriate accessibility measures.

Although the term "accessibility" is used frequently in spatial economics, a review of prior research reveals only limited literature addressing this well-used concept. Alternatively, activity-based approaches, which are a relatively new development and have a brief history constitute a sizable body of references. To provide better perspective to this body of research, the research on activity-based analysis is reviewed and classified into eight main categories according to their applications or research topics; the general framework is also studied to provide a better understanding of the activity-based approach. Summaries and critiques are made at the end of each section, and are used as a basis to build the conceptual framework of proposed research. In the last section, a refined measure of accessibility that integrates temporal aspect and activity characteristic is proposed.

## **2.2 ACCESSIBILITY MEASUREMENT**

The concept of accessibility is often used to explain the spatial variation. In urban geography, it is an important indicator of the growth of towns, location of facilities and functions and juxtaposition of land uses. Recently, attention has centered on the role of accessibility in trip generation in urban areas, i.e., on the question of the effect on travel demand of changing accessibility associated with a change in the urban transportation system.

Traditional measures of accessibility, such as those conducted during the 1960's, are based on an aggregate foundation. In one sense, accessibility means "capable of being reached", thus implying a measure of the proximity between two points. Alternatively, accessibility is related to the ability of a transportation system to provide a low cost and/or quick means of overcoming the separation between different locations. The traditional concept of accessibility can be operationized only on an average and aggregated basis lacking information on personal behavior. In the following sections, the development of accessibility measurements is examined and a discussion of existing measurement is presented.

### **2.2.1 Development of Accessibility Measurements**

Accessibility has played the major explanatory role in spatial economics of the city. The term "accessibility" also is frequently used in urban geography in explanations

of the spatial variation of phenomena. From previous summaries of policy trends in transportation planning (Jones, 1983), provision of accessibility is still considered as an important policy goal; how to effectively apply accessibility measures in transportation planning, and its use as an index to evaluate the impact of policy implementation is important.

Traditional accessibility can be defined as an interaction of location of activity with the provision of transport services. Wachs and Koenig (1979) defined accessibility as a measure of the "supply" of opportunities available to a household or an aggregation

$$A_i = \sum_{j=1}^n O_j \bullet F( c_{ij} )$$

of households. A general form of accessibility is defined by the equation below:

where  $A_i$  = accessibility from zone i to the considered type of opportunities;

$O_j$  = number of opportunities of the considered type in zone j (such as employment place, shops, etc.);

$c_{ij}$  = generalized cost from i to j, and

$F(c)$  = impedance function.

Conceptually, accessibility is defined, under a distinction drawn by Ingram (1971), as relative accessibility and integral accessibility, as follows:

$$A_i = \sum_{j=1}^n a_{ij}$$

where  $A_i$  = integral accessibility at the  $i_{th}$  point;

$a_{ij}$  = relative accessibility of point  $j$  at  $i$ , and

$n$  = total number of points.

Relative accessibility has been defined as the degree to which two places on the same surface are connected, while integral accessibility as the degree of interconnection for a given point with all other points on the same surface. The most popular operational

$$A_{ik} = \frac{\sum_{j=1}^n w_{jk} \bullet e^{-\beta c_{ij}}}{\sum_{j=1}^n w_{jk}}$$

form of accessibility is based on the Hansen-type (Hansen, 1959) definition:

Where  $A_{ik}$  = the accessibility of zone  $i$  to opportunities of type  $k$  in all zones;

$w_{jk}$  = A measure of attractiveness of zone  $j$  to activities of type  $k$ ;

$c_{ij}$  = the generalized cost of travel from  $i$  to  $j$ , and

$\beta$  = a scale coefficient.

Ingram, and Dalvi and Martin provided a systematic review of different indices (Ingram, 1971; Dalvi and Martin, 1976; Dalvi, 1979), comparing and contrasting accessibility measures based on different types of distance metrics and functional forms.

In some derivations, accessibility has been related to utility maximization and entropy theory (Williams and Senior, 1978). In addition, some researchers (Dunphy, 1973; Sherman, Barber, and Kondo, 1974) used isochron analysis to define and analyze accessibility. For example, the fraction of regional employment within x minutes by car might be used as a measure of highway accessibility. However, all of this research on accessibility is restricted to spatial interaction only.

### **2.2.2 Critiques and Suggestions of Traditional Accessibility Measures**

From the previous research mentioned, it is concluded that the traditional measures of accessibility are characterized by several shortcomings:

1. They employ home-based measurements.
2. The distance used is based on average or zonal measures.
3. There is no individual behavior aspect in the measurement.
4. There is no recognition that trips may be a part of a tour that is a combination of several trips.

Some of these limitations have been addressed by research that has expanded the previous studies by considering temporal and microscopic aspects. Burns proposed a temporal component of accessibility (Burns, 1979), 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. Furthermore, Ben-Akiva (1979) defined accessibility as the expected maximum utility obtained from a hierarchical

discrete choice model. For any single decision the individual will select the alternative

$$\text{Max}_{i \in C_t} U_{it}$$

which maximizes his/her utility; thus a simple form of accessibility is :

where  $U_{it}$  = the utility of individual  $t$  with alternative  $i$ , and

$C_t$  = the alternative set of individual  $t$ .

The expected value of this maximum utility is defined as the value of the accessibility. The addition of these components make the measure of accessibility both more complicated and more sensitive. Furthermore, the traditional macroscopic form of the measure can be divided into a microscopic form, with the temporal dimension making the measure of accessibility more realistic.

Despite these advances, a new definition of accessibility is necessary to accommodate policy dimensions that result in redistribution of "accessibility" among individuals in the same household and between time periods for the same individual. It should be related not only to transportation system and land use but also to individual demographic characteristics and to household transportation supply environment. The measure should be both general and operational and also should reflect individual differences.

### **2.3 ACTIVITY-BASED ANALYSIS**

Activity-based analysis had only a brief history of development, being initiated in the early 1970's. The activity-based approach is actually a composite of complicated problems. "[It] is, at the simplest, a discrete choice-continuous allocation problem with correlated multiple alternatives, combined with the traveling salesman problem, problem of collective decision-making and household coupling constraints, which is in part a logistic problem." (Kitamura, 1988). In its broader concept in development and research, it incorporates such numerous analytical topics as demand analysis, activity scheduling, household life cycle, structure analysis and *et cetera*. The general Household Activity Pattern Problem (HAPP) is a combination of several activity-based analyses and plays an important role in determining personal travel/activity behavior within a household texture. It is purported that HAPP could be treated as a core element during the planning process, and can be incorporated with other components to develop a sensitive planning tool.

### **2.3.1 Classification of General Frameworks**

In response to the deficiency of and dissatisfaction with traditional trip-based analysis, researchers tried to develop new studies based on how people participate in activities, how people choose schedules and destinations, and how people integrate these aspects to form a pattern of social/geographical interaction. This basic thought behind these research studies has been developed by exploring new research based on a totally

different framework in which single trip-based analysis is replaced by contextual analysis of trip linkages.

Although the history of activity-based analysis is brief, a profusion of research studies has been conducted. The topics studied span a breadth of behavior analysis and traditional transportation planning. Most of the works can be classified as based on two general frameworks: 1) time-space geography, and 2) TSU (Transport Studies Unit) framework.

#### 1. Time-space geography framework

This approach was originated by Hagerstrand (1970,1973) who presented a general model of human interaction (in a geographical dimension). It has been applied as a basis for deductive accessibility measurement and as one of the foundations for inductive diary analysis. As described by its category, time-space geography is the foundation of this research. Typically, the spatial aspect is expressed as a two-dimension plane, while the temporal aspect is depicted by the vertical axis. With these three-dimension display, so-called time-space prisms can be created to constrain possible paths. It is also commonly referred to as "constraint-based approach" for its focus on the constraint on spatial and temporal aspects.

Extension and application of this approach are studied by Cullen (1972). Stephens (1975) applied a simulation model by constructing a subjective active flexibility measure, which ranged from "unexpected and unplanned" to "prearranged and routine", and combined this measure with objective environmental constraints and various

hypotheses concerning individual's time-space behavior. Lenntorp (1976) extended Hagerstrand's approach by developing a model that calculated the total number of time-space paths that an individual could follow, given a specific activity program. The development of PESASP (Program Evaluating the Set of Alternative Sample Paths) is especially noteworthy. It represented the first attempt to operationize Hagerstrand's framework to meaningful policy evaluation. In a methodological research of accessibility, Burns (1979) 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 environment and temporal and spatial components. 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.

## 2. TSU (Transport Studies Unit) framework

This approach, presented by Jones *et al.*(1983), provided a broader context for modeling travel patterns by moving away from a rigorous temporal-spatial framework toward one that attempted to categorize activity participation over time. This approach is built on a broad concept of household integration, and considers the interaction of different individuals' activity requirements within a household as additional influences on the activity choice set and constraints. Based on this approach, some developments were presented. They included a gaming approach to activity analysis, and activity scheduling

models, such as CARLA (Combinatorial Algorithm for Rescheduling Lists of Activities) (Clarke, 1980), which predicted likely responses in activity patterns to external changes.

### **2.3.2 Activity-Based Travel Behavior Analysis**

Activity-based thought in travel behavior analysis flourished during the 1980's. A sizable body of research was conducted on topics of great breadth. In this discussion, we extract some of the typical topics and applications, and discuss both the advantages and shortcomings.

Some recent developments and application in activity-based approach are listed in Table 1 and described as follows:

1. Demand analysis

Reviewing the evolution of travel demand modeling effort over the past few decades, we observe increasing recognition of the needs for detailed information, portending the growing interest in modeling complex travel behavior as a way to improve the shortcomings and incompleteness of conventional approaches. The activity-based approach was advanced as an option for overcoming the previous trip-based models that might lead to mis-specification and biased assessment. The motivation for the development of activity-based analysis was derived largely from dissatisfaction with

established procedures. In some instances the predictions of trip-based models have proved to be inaccurate or inappropriate in representing travel behavior relationships. An activity-based analysis approaches these problems through a deeper understanding of travel behavior. This has provided a better explanation and representation of travel behavior, and resulted in a more complex treatment of travel.

Since the 1980's, a significant body of research focused on travel/activity behavior studies has emerged to accommodate a variety of features, including (Pas, 1985):

- a. Explicit treatment of travel as a derived demand.
- b. Focus on sequences or patterns of behavior rather than an analysis of discrete trips.
- c. Emphasis on decision-making in a household context, taking into account linkages and interactions among household members.
- d. Emphasis on the detailed timing as well as the duration of activity and travel, rather than just using the simple categorization of "peak" and "off-peak" events.
- e. Explicit consideration of spatial, temporal, and interpersonal constraints on travel choice and resource allocation.
- f. Recognition of the interdependencies among events that occur at different times, involve different people, and occur in different places.
- g. Use of household and person classification scheme.

Within the last ten years, dynamic analysis has received considerable attention, and Wrigley terms it "the era of longitudinal data analysis" (Wrigley, 1986). Use of longitudinal data nudges travel demand modeling toward a more comprehensive

understanding of travel behavior, not just in daily diary but also day-to-day variability.

From aggregate to disaggregate, static to dynamic, trip-based to activity-based, and prediction to explanation, travel demand modeling plays an important role in supporting transportation planning. Due to the lack of appropriate specification, and the need for more comprehensive understanding of user behavior, activity-based and dynamic analyses have entered the mainstream of this field. The emergence of these ideas is definitely not new. However, as described by Kitamura the development is fragmented, and how to and what to do in order to build a rigid foundation for an operational framework emerge as reasonably urgent tasks.

## 2. Household life-cycle and household structure

The Oxford group insists that household life-cycle predominantly determines what members of a household do (Clarke, Dix, and Goodwin, 1982). Extensive analysis has also been made on the association between activity travel pattern and household life-cycle.

of decision making has also led to a review of the effectiveness of household and person attributes that are believed to be the predictor variable of activity travel behavior. It is noted that McDonald and Stopher (1983) also presented a computer-oriented model system to study the predictive effectiveness of household structure variables, although the result is controversial.

## 3. Activity participation and scheduling

The topic of activity participation comprises largely descriptive analyses. The time-geographic paradigm of Hagerstrand (1970) continues to be the backbone of this area. Recent works include conceptual analysis of activity substitution (Salomon, 1985), and additional empirical analyses of time use (Palm, 1981; Allaman, 1982).

**Table 1 Recent Developments and Applications of Activity-Based Approaches**

Topics in Activity Analysis	Analytical Method	Research Subject	Research Publication
Household Life-cycle and Household Structure	Experimental method  Computer-oriented model system	Gender and work status  The predictive effectiveness of household structure variables	Oxford group Clarke, Dix, and Goodwin, 1982 Jones <i>et al.</i> , 1983 Kitamura, 1986 McDonald and Stopher, 1983
Activity Participation and Scheduling Analysis	Time geographic paradigm  Classificatory analysis	Conceptual analysis of activity substitution. Time use	Salomon, 1985  Palm, 1981 Allaman, 1982
Activity Pattern Analysis	Classificatory analysis  Sequencing	Daily pattern	Recker, McNally and Root, 1985, 1986b, 1986c Kitamura and Kermanshah, 1983, 1984

	<p>scheme</p> <p>Structural equation and multivariate analysis</p> <p>Computer-oriented model system</p> <p>Classificatory method</p>	<p>multiday pattern</p>	<p>Golob, 1985, 1986</p> <p>Golob and Meurs, 1987</p> <p>HATS, Jones <i>et al.</i>, 1983</p> <p>Koppleman and Pas, 1985</p> <p>Pas and Koppleman, 1985, 1986</p> <p>Hanson and Huff, 1985</p> <p>Huff and Hanson, 1986</p> <p>Jones and Clarke, 1987</p>
Trip Chaining Analysis	<p>Markovian analysis</p> <p>Simulation analysis</p> <p>Mathematic formulation</p> <p>Discrete choice model</p> <p>Utility maximization</p>	<p>Trip chaining behavior</p> <p>Shopping-based trip chaining behavior</p>	<p>O'Kelly, 1981</p> <p>Kitamura, 1983</p> <p>Southworth, 1985a, 1985b</p> <p>Mazurkiewicz, 1985</p> <p>Barnard, 1986</p> <p>Horowitz, 1982</p> <p>Narula <i>et al.</i>, 1983</p> <p>Kitamura, 1985</p> <p>Thill, 1985</p> <p>Kondo and Kitamura, 1987</p>
Interaction among Individuals	<p>Utility maximization process</p>	<p>Task allocation</p>	<p>Koppleman and Townsend, 1987</p> <p>Townsend, 1987</p>
Adaptation and Dynamic Aspects	<p>Panel surveys and experiments</p> <p>Experimental method (simulated real time environment)</p>	<p>Response lags, initial, learning, cohort effects</p> <p>Departure time decision and, learning and habit formation</p>	<p>Goodwin, 1977, 1986</p> <p>Clarke, Dix, and Goodwin, 1982</p> <p>Kitamura and van der Hoorn, 1987</p> <p>Kostyniuk and Kitamura, 1987</p> <p>Mahmassani, Chang and Herman, 1986</p> <p>Mahmassani and Chang, 1987</p>
Demand Model	<p>Simulation and</p>	<p>Transportation</p>	<p>Kitamura <i>et al.</i>, 1994</p>

System Revision	adaptation process	Demand Management applications	Stopher <i>et al.</i> , 1994
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#### 4. Activity pattern analysis

In an effort to better understand travel behavior and induced trip making, researchers have examined the household's travel pattern in its entirety. Daily and multi-day activity pattern analysis is an important category in activity-based analysis. Classificatory methods are quite frequently used either to enumerate feasible daily activity patterns (Recker, McNally, and Root, 1985, 1986b, 1986c) or to characterize multi-day patterns (Koppleman and Pas, 1985; Pas and Koppleman, 1985, 1986; Hanson and Huff, 1985; Huff and Hanson, 1986; Jones and Clarke, 1987). Because of the extremely complicated dimensionality, sequential procedures have been applied to reduce the complexity in forming the activity pattern (Kitamura and Kermanshah, 1983, 1984). Structural equation systems and multivariate analysis are also notable in determining the relationship between activity patterns and socio-demographic attributes (Golob, 1985, 1986; Golob and Meurs, 1987).

Computer-oriented model systems have been presented and offer the enumeration of feasible activity travel patterns, selecting those most likely to be chosen by household members with given characteristics; most notable among these being STARCHILD (Recker *et al.*, 1986b, 1986c). This model system is complementary to the Household Activity Travel Simulator (HATS; Jones *et al.*, 1983), which is a home interview instrument that solicits possible activity travel patterns adopted in response to changes in the travel environment.

## 5. Trip chaining analysis

Another category of study concerns trip chaining analysis. Much of the early stage of these analyses relied on Markovian analysis (O'Kelly, 1981; Kitamura, 1982) to validate the Markovian assumption when applied to trip chaining behavior. Research has also included the mathematical formulation of the distribution of number of stops in trip chain (Mazurkiewicz, 1985). Practical application of the trip chaining concept by means of simulation (Southworth, 1985a, 1985b), as well as econometric models in which trip chaining behavior is formulated as discrete choice of alternative travel patterns (Barnard, 1986) have also been presented. Horowitz (1982) approached this topic through the process of the maximization of time-dependent utility, while other research based on shopping trips has also been conducted. All of the works fall under the framework of utility maximization or cost minimization.

Narula *et al.* (1983) viewed trip chaining as a result of household rational decision on shopping. This model, which can be considered as a theoretical model of trip generation and trip chaining, is constructed under the assumption that the accumulation of needs triggers trip making. Thill (1985) and Kitamura (1985) considered multi-shop and the spatial distribution of stop location under an idealized setting, respectively.

## 6. Interaction among individuals

Work addressing the collective travel behavior by household members is quite limited. Townsend (1979) and Koppleman and Townsend (1987) have formulated task allocation among household members as a utility maximization process under time

budget constraints. They derive expressions for the amount of time allocated to household members by activity type to reflect the interaction among individuals.

#### 7. Adaptation and dynamic aspects

Temporal factors are important in activity analysis. Use of longitudinal observations of the behavioral unit allows more direct observation of change in control factors and change in activity participation. Activity choice and scheduling involve the time dimension, and the only way to thoroughly understand these aspects is to trace behavior over time. Moreover, behavior adaptation may span longer time periods. This led to the development of habit formation and persistence (Goodwin, 1977,1986; Clarke, *et al.*, 1982, Kitamura and van der Hoorn, 1987; Kostyniuk and Kitamura, 1987).

In other work, Mahmassani and his colleagues developed a series of studies based on the observation of departure time decisions by commuters in a simulated, but realistic and real-time, environment (Mahmassani, Chang and Herman, 1986; Mahmassani and Chang, 1987).

#### 8. Demand model systems revision

This is basically an old category with a new approach in which activity-based analyses are combined with the previous four-step process and land use models to explore a new system grounded on the activity-based approach. The most recent such attempts have been performed by Kitamura *et al.* (AMOS, 1994) and Stopher *et al.* (SMART, 1994).

Kitamura *et al.* (Activity MObility Simulator, AMOS) try to develop a new planning system to replace the conventional forecasting model systems. The key features constituting SAMS (Sequenced Activity-Mobility System), which is a core component of AMOS, include: an activity-based approach; explicit modeling of adaptation behavior as a learning process; forecasting by micro simulation; GIS-based spatial analysis; and endogenous forecasting of socio-demographics, land use, and travel.

Proposed by Stopher *et al.*, SMART (Simulation Model for Activities, Resources and Travel) integrates household activities, land use patterns, traffic flows, and regional demographics into a model system with the purpose of replacing UTPS modeling systems. Operating in a GIS environment, the model's heart is a Household Activity Simulator that determines the locations and travel patterns of household members' daily activities in three categories: mandatory, flexible and optional.

All of the aforementioned research efforts are part of the development of activity-based analysis. The categorization of the previous research helps to quickly identify the core elements and to easily understand the content of those studies. It is also useful in identifying the available resources that can be applied to modify traditional accessibility.

### **2.3.3 Activity-Based Modeling Approaches**

Activity-based modeling approaches, as mentioned earlier, involve a broad concept and fragmented grounding. The extreme complexity and multiple dimensionality lend the modeling work to be diffuse. Typical approaches include: mathematical

programming models, simulation models, choice-based models, and computer-based gaming models with visual equipment. Each type of model has its associated advantages and shortcomings. Furthermore, because of the lack of unified common theoretical foundation, the modeling is quite problem-specific. The following is a summary of well-known modeling techniques that may find useful application in activity-based modeling:

1. Mathematical programming

By using mathematical programming, some standard formulations can be identified and tested. Problem formulation can be expected to be integer program related; typically ILP (Integer Linear Programming) can be applied for solution approaches. Dynamic programming is also quite useful in the modeling process. Some disadvantages come with mathematical programming approaches, including:

- a. Such formulations contain a large number of constraints and variables in the model;
- b. The computation complexity increases with an exponential rate, and
- c. It is cumbersome to solve large scale problems.

There are also advantages associated with this approach. First, it is the standard approach to verify the existence and correctness of certain types of formulations. Secondly, the solution generated by the model could be used in comparison to the solutions obtained from other approaches.

## 2. Combinatorial methods:

This approach involves enumerating all the possible arrangements and then choosing the optimal one directly. Basically, this approach belongs to a wider branch of heuristic algorithms to deal with combinatorial problems. An extensive study of combinatorial methods have been developed based on graph theory. Some typical examples of combinatorial problems are activity participation problem, trip chaining problem and so forth.

Combinatorial problems which can be solved by optimization methods, combinatorial enumeration, or heuristic methods, is commonly associated with sequencing and path-based approaches. The emphasis of enumeration is often put on the combinatorics of sequence and path.

## 3. Heuristic methods:

Because the extreme complexity existing in activity model, most of the problems belong to the so-called NP-Hard problem, which stands for non-deterministic polynomial time. The number of fundamental computations increase exponentially with the size of the problem. It is almost impossible to solve a large scale problem in a limited amount of time. Heuristic algorithms which use "common sense" rules to limit the number of alternatives examined and so reduce the time required are be efficient methods to solve such problems.

Stochastic heuristic methods have been developed to improve traditional descent gradient method during the search process. Simulated annealing, and evolutionary

programming are typical methods of this sort of research. They both use stochastic procedures to deal with the local search process to avoid getting trapped in a local optimum. The application of this sort of technique is new and has been proved to be efficient.

## **2.4 CONCEPTUAL FRAMEWORK**

From the review of the traditional measurements of accessibility, some shortcomings and incompleteness of traditional measures are found. It is suggested that modifications of the measure of accessibility be made so that it would better incorporate the following aspects:

1. It should be policy sensitive;
2. It should reflect personal characteristics and differences;
3. It should reflect temporal aspects in the measurement, and
4. It should reveal the transference effect.

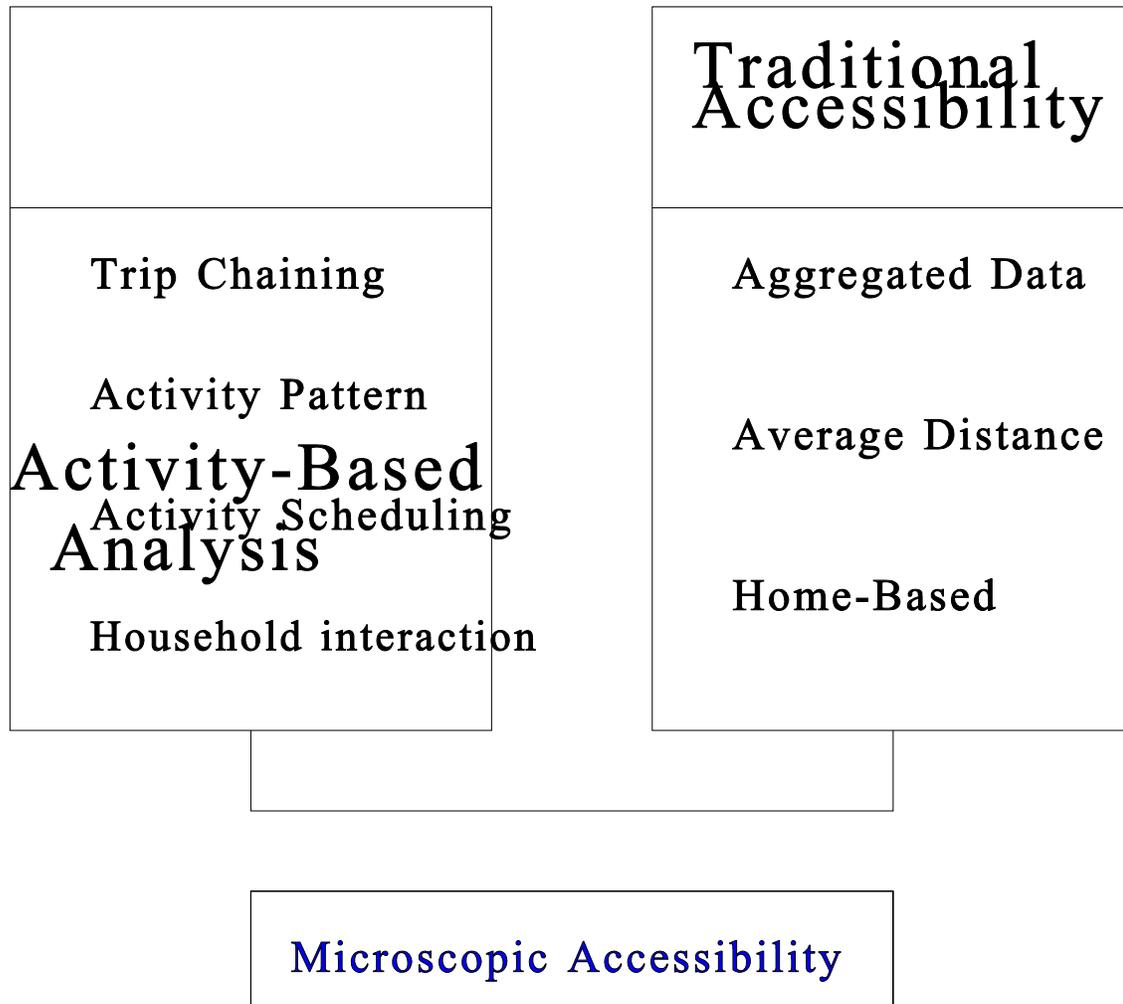
A background review of activity-based analysis suggests its potential to compensate for the deficiencies of traditional measures of accessibility. From this, a conceptual framework emerges which originates from the participation of activity, and the linkage between activities, and in which all of the required components are contained in the activity scheduling and trip chaining problem (Figure 1).

The basic motivation of this conceptual framework stems from the idea that an activity-based approach can compensate for the deficiencies of traditional

accessibility measurement by combining the trip chaining problem, activity participation problem, activity scheduling problem, and household interaction problem together. Taken together, these form the household activity pattern problem (HAPP); the solution patterns reveal personal behavior under the household context with the person-specific generalized cost, (from the objective function of HAPP) used as the measure of generalized cost in the expression of accessibility. The generalized cost generated by the HAPP not only contains several aspects that can be used to reflect a personal behavioral element within the household texture, but also is based on the interaction of transportation supply environment and household demographic situation. Using this cost in the measurement of accessibility will avoid the deficiencies caused by traditional measurement by removing the restrictions in traditional accessibility measures which rely on aggregated data, average distance, and home-based measurements. The proposed new accessibility is defined as a microscopic accessibility measure indicating personal accessibility within a restricted transportation environment.

## **2.5 DEFINITION OF MICRO ACCESSIBILITY**

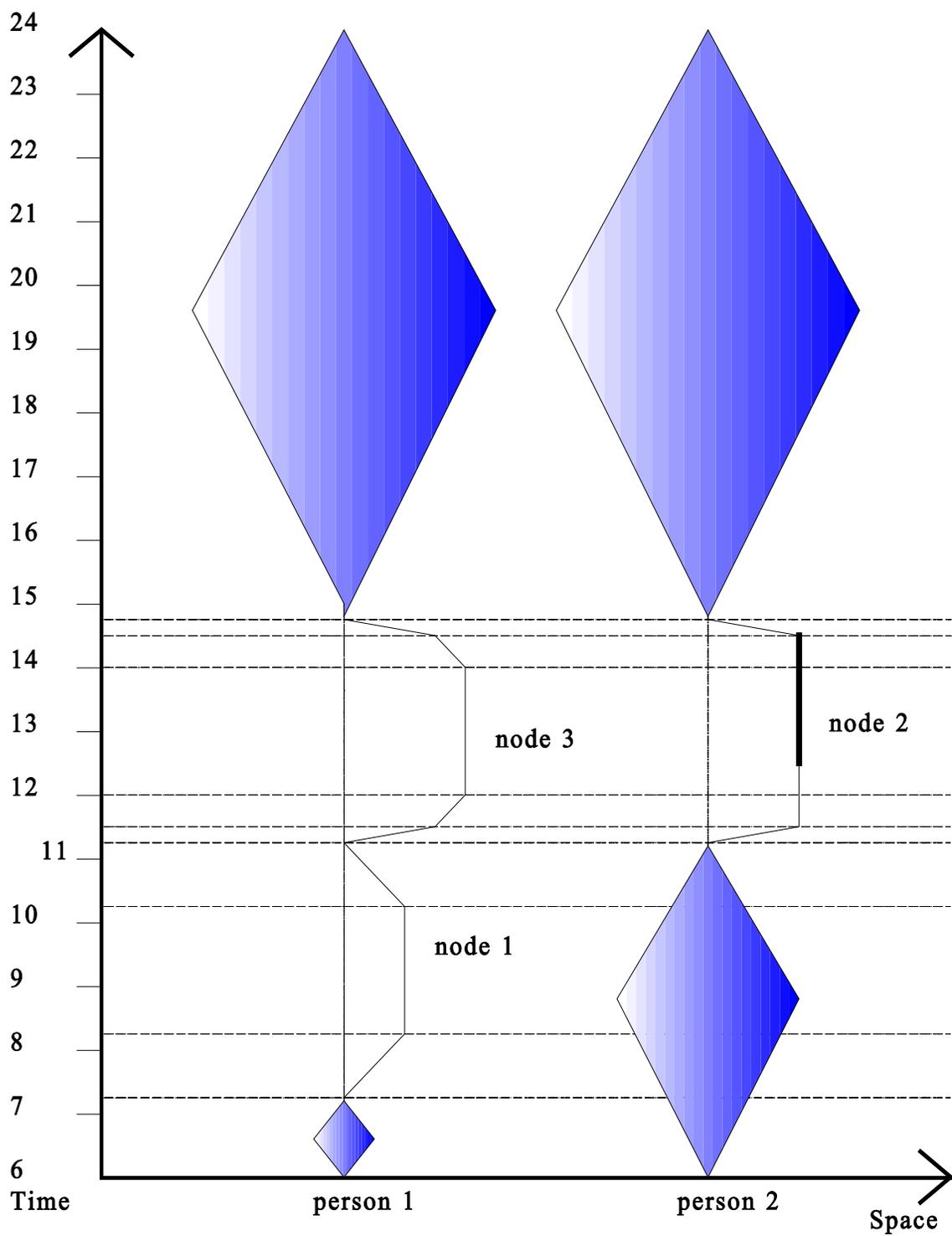
The proposed definition of personal accessibility is then described as a spatio-temporal measure of "individuals' ability to reach activity opportunities." Based on this definition, the measure of accessibility adopted for this dissertation research can be defined as the available opportunities that a person or household can reach by using an auto-related travel mode within a specific active period, typically from 6:00 AM to 12:00



Measurement

Empirical Applications

Midnight. The addition of a temporal dimension provides the ability to measure the variation of accessibility by time-of-day. Furthermore, the analysis of personal accessibility facilitates a better understanding of transference of accessibility among household members, in terms of ride sharing and trip chaining behaviors.



The calculation of accessibility is based on the concept of space-time prisms, by which accessibility can be explained as the potential reachability of specific members in the household. This means of illustration utilized by Hagerstrand (1970) was that of the now familiar three-dimensional space-time model, in which geographical space is represented by a two-dimensional plane and time is defined on the vertical axis. The location of activity sites, together with the maximum speed an individual can travel in a given direction, establishes the individual's space-time prism, the volume of which represents the full range of possible locations at which an individual can participate. Once an individual travels to a specific location, the potential action space for any subsequent activities will be reduced depending on the prior activity's duration. In this application, space-time prism is used with the same meaning. Figure 2 is an example to illustrate the accessibility measurement of a household, if the associated activity diary is known. In the figure, the accessibility is measured by the volume of the shaded diamond for each individual.



## **CHAPTER 3**

### **MODEL FORMULATION AND INITIAL SOLUTION PROCESS**

#### **3.1 INTRODUCTION**

The research focus of this dissertation involves a comprehensive study of a complicated network-based model that incorporates routing, scheduling, and assignment related to household activity/travel decision-making. Presented in this chapter is the development of an optimization-based approach and model that is capable of describing household activity/travel decisions including scheduling, automobile assignment and task assignment for the case of solo driver personal automobile mode of travel. GAMS (General Algebraic Modeling System) is used as a temporary tool to verify and test the mathematical formulation. Since the addition of ride sharing components to the model severely increases the complexity, the exploration of applying heuristic methods is considered in subsequent chapters as a better approach to reducing the dimensionality of the full model with ridesharing options to a reasonable level.

#### **3.2 DEFINITION AND FORMULATION**

Consider 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 is 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 Household Activity Pattern Problem (HAPP) is described as: To minimize a hypothetical objective function, which can generally express the cost within the household in order to complete all of the activities needed to be performed by the household members subject to the constraints related to transportation supply, time windows, vehicle capacity, and logical connection between activity nodes.

Therefore, the Household Activity Pattern Problem, 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 should be performed either by some specific person or by anyone available, are sustained within this model. The development of this proposed model formulation is originated from the concept in VRP.

Therefore, 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 on the time period of performing the activity. In addition, the person who performs activities must use a stable of vehicles available to the household to travel the network. Furthermore, a limited version of ride-sharing behavior is incorporated within this model for the persons who have to perform activities although they are not qualified to drive.

Based on the characteristics of the problem, some notation and definitions are described in the next section.

### 3.2.1 Definition and Notation

The use of existing network-based modeling techniques provides a useful approach to formulate the Household Activity Pattern Problem, which is a key element in the activity-based analysis. Before stating the detailed formulation of HAPP, it is necessary to define clearly the notation and symbols used in the equations.

Different sets of activity nodes, household members, available vehicles and function for a given household are defined and described as follows:

$$\begin{aligned}
 P &= \{1, 2, \dots, n-1, n\} \\
 P' &= \{0, 1, 2, \dots, n-1, n, d\} \\
 H &= \{h_1, h_2, \dots, h_{n-1}, h_n\} \\
 H' &= \{0, h_1, h_2, \dots, h_{n-1}, h_n, d\} \\
 N &= \{1, 2, \dots, n-1, n, h_1, h_2, \dots, h_{n-1}, h_n\} \\
 N' &= \{0, 1, 2, \dots, n-1, n, h_1, h_2, \dots, h_{n-1}, h_n, d\} \\
 \eta &= \{1, 2, \dots, |\eta|\} \\
 v &= \{1, 2, \dots, |v|\} \\
 \gamma &= \{1, 2, \dots, |\gamma|\} \\
 F &= \{1, 2\}
 \end{aligned}$$

where:

$P$  the set of all activity nodes scheduled to be completed by members in the household

$P'$	the set of all activity nodes as well as starting node and ending node
$H$	the set of all temporary returning home nodes associated with each activity node
$H'$	the set of all home nodes including starting node and ending node
$N$	the set of all activity nodes and returning home nodes associated with each activity node
$N'$	the set of $N$ as well as the starting node and ending node
$O$	the set of all of the members in the household
$<$	the set of all of the available vehicles used by members in the household to complete their scheduled activities
$($	the set of number of people in a vehicle (including the driver and the passengers)
$F$	the set of functions that could be performed at an activity node, with "1", representing delivery, and "2", pickup (physically, these functions are performed at the locations of the associated activity nodes, and logically, these functions are used to represent those expanded nodes associated with the original activity nodes)

Some parameters are defined as follows:

$u,w$	node representing activity
$0$	departure depot node (starting node)
$d$	final arrival depot node (ending node)

$e, f$	function performed at node
$v$	vehicle within the household
$r$	number of people in a vehicle
$''$	member within the household
$a_{u,e}$	early time window of available start time associated with activity node $u$ while performing function $e$
$b_{u,e}$	late time window of available start time associated with activity node $u$ while performing function $e$
$M$	an arbitrarily large number
$a_1, a_2, c$	weights associated with the objective function of the HAPP (equal weights are selected in this research)

Some additional sets are introduced to limit feasible connections among activity nodes, and they are:

$\Omega_{H_{''}}$	the set of activities that can not be performed by household member $''$
$\Omega_{v_v}$	the set of activities that can not be reached by vehicle $v$
$\Psi_{u,w,e,f}$	the feasible connection set between node $u$ with function $e$ and node $w$ with function $f$
$I$	the set of infeasible vehicle-person pairs (meaning an auto can not be used as an active travel mode by a person without driver license)

The decision variables representing the routing aspects of vehicles and persons, temporal aspects regarding activity begin time and waiting time, assignment of vehicles and persons, and such other aspects as capacity are defined below:

$X_{u,w,e,f}^{v,r}$  binary decision variable equal to unity if vehicle  $v$  travels from activity node  $u$  after performing function  $e$  to activity node  $w$  to perform function  $f$  with  $r$  people in vehicle  $v$ , and zero otherwise

$Y_{u,w,e,f}^{\alpha}$  binary decision variable equal to unity if household member " $\alpha$ " travels from activity node  $u$  after performing function  $e$  to node  $w$  to perform function  $f$ , and zero otherwise

$T_{u,e}$  the time at which participation in activity  $u$  to perform function  $e$  begins

$H_{u,1}^{v,\alpha}$  the time at which for household member " $\alpha$ " to participate in activity  $u$  by using vehicle  $v$  begins

$R_{u,e}^{v,\alpha}$  the time at which household member " $\alpha$ " arrives at node  $u$  to perform function  $e$  by using vehicle  $v$

$W_{u,e}^{v,\alpha}$  waiting time for member " $\alpha$ " by using vehicle  $v$  while staying at activity node  $u$  to perform function  $e$

$AH_{u,\alpha}$  binary decision variable equal to unity if activity node  $u$  is assigned to household member " $\alpha$ ", and zero otherwise

$Av_{u,w}$  binary decision variable equal to unity if vehicle  $v$  is used to participate in activity  $u$ , and zero otherwise

$Z_{h,h}^u$  cumulative load with household member  $h$  when participating in activity  $u$  and performing function  $e$

There are also some parameters associated with network traveling time and cost, duration of activity node and load of activity node, which is equivalent to a hypothetical index of measuring loading associated with performing that activity node, and household budget as below:

$t_{uw}$  travel time from the location of activity  $u$  to the location of activity  $w$

$C_{uw}$  travel cost from the location of activity  $u$  to the location of activity  $w$

$s_{u,e}$  duration of staying at activity node  $u$  to perform function  $e$

$L_{u,e}$  load associated with activity node  $u$  while performing function  $e$

$BC$  the household travel cost budget

$BT_h$  the travel time budget of household member  $h$

### 3.2.2 Mathematical Formulation

The HAPP is formulated as an Integer Linear Programming (ILP) model with decision variables and parameters defined in the previous section. The objective function is to minimize the weighing combination of total travel time, waiting time and out-of-home cost for each member. It is conjectured that the HAPP is a complicated version of VRP; the formulation is

constructed based on the separation of the movement of vehicle-person pairs and leads to the formulation on vehicle movement and member movement, respectively. Coupling constraints are used to insure the compatibility of these movements.

The constraint sets in the ILP are classified into six groups. They are: (a) routing for vehicle and household member; (b) scheduling for vehicle and household member; (c) assignment for vehicle and household member; (d) time window constraints; (e) coupling constraints of routing variable for household member and vehicle, and (f) side constraints including budget, capacity, and rule for ride-sharing behavior.

Routing constraints basically define spatial movement of vehicles and household members; it contains those constraints that guide flow conservation, and the origination and end conditions of the movement. Scheduling constraints, as described by its category, specify the relationship of arrival time, activity begin time, and waiting time, and continuity condition along the temporal dimension. Assignment constraints are applied to match the relations between activity participation and vehicle usage as well as activity performers (household members). In addition to scheduling constraint, time window constraints are facilitated to specify available schedules for activity participation. Meanwhile, coupling constraints are constructed to set the relations between vehicle-related variables and member-related variables. Finally, a set of side constraints are used to eliminate illogical connections between activity nodes.

The mathematical formulation is expressed as follows:

$$\begin{aligned} \text{Min } Z = & a_1 \cdot \sum_{u \in N} \sum_{\theta \in P} \sum_{w \in N} \sum_{f \in P} \sum_{\alpha \in \eta} Y_{u^{\theta} w f}^{\alpha} \cdot t_{uv} + a_2 \cdot \sum_{u \in P} \sum_{\theta \in P} \sum_{v \in N} \sum_{\alpha \in \eta} \\ & + a_3 \cdot \sum_{w \in P} \sum_{f \in P} \sum_{\alpha \in \eta} Y_{0^1 w f}^{\alpha} \cdot K \end{aligned}$$

subject to

$$\sum_{w \in P} \sum_{f \in P} Y_{0^1 w f}^{\alpha} \leq 1, \alpha \in \eta \quad (1)$$

$$\sum_{w \in P} \sum_{f \in P} \sum_{\alpha \in \eta} Y_{0^1 w f}^{\alpha} \geq 1 \quad (2)$$

$$\sum_{u \in P} \sum_{\theta \in P} Y_{u^{\theta} d^1}^{\alpha} = \sum_{w \in P} \sum_{f \in P} Y_{0^1 w f}^{\alpha}, \alpha \in \eta \quad (3)$$

$$\sum_{w \in P} \sum_{f \in P} \sum_{r \in \gamma} X_{0^1 w f}^{v r} \leq 1, v \in V \quad (4)$$

$$\sum_{w \in P} \sum_{f \in F} \sum_{v \in V} \sum_{r \in \Gamma} X_{0^1 w f}^{v r} \geq 1 \quad (5)$$

$$\sum_{u \in P} \sum_{e \in F} \sum_{r \in \Gamma} X_{u^e d^1}^{v r} = \sum_{w \in P} \sum_{f \in F} \sum_{r' \in \Gamma} X_{0^1 w f}^{v r'} \quad v \in V \quad (6)$$

$$\sum_{u \in N} \sum_{e \in F} \sum_{v \in V} \sum_{r \in \Gamma} X_{u^e w}^{v r} = 1, \quad w \in P \quad (7)$$

$$\sum_{u \in N} \sum_{e \in F} Y_{u^e w f}^\alpha = \sum_{u' \in N} \sum_{e' \in F} Y_{w f u'}^\alpha, \quad w \in N, f \in F, \alpha \in \eta \quad (8)$$

$$\sum_{u \in N} \sum_{e \in F} \sum_{r \in \Gamma} X_{u^e w f}^{v r} \cdot r = \sum_{u' \in N} \sum_{e' \in F} \sum_{r' \in \Gamma} X_{w f u'}^{v r'} \cdot r', \quad w \in N, f \in F, v \in V \quad (9)$$

$$\sum_{v \in V} \sum_{r \in \Gamma} X_{u^e w f}^{v r} \cdot r = \sum_{\alpha \in \eta} Y_{u^e w f}^\alpha \cdot u, \quad w \in P, e, f \in F \quad (10)$$

$$\sum_{v \in V} \sum_{r \in \mathcal{R}} X_{u^e d^1}^{v r} \cdot r + \sum_{v \in V} \sum_{r \in \mathcal{R}} X_{u^e w^1}^{v r} \cdot r = \sum_{\alpha \in \mathcal{H}} Y_{u^e d^1}^\alpha + \sum_{\alpha \in \mathcal{H}} Y_{u^e w^1}^\alpha \quad (11)$$

$u \in P, w \in H, e \in F$

$$\sum_{u \in H} \sum_{v \in V} \sum_{r \in \mathcal{R}} X_{u^1 w^f}^{v r} \cdot r = \sum_{u \in H} \sum_{\alpha \in \mathcal{H}} Y_{u^1 w^f}^\alpha, \quad w \in P, f \in F \quad (12)$$

$$\sum_{\alpha \in \mathcal{H}} AH_{u\alpha} = 1, \quad u \in P \quad (13)$$

$$-(1 - Y_{u^1 u^2}^\alpha) \cdot M \leq AH_{u\alpha} - Y_{u^1 u^2}^\alpha \leq (1 - Y_{u^1 u^2}^\alpha) \cdot M, \quad u \in P, \alpha \in \mathcal{H} \quad (14)$$

$$-[(1 - \sum_{u \in N} Y_{u^1 w^1}^\alpha) + (1 - \sum_{u \in N} \sum_{v \in V} X_{u^1 w^1}^{v 1})] \cdot M \leq AH_{u\alpha} - \sum_{u \in N} Y_{u^1 w^1}^\alpha$$

$$Av_{wv} = \sum_{u \in N} \sum_{e \in F} \sum_{r \in \mathcal{R}} X_{u^e w^1}^{v r}, \quad w \in P, v \in V \quad (15)$$

$$w \in P, \quad (16)$$

$$\begin{aligned}
-(1 - \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, 1}) \cdot M &\leq \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, 1} - \sum_{u' \in N} \sum_{e' \in E} X_{w^{e'} u'}^{v, 1} \\
&\leq (1 - \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, 1}) \cdot M \quad (17) \\
&\quad w \in P, w \neq u \neq u', v \in V
\end{aligned}$$

$$\begin{aligned}
-(1 - \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, r'}) \cdot M &\leq \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, r'} - \sum_{u' \in N} \sum_{e' \in E} X_{w^{e'} u'}^{v, r'} \\
&\leq (1 - \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, r'}) \cdot M \quad (18) \\
&\quad w \in P, w \neq u \neq u', v \in V, r' = r + 1
\end{aligned}$$

$$\begin{aligned}
-(1 - \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, r}) \cdot M &\leq \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, r} - \sum_{u' \in N} \sum_{e' \in E} X_{w^{e'} u'}^{v, r} \\
&\leq (1 - \sum_{u \in N} \sum_{e \in E} X_{u^e w}^{v, r}) \cdot M \quad (19) \\
&\quad w \in P, w \neq u \neq u', v \in V, r' = r + 1
\end{aligned}$$

$$\begin{aligned}
-[(1 - Y_{u^e, w, f}^\alpha) + (1 - \sum_{r \in \gamma} X_{u^e, w, f}^{v, r})] \cdot M &\leq R_{u^e}^{v\alpha} + W_{u^e}^{v\alpha} + t_{uw} + s_{u^e} \cdot A \\
&[(1 - Y_{u^e, w, f}^\alpha) + (1 - \sum_{r \in \gamma} X_{u^e, w, f}^{v, r})] \cdot M^{(20)} \\
&u, w \in P, e, f \in E
\end{aligned}$$

$$\begin{aligned}
-[(1 - \sum_{u \in H} Y_{u^1, w, f}^\alpha) + (1 - \sum_{r \in \gamma} X_{u^1, w, f}^{v, r})] \cdot M &\leq H_{u^1}^{v\alpha} + t_{uw} - R_{w, f}^{v\alpha} \leq \\
&[(1 - \sum_{u \in H} Y_{u^1, w, f}^\alpha) + (1 - \sum_{r \in \gamma} X_{u^1, w, f}^{v, r})] \cdot M^{(21)} \\
&u^1 \in H, w \in P, f \in F, \alpha \in \eta_b, v \in V
\end{aligned}$$

$$\begin{aligned}
-[(1 - Y_{u^1, w, f}^\alpha) + (1 - \sum_{u^1 \in H} \sum_{r \in \gamma} X_{u^1, w, f}^{v, r})] \cdot M &\leq H_{u^1}^{v\alpha} + t_{uw} - R_{w, f}^{v\alpha} \leq \\
&[(1 - Y_{u^1, w, f}^\alpha) + (1 - \sum_{u^1 \in H} \sum_{r \in \gamma} X_{u^1, w, f}^{v, r})] \cdot M^{(22)} \\
&u \in H, w \in P, f \in F, \alpha \in \eta_b, v \in V
\end{aligned}$$

$$\begin{aligned}
-[(1 - Y_{u^e w^1}^\alpha) + (1 - \sum_{w' \in H} \sum_{r \in \gamma} X_{u^e w^1}^{v r})] \cdot M &\leq T_{u^e} + t_{uw} + s_u : AH_u \\
&[(1 - Y_{u^e w^1}^\alpha) + (1 - \sum_{w' \in H} \sum_{r \in \gamma} \dots)^{(23)} \\
&u \in P, w \in H, e \in F,
\end{aligned}$$

$$\begin{aligned}
-[(1 - \sum_{w \in H} Y_{u^e w^1}^\alpha) + (1 - \sum_{r \in \gamma} X_{u^e w^1}^{v r})] \cdot M &\leq T_{u^e} + t_{uw} + s_u : AH_u \\
&[(1 - \sum_{w \in H} Y_{u^e w^1}^\alpha) + (1 - \sum_{r \in \gamma} \dots)^{(24)} \\
&u \in P, w \in H, e \in F,
\end{aligned}$$

$$\begin{aligned}
-[(1 - Y_{u^e w^2}^\alpha) + (1 - \sum_{r \in \gamma} X_{u^e w^2}^{v r})] \cdot M &\leq R_{w^2}^{v\alpha} + W_{w^2}^{v\alpha} - T_{w^2} \\
&\leq [(1 - Y_{u^e w^2}^\alpha) + (1 - \sum_{r \in \gamma} X_{u^e w^2}^{v r})] \cdot M \quad (25) \\
&u, w \in P, e \in F, \alpha \in \eta_b, v \in V
\end{aligned}$$

$$\begin{aligned}
-[(1 - Y_{u^e w^f}^\alpha) + (1 - Y_{u^e w^f}^{\alpha'}) + (1 - X_{u^e w^f}^{v r})] \cdot M &\leq R_{w^f}^{v\alpha} - R_{w^f}^{v\alpha'} \leq \\
&[(1 - Y_{u^e w^f}^\alpha) + (1 - Y_{u^e w^f}^{\alpha'}) + (1 - X_{u^e w^f}^{v r})] \cdot M^{(26)} \\
&u \in N, w \in P, e, f \in F, \alpha, \alpha' \in \eta_b, v \in V
\end{aligned}$$



$$-[(1 - AH_{uv}) + (1 - Av_{uv})] \cdot M \leq R_{u1}^{v\alpha} + W_{u1}^{v\alpha} - T_{u1} \leq [(1 - AH_{uv})] \quad (27)$$

$$-[(1 - Y_{u'e_w}^{\alpha}) + (1 - Y_{u'e_w'}^{\alpha'}) + (1 - X_{u'e_w}^{v'r})] \cdot M \leq H_{w1}^{v\alpha} - H_{w1}^{v\alpha'} : \\ [(1 - Y_{u'e_w}^{\alpha}) + (1 - Y_{u'e_w'}^{\alpha'}) (1 - X_{u'e_w}^{v'r})] \cdot M \quad (28)$$

$w, w' \in H, u \in P, e \in F, \alpha, \alpha' \in \eta, v \in \mathcal{V}$

$$-[(1 - X_{u'e_w}^{v'1}) + (1 - X_{u'e_w}^{v1}) + (1 - Y_{u'e_w}^{\alpha})] \cdot M \leq H_{w1}^{v\alpha} - H_{w1}^{v'\alpha} : \\ [(1 - X_{u'e_w}^{v'1}) + (1 - X_{u'e_w}^{v1}) + (1 - Y_{u'e_w}^{\alpha})] \cdot M \quad (29)$$

$w, w' \in H, u \in P, e \in F, \alpha \in \eta, v, v' \in \mathcal{V}$

$$-[(1 - AH_{uw}) + (1 - Y_{u'e_w}^{\alpha})] \cdot M \leq L_{u'e}^{\alpha} + l_{u'e} - L_{w'f}^{\alpha} \leq \\ [(1 - AH_{uw}) + (1 - Y_{u'e_w}^{\alpha})] \cdot M \quad (30)$$

$u, w \in N, e, f \in F, \alpha \in \eta$

$$a_{w^f} T_{w^f} \leq (1 - \sum_{u \in P} \sum_{e \in F} \sum_{v \in V} \sum_{r \in \Gamma} X_{u^e, w^f}^{v, r}) \cdot M \geq -b_{w^f} + T_{w^f}, w \in P \quad (31)$$

$$\sum_{u \in N} \sum_{e \in F} \sum_{w \in N} \sum_{f \in F} \sum_{v \in V} \sum_{r \in \Gamma} X_{u^e, w^f}^{v, r} \cdot c_{uv} \leq BC \quad (32)$$

$$\sum_{u \in N} \sum_{e \in F} \sum_{w \in N} \sum_{f \in F} Y_{u^e, w^f}^\alpha \cdot t_{uv} \leq BT_\alpha, \alpha \in \eta \quad (33)$$

$$\sum_{v \in V} \sum_{r \in \Gamma} X_{u^e, w^f}^{v, r} = 0, (u^e, w^f) \notin \Psi_{u^e, w^f} \quad (34)$$

$$X_{u^1, u^2}^{v, r} = 0, u \in P, v \in V, r \in \Gamma, r \geq 2 \quad (35)$$

$$X_{u^1, w^2}^{v, 1} = 0, u, w \in N, v \in V \quad (36)$$

$$X_{u,v}^{v,1} + Y_{u,v}^u \leq 1, u, w \in P', \{v, \alpha\} \in I \quad (37)$$

Equations (1) and (2) depict the origination of a person tour, and allow the possibility of a member to stay at home. Equation (3) specifies that the end of a person tour must be associated with the corresponding beginning of the person tour. Equations (4)-(6) have the same functions as Equations (1)-(3) but are applied to the vehicle tour variable. Equation (7) states that each activity node must be visited by one vehicle while performing the service of the activity. Equation (8) ensures the flow conservation constraint between all activity nodes; that is, the number of people going into the activity node must be equal to the number of people going out of the activity node. The same situation can be formulated as Equation (9) when applied to a vehicle tour. The coupling constraints for the vehicle routing variable and person routing variable are specified in Equations (10) to (12). Equation (10) sets up the one-to-one relationship at activity nodes for vehicle-routing variable and person-routing variable. Equations (11) and (12) allow for the transference of vehicle and member when either arriving at or departing from home nodes. The association of activity and member can be described by Equations (13)-(15). Equation (13) specifies that each activity must be performed by one, and only one, member. Equations (14) and (15) set the relation between assignment variable and person-routing variable. The relation between assignment variable of vehicle and vehicle

routing variable is specified by Equation (16). Equation (17) addresses the flow conservation constraint for one-person vehicles (drive-alone vehicle). Equations (18) and (19) describe the change in the number of people inside a vehicle when stopping at a delivery node and a pickup node, respectively. Temporal constraints are listed from Equation (20) to Equation (29). Equation (20) ensures the continuity of temporal space between activity nodes. Equations (21) and (22) match the temporal constraint for the links departing from different home nodes when person or vehicle transference is allowed. The same condition can be applied to Equations (23) and (24) for the links arriving at different home nodes. Equations (25) and (26) describe the relation between arrival time and activity begin time. The coupling constraints of the arrival time variable for different persons is matched by Equation (27). Equations (28) and (29) ensure that the activity begin time of the home nodes be equal when transference of person or vehicle is allowed. The load budget constraint in Equation (30) describes the accumulative load at each activity node. The time window constraint in Equation (31) limits the freedom of performing an activity at certain time periods. Equations (32) and (33) specify the budget constraints of travel cost and travel time for each household member and the whole household, respectively. All illogical connections are listed in Equations (34) to (36). Finally, infeasible person-vehicle pairs are excluded to ensure that a vehicle is used by a qualified driver in Equation (37).

Some of the constraints are constructed based on the characteristics of binary variables; the formulations with such statements produce a conditional constraint, in which if the value of the variable is equal to "1", then some conditions will be fulfilled, otherwise it becomes a non-

binding constraint. This class of formulation is restrictive because it is bound only at some specific values of the binary variables. Therefore, most of the time, linear relaxation of this class of constraints with binary variables will not be active while solving the relaxed program.

## **CHAPTER 4**

### **DEVELOPMENT OF SOLUTION PROCESSES AND COMPUTATIONAL RESULTS**

#### **4.1 INTRODUCTION**

Formulation of the HAPP builds a possible foundation to understand travel behavior from a household decision context. Several different situations are initially tested with the formulation mentioned. The solution of each case is initially solved by GAMS (General Algebraic Modeling Systems). Because of the extreme complexity of the original formulation, effective and efficient methods need to be developed in order to solve larger size problems. Different heuristic methods are also taken into consideration to reduce the complexity, and a special conceptual relaxation on the limitation of number of available vehicles in a household is adopted to reduce the original formulation to a VRPTW (Vehicle Routing Problem with Time Windows constraint) type problem. This relaxation assists solution to the complicated problem because the VRPTW problem has been studied extensively as an outgrowth of the success of explorations on Vehicle Routing Problems.

The solution procedures for the first stage can be obtained by combining modified dynamic programming-based algorithm with the concept of opportunity cost derived from the savings method; procedures of the second stage are basically heuristic. Computation time and complexity of the problem are discussed, and the path of each case

is displayed by a network figure and a two-dimension time-space diagram.

## **4.2 INITIAL TESTING USING GAMS CPLEX MODULE**

The formulation of the model is tested with GAMS (General Algebraic Modeling System), which is a commercial package developed by The Word Bank. The package comprises several modules that deal with such problem formulations as linear, integer, mixed integer, binary, non-linear and combinations of the above.

Some restrictive versions of the HAPP mixed integer model with a limited number of activities were solved using the ZOOM and CPLEX module of GAMS. Several different cases representing different situations were created to verify the correctness of the formulation. Specifically, two limiting cases in the form of the simple VRP and VRPTW (which are special examples of HAPP) were solved with the use of CPLEX in GAMS, together with a simple case of a two-member household with one vehicle and three activities.

The optimal solutions of these simple cases were obtained by the GAMS program on a personal computer rated 486 DX 50 with 16 MB RAM. Even in the simple case of only three activities, the number of constraints exceeds fifty thousand and the number of variables can exceed five thousand. This huge dimensionality renders the solution process difficult, especially in the execution of branch and bound. The computation time needed is as many as 30 minutes, and can even extend beyond a day for an increase in any such related components as number of activities, household size, or number of

vehicles. Although providing an initial check on the formulation, the computation results for these simple cases clearly demonstrate that standard treatments by mathematical programming are not practically feasible with such a complex formulation. The development of an effective and efficient solution procedure is crucial if applications of this model involving practical cases are to be conducted.

### **4.3 SOLUTION APPROACHES OF THE ORIGINAL PROBLEM**

As indicated in the previous section, the GAMS CPLEX module was used as a temporary tool to find the solutions to a series of test cases to ensure validity of the model formulation. The dimensionality of the original formulation restricted the exploitation of commercial ready-to-use packages to solve HAPP efficiently. In addition, the demonstration of the test problems only depicts the applicability of the HAPP model; more effective and efficient algorithms need to be explored to develop better performance for larger household sizes and more complex activity agendas. The characteristics and performance of several methods, including mathematical programming approaches and heuristic algorithms, are addressed below.

#### **4.3.1 General Approaches**

A number of solution algorithms are available for a general combinatorial optimization problem. Some well-known and useful methods are evaluated and

discussed as follows:

### 1. Relaxation methods

Among the several kinds of relaxation methods the most commonly used are linear relaxation and Lagrangean relaxation methods. Linear relaxation is a standard procedure to solve integer programming problems. Typically, there are two phases associated with this relaxation. First, integer constraints are released and the whole problem becomes a linear programming problem. Then, a branch-and-bound procedure is performed to find the optimal integer solution; computational efficiency becomes critical as the dimensionality of the problem increases. The simplex method can be used to solve such large-scale problems and obtains a lower bound for the original problem in a relatively short period of calculation time.

Lagrangean relaxation is another important category and is quite often used in mathematical programming. The relaxation of some constraints by adding the product of the constraints and the multipliers associated with them to the objective function produces a Lagrangean dual problem. Eventually, the determination of the value of the multiplier is the key point of solving the problem. How to generate effective values of the associated multiplier plays a critical role in obtaining good enough solution.

### 2. Decomposition methods

The decomposition method is particularly useful for problems with well-specified structure. Because of the structure ( typically, the constraint set contains several independent subsets of related variables and one constraint which includes all the

variables ), the decomposition method can be applied by fixing the value of some variables and separating the problem into a master problem which is mostly an integer programming problem and a sub-problem which is typically a linear programming problem. This kind of decomposition is termed Benders' decomposition (Magnanti, 1978; Mirchandani and Francis, 1990). The fixed value of those variables generates a Benders cut for the other variables. By repeating the process, decomposition methods will be terminated in a finite number of iterations.

### 3. Evolutionary programming methods

Evolutionary programming, which belongs to the category of stochastic search methods, is a process to simulate evolution (Fogel, 1990, 1993). Basically, this method is broadly similar to genetic algorithms (Fogel, 1990; Reeves, 1993) but differs in specific implementations. Genetic algorithms emphasize the genotype, that is, the coding structure and operations that transform that coding. The coding is taken originally as a string of bits and is manipulated with genetic operations, such as crossover, inversion and mutation, to generate lower generations of solutions. Evolutionary programming focuses on the phenotype, that is, the observed behavior of a particular coding structure. The coding of a given problem is expressed as an abstraction of phenotypic traits (expressed characteristics). There are no restrictions on the suitable representation, and no restriction on the possible transformation operations (mutations). Applications of evolutionary programming methods to the Traveling Salesman Problem (TSP) have been conducted successfully (Fogel, 1993). The extension of this approach to HAPP is

confounded by the difficulty of maintaining feasibility during the searching process.

#### 4. Heuristic methods

Heuristic methods constitute another important group of solution methods, especially for problems with the property of NP-hardness. VRP is NP-hard, and by deduction, VRPTW is also NP-hard. Since the formulation of HAPP is definitely more complicated than either the VRP or VRPTW, heuristic methods are well suited for consideration. The implicit advantage of using heuristic methods is the gain in speed compared to exact approaches. From the opposite viewpoint, the cost of such methods is the loss in quality of the solution obtained.

The general solution procedure alternatives are in Figure 3. In the figure, all of the methods listed on the upper part are used to generate upper bounds. Similarly, in the lower part, some popular relaxation methods, linear relaxation and Lagrangean relaxation, are used to generate lower bounds. The upper bounds can be generated by the use of such heuristic methods as modified savings method, insertion method, and stochastic search method (evolutionary programming method). The difficulty associated with the ride-sharing component challenges the solution process. Eventually, the optimum solution of HAPP will be obtained by narrowing the gap between the upper bound and the lower bound.

#### **4.3.2 Specific Applications of the Vehicle Routing Problem with Time Windows**

The Vehicle routing and scheduling problem has been a popular research subject.

Several excellent articles discussing various approaches have been published (Bodin, Golden, Assad and Ball, 1983; Bott and Ballou, 1986). From those publications, classifications of solution algorithms are made according to the characteristics of the algorithms:

1. Heuristic approaches

Due to the complex combinatorial nature of the Vehicle Routing and Scheduling (VRS) problem, heuristic techniques dominate the solution procedures, Four methodologies in this category are utilized:

- a. Cluster-first, route-second procedures;
- b. Route-first, cluster-second procedures;
- c. Saving or insertion procedures, and
- d. Exchange or improvement procedure.

2. Exact approaches

Although exact solution procedures are almost always desirable, such approaches have often been too computationally complex for practical implementation. Christofides, Mingozzi and Toth (1981a, 1981b) have derived two different branch and bound algorithms. The first uses dynamical programming to obtain effective lower bound, whereas the second uses an improved Lagrangean relaxation procedure to optimally solve small problems.

### 3. Interactive approaches

The third solution strategy is the simplest, but in some respects it may be the most powerful of the procedures. The methods involve either a simulation or cost calculator approach, or graphics ability to aid the decision maker. The obvious drawback to this approach is the skill and ability of the decision maker, particularly as the problem size and complexity increases.

### 4. Combination approaches

Combination of the above three approaches have proven very popular. Several studies combining mathematical programming and heuristic techniques have performed very well. Fisher and Jaikumar (1981) converted the VRS into a generalized assignment problem and a Traveling Salesman Problem by using Lagrangean relaxation, which assigns customers to vehicles without violating their capacity constraint.

The routing and scheduling problem with time windows is basically an extension of VRS (which contains only spatial aspects) by adding temporal aspects into consideration. Some excellent surveys of the formulation, characteristics, and solution procedures of the Routing and Scheduling Problem with Time Window (VRPTW) constraints can be found in Solomon and Desrosiers (1988) and Desrochers *et al.* (1988). Solomon and Desrosiers proposed a general mathematical formulation of various routing and scheduling problems with time window constraints such as the Traveling Salesman Problem (TSP), Vehicle Routing Problem (VRP), Shortest Path Problem (SPP), Minimum Spanning Tree Problem (MSP), Pickup and Delivery Problem (PDP), and

Dial-A-Ride Problem (DARP). Desrochers *et al.* surveyed the solution methods for the routing problem with time window constraints. Among the problems considered are the TSP, VRP, PDP, and DARP. The authors presented optimization algorithms based on branch and bound, dynamic programming, set partitioning, and approximation algorithms based on construction, iterative and incomplete optimization.

The literature on the generic VRPTW deals mainly with case studies. Heuristic methods are often used to generate near-optimal solutions. Pullen and Webb (1967) used heuristic techniques and focused on allocation of jobs to vehicles. Knight and Hofer (1968) presented a case study involving a development of a heuristic method to increase the utilization of vehicles. Madsen (1976) developed a simple algorithm based on Monte Carlo simulation to solve a routing problem with tight due dates. Route construction methods for VRPTW have been designed and analyzed by Solomon (1987) with the use of a sequential time-space insertion algorithm. In addition, such route improvement heuristics as k-opt, branch and bound procedure, and M-tour have also been conducted by Cook and Russell (1978), Solomon *et al.* (1986), and Russell (1977), respectively.

The approximation methods for VRPTW were derived through worst case analysis of heuristic in Solomon (1986), and Frieze *et al.* (1982) obtained similar findings in TSPTW. While the popular uses of heuristic techniques in solving large-size VRPTW, optimal approaches have lagged considerably behind. Kolen *et al.* (1986) extended the shortest q-path relaxation algorithm to problems with time windows. The largest problem solved to optimality involved 4 vehicles servicing 14 customers with tight time windows. Jornsten *et al.* (1986) also proposed a Lagrangean relaxation for the

computation of a lower bound for the VRPTW.

Recently, Koskosidis *et al.* (1992) extended the cluster-first, route-second algorithm of Fisher and Jaikumar (1981) by developing an optimization-based heuristic. They presented a new formulation based on the treatment of the time window constraints as soft constraints that can be violated at a cost and decomposed the problem into an assignment/clustering component and a series of routing and scheduling components. Russell (1995) incorporated both tour construction and local search tour improvement heuristics into a new hybrid heuristic method. A major promise of the paper is that embedding global tour improvement procedures within the tour construction process can lead to improved solutions.

#### **4.3.3 Solution Algorithms For VRPTW**

The solution procedures for the routing problem with time windows range from optimization algorithms to heuristic techniques. The optimization algorithms employ the two standard principles of implicit enumeration: dynamic programming and branch and bound. Branch and bound is mainly used to obtain integer solutions when combined with some other relaxation method. Alternatively, dynamic programming is mainly applied to solve single-vehicle problems; sometimes, it appears as subroutines in branch and bound methods. The elements of a dynamic programming algorithm are states, stages and recurrence equations that determine the value of the objective function at each state. For example, consider a standard shortest path problem on a graph  $G=(V, A)$ , where  $V$  is the

set of all vertices, and  $A$  is the set of all arcs. Each vertex represents a state; there are  $n$  states with  $n$  stages to go through, and the value  $c(j)$  associated with state  $j$  is the least cost value from the source  $o$  to the vertex  $j$ . The recurrence equations are:

$$c(0)=0$$

$$c(j)=\min \{c(i)+t_{ij} \}, j \in V \setminus \{i\}$$

Set partitioning methods constitute another type of solution algorithm for VRPTW with a different formulation. This type of problem is formulated with variables corresponding to feasible tours. The solution procedure proceeds by relaxing the integer constraints and generating a new column of minimum marginal cost. If the marginal cost is negative, then it is added to the linear program, the problem is re-optimized and column generation is applied again until no more negative marginal cost tour is found.

The savings method of Clarke and Wright (1964) is probably the first and the best known heuristic proposed to solve VRP. In this method, tours are created sequentially. Initially, there are  $n$  single-vertex tours, and then based on a measure of cost savings and subject to vehicle capacity constraints, two tours are combined into one. In the case of VRPTW, some modifications of the original savings method are necessary to accommodate such temporal aspects as time window constraints and waiting time.

#### 4.4 PROPOSED APPROACH TO THE SOLUTION PROCESS

Direct treatment of the HAPP with any exact method seems to be impractical because of the huge dimensionality embedded in the problem. The formulation of HAPP originating from the vehicle routing problem is constructed with an augmented network which is four times that of the original related vehicle routing problem. Moreover, the additional complexity associated with the included indices representing vehicle and person and additional constraints on temporal feasibility and resource budgets make the problem even more difficult. Heuristic methods are judged the best candidate for this sort of problem characterized by an irregular form of constraints (the use of decomposition method is ineffective). Observing the structure of the proposed model, we find that the limitation on the number of vehicles available within a household plays an important role in simplifying the original model. The proposed 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 various budget constraints.

With the relaxation on the number of available vehicles within a household, the original problem can be reduced to a VRPTW. Furthermore, assuming that the triangle inequality is satisfied, the solution of VRPTW is a lower bound to the original problem. The proof can be conducted by assuming that, without loss of generality, there is a typical tour with ride-sharing behavior of two persons sharing a vehicle on the network of  $n$  nodes,  $(1, \dots, i, j, \dots, k, \dots, n)$ . The objective function is represented by  $f$  (which is

assumed to be only a function of travel time), and the resultant tour has the following sequences:

0-i-0 for person 1

0-i-j-i-0 for person 2

The value of the objective function of this ridesharing problem is

$$f = t_{0i} + t_{i0} + t_{0i} + t_{ij} + t_{ji} + t_{i0} = 2 \bullet (t_{0i} + t_{ij}) + 2 \bullet t_{0i}$$

$$< 2 \bullet t_{0j} + 2 \bullet t_{0i} = (t_{0i} + t_{i0}) + (t_{0j} + t_{j0}), \text{ the spatial cost of VRPTW.}$$

where:  $t_{ij}$  is the spatial cost from node  $i$  to  $j$

0 is the source node

The triangle inequality must be enforced to enable the existence of the inequality in the previous equation. Finally, the proof can be completed by observing that the number of persons leaving home does not change, and that the time window constraints ensure that the temporal cost (waiting time) of the ridesharing problem should be at least as much as the relaxed problem if the original problem is feasible.

With this general rule, the solution procedure can be divided into a two-stage process. At the first stage, VRPTW is solved to generate initial feasible solutions; at the second stage, some enumerations of the tour with ride-sharing options are generated

subject to the number of available vehicles and a series of filters to screen out all illogical connections between activities. It can be easily proved that the solution generated from the first stage is feasible if any solution of the second stage is feasible. The proof is accomplished by observing that the feasible solution space of the first stage is larger than that of the second stage, and the objective function is the same. This offers a way of reducing the generation of all enumerations by eliminating all infeasible initial solutions. The procedure of the proposed heuristic method can be depicted by a two-stage process as in Figure 4. The first stage tries to generate all feasible solutions by solving a VRPTW. After the generation of a feasible solution, matching of ride-sharing options is conducted, subject to the number of available vehicles, by a process of matching-and-permuting, which matches the persons that perform ride-sharing behavior and permutes the order of activities to obtain an optimal tour. If there is no feasible ride-sharing option, go back to solve the VRPTW and find the next optimal solution, and repeat until the optimum is found.

#### **4.4.1 Solution Process of the First Stage**

A VRPTW-based problem with resource constraints is constructed with the introduction of a vehicle relaxation concept. The solution of the first stage facilitates an initial solution of the second stage that is discussed in a later section. The solution procedures of the first stage are motivated from an analysis of constrained shortest path problems and the concept of opportunity from savings methods. By adopting a shortest

path algorithm, it is possible to find the locally (with respect to the whole network) least cost tours. With the application of savings methods, the relative savings information provides excellent comparisons among the links to be inserted to the least cost tours. The combination of a constrained shortest path algorithm and savings method adopts the concept of a hybrid heuristic that integrates tour construction and tour improvement heuristic together in order to obtain better results. The algorithm is described as follows:

Given a multipartite network with  $N \times N$  nodes

step 0: set  $k=0$ .

step 1: calculate savings matrix  $S=[s_{ij}]$ ,  $s_{ij}=(t_{0i}+t_{0j}-t_{ij})-w_{ij}$

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

where  $w_{ij}$  is the minimal required waiting time to go from node  $i$  to  $j$

$awin_j$  is the early time window at node  $j$

$T_i$  is activity begin time at node  $i$

$s_i$  is activity duration at node  $i$

$tt_{ij}$  is travel time from node  $i$  to node  $j$

step 2: calculate opportunity cost matrix  $O=[o_{ij}]$ ,  $o_{ij}=\max_{m,n} \{S_{mn}\} - S_{ij}$

step 3: define the initial condition and the recurrence equation:

$$f_0(o)=0$$

$$f_{k+1}(j)=\min\{f_k(i)+o_{ij}+tt_{ij}+w_{ij}\}, j \in V \setminus \{i\}$$

step 4: check feasibility of including the next node; if yes, go to step 4; if not, go to step 6.

step 5:  $k=k+1$ , calculate  $f_k(N)$  for each node until finish all stages.

step 6: calculate the cost of the whole network based on the sum of the constructed tours and all the other single vertex tours left over.

step 7: If no nodes remains 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 possible loss of not combining the 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 checked for temporal feasibility, in terms of time window constraints, and person-node pair, which mates activity node with the person to perform. The scheduling part is handled by "moving forward", in which the arrival time to the activity node and the activity begin time are adjusted by moving forward the time frame to find the first available time point. Meanwhile, the maximum time to shift forward and shift backward are put into storage, and will be manipulated to fit the time window of the next node. If the combining of the next node or the savings is negative, a new defined cost that takes account of the spatial and temporal cost of the up-to-now tour and all the other single-node tours is calculated and stored in the objective list for further comparison. Otherwise, combination of the node continues until the end of the stage.

#### **4.4.2 Solution Process of the Second Stage**

In the second stage, the heuristic method described above is modified by an insertion algorithm in order to deal with large-size problems. A new term, "wasting," is introduced with a meaning similar to the savings method. The wasting is defined as the additional travel time needed to perform ride-sharing behavior, and is calculated by the

formula below:

$$\begin{aligned} \text{wasting}_{uw} &= tt_{0u} + tt_{uw} + tt_{wu} + tt_{u0} + tt_{0u} + tt_{u0} - (tt_{0u} - tt_{u0} - tt_{0w} - tt_{w0}) + w_{uw} \\ &= 2tt_{0u} + 2tt_{uw} - 2tt_{0w} + w_{uw} \end{aligned}$$

where:

$\text{wasting}_{uw}$  is the wasting of travel time when node u is car pooled by node w

$tt_{uw}$  is the travel time from node u to node w

$w_{uw}$  is waiting time at node w

The algorithm is motivated by the concept that a tour with more ride-sharing node-pairs is inferior to the one with fewer ride-sharing node-pairs, if the travel time from depot to the pickup node is small. The concept is illustrated by the example of a 4-node tour.

Without loss of generality, the tour of a single ride-sharing node-pair can be expressed as a sequence as below:

0-1-2-3-4-1-0

All of the nodes from node 1 to node 1 form a complete ride-sharing tour.

A simple case of a tour with multiple ride-sharing node-pairs can be expressed as:

0-1-2-3-1-0-4-0

In this case, there is a ride-sharing node-pair and a single independent node to form this tour.

The travel time needed for the former tour is less than the latter tour if the travel time from 0 to 1 is small. The condition is always true if the travel time matrix satisfies the triangle inequality. It is desired to put all the nodes into a single ride-sharing node-pair to obtain a less costly tour.

The algorithm is a modification of the savings method and can be described as follows:

- step 1: The "wasting" of ride-sharing and savings of combining two nodes into a tour is calculated from the travel time matrix  $T$  and waiting time
- step 2: The wasting and savings of each node-pair is sorted ascendingly
- step 3: The minimal wasting node-pair is selected to be the ride-sharing option, and then the savings method are applied to insert the other nodes into the first node-pair
- step 4: The side constraints are checked without violating the time window, budget and load constraints, and vehicle-node pair constraint. If violation of the side constraints is detected, select the node-pair with the next minimal wasting and go to step 3

The algorithm is repeated until all of the nodes are exhausted.

The algorithms mentioned can be characterized by the phenomena of available matching patterns, which are quite selective and regular. This special characteristic

simplifies the ride-sharing matching process into a combination of wasting and savings for all available nodes, and makes the algorithm efficient.

#### **4.5 COMPUTATIONAL RESULTS OF THE TEST CASES**

To test the applicability of the proposed model and solution procedures, a variety of different situations were selected. They range from the simplest form of VRP to a very complex form including person and vehicle transference and ride-sharing behavior.

The test cases analyzed were:

Case 1: Each member in the household has his/her own vehicle, and each activity can be performed by any of those members and must be performed only once.

Case 2: All of the members share a fixed number of vehicles, and only ride-sharing pattern is permissive.

Case 3: All of the members in the household share some vehicles, and ride-sharing behavior and drive-alone situation is allowed among household members.

Case 4: All of the household members share all the vehicles, and vehicle transference behavior is allowable only at eventually returning home nodes.

Case 5: All of the household members share the vehicles, and person transference behavior is only allowable at eventually returning home nodes.

Case 6: All of the activities are performed by one person with different vehicles.

Case 1 is the simplest case, which is a simple vehicle routing problem. In this case, ride-sharing and time window constraints are relaxed (time window range is extended to be from 6 to 24, which is the active period by assumption) and it becomes a

pure Vehicle Routing problem. Case 2 is complicated by adding ride-sharing options into the model, and only ride-sharing is allowed. The restriction on ride-sharing option is performed by setting that the other members (except the driver) of the tours are non-drivers and the time windows associated with the activities are allowed. Case 3 is even more complex and allows for the existence of ride-sharing and drive-alone behaviors which is depicted by relaxing time window constraints of case 2 (by shortening the range of associated time windows). Vehicle and person transference behavior can be tested by Case 4 and Case 5; in these cases, some of the activities are restricted to be performed by some specific vehicles and persons, respectively. In addition, transference behaviors are allowed only at eventually returning home nodes for these cases. Case 6 is an extreme case of performing all activities by different vehicles. It is treated by setting that each activity node should be visited by different vehicle.

The example data set of each case is presented in Appendix A, and the results are displayed in Figures 5 through 16. The solutions for all of the situations can be described alternatively by the time-space diagrams displayed in Figures 11 through 16, with the vertical axis representing temporal dimension, and the horizontal axis depicting the spatial aspect. The path in these diagrams represent the interactions of vehicle tours and person tours. Additional network figures (Figures 5 through 10) are presented to help understand separate vehicle and person path of each case. The network figure is displayed via a person tour and a vehicle tour that incorporate the tour of HAPP. The person tours depict the routing behavior associated with person-based variables, and the vehicle tours with vehicle-based variables.

These test problems are used to demonstrate the usefulness of HAPP in characterizing activity-based travel. The results of the tests displayed indicate that the formulation of such a problem is applicable.

The efficiency of the proposed algorithm can be illustrated by an example of a 3-node case (Figure 17). The original model contains a 6x6 multi-partite diagram. In the diagram, activity nodes 1 and 3 are visited by person 1, and node 2 by person 2. Person 1 is capable of performing activity independently, and person 2 has to be car-pooled by person 1. The route is depicted with the arrow headed lines in the diagram. After the reduction process, the model is reduced to a simpler and smaller 3x3 multi-partite diagram without ride-sharing option (which is only one fourth of the original problem). In this 3x3 diagram, node 1 has the same situation as in the previous diagram, but the ride-sharing behavior between person 1 and person 2 is first replaced with two single routes by person 1 and person 2, respectively. Finally, matching-and-permuting is applied to obtain a new route equivalent to the original model. This reduction simplifies the complication of the original model in model structure and computation time effectively.

## **CHAPTER 5**

### **DATA**

#### **5.1 INTRODUCTION**

Applications of this research have stringent requirements on data. Because the model that has been developed represents disaggregate activity/travel behaviors among different members in a household, detailed information on travel and activity participation for each member of the household, together with the associated existing transportation supply environment, are critical. In addition, the application presented herein is constrained to draw from existing data sources. Therefore, a review of available data sets was conducted in order to select the best suited data set. Some basic requirements of a suitable data set are reviewed and a list of necessary information relative to data evaluation and selection is provided.

#### **5.2 SELECTION OF DATA SET**

The proposed model system is characterized by its description of household activity patterns by exploiting a network-based model; it is important to select suitable data sets based on the specification of the proposed model. Based on the model system, we first list the categories of information needed for application of the model system.

They are:

1. transportation supply environment,
2. activity information on location, service time and time windows,
3. travel information including travel time and mode availability, and
4. activity and vehicle assignment.

Constrained by rigid data requirements, the data sets suited for the current research are limited. Two recently obtained data sets, the Orange County portion of the Southern California Association of Government (SCAG) Survey of 1991, and the Southwest Washington and Oregon Area 1994 Activity and Travel Behavior Survey received serious consideration because of their provision of detailed information on travel/activity diary, mode availability and options, and travel conditions. The SCAG Survey was conducted in 1991 in the area of Southern California including Orange, Los Angeles, Ventura, Santa Barbara, and Riverside Counties. This survey provides information on the travel/activity diary of each household member, travel and activity begin time and end time, trip purpose, origin and destination, vehicle usage, and travel cost. The data set from Portland and Southwest Washington additionally offers some information on in-home activities, and more detailed coding of travel and activity data. Moreover, this data set is geo-coded, a factor that is useful in calculating the travel time matrix that is required in the application of the proposed model system.

Reviewing the basic requirements of the data set and the information provided by each source, the data set from Portland was selected for analysis because it not only is complete but also provides more detailed activity/travel information.

### 5.3 SOUTHWEST WASHINGTON AND OREGON DATA SET

The 1994 Activity and Travel Behavior Survey was conducted in the Portland Metropolitan areas for a consecutive two-day period. The whole survey comprises of an Activity and Travel Survey, a Residential Choice Survey, and a Travel Behavior Survey. The sample includes 2,232 households and 5,125 persons with a total number of 67,016 activities performed and 37,965 trips made.

The Travel Behavior Survey is designed to investigate how residents might change their travel habits if travel conditions were different from what they are currently. During the survey, each participant is presented with eight tables outlining future travel options and travel conditions for a typical trip, and each table is followed by two questions about users' decisions and any change of behavior.

Residential choice information can be obtained from the Residential Choice Survey. The purpose of this survey is to determine the types of housing and residential settings of local residents. Residential choice involves trade-offs among housing costs, residential size, such community amenities as shopping, parks and recreation, and other factors that influence the type of community in which the resident chooses to live. This survey is designed to investigate what type of residential situation local residents might choose if they were considering a move.

During the survey, each participant is presented with a series of eight tables outlining possible future residential options. After evaluating each table, the participants are asked to indicate the housing option they would mostly likely choose and the possible

change on the number of vehicles needed, and the consideration of staying or moving.

The most important ingredient of the survey to this study is a two-day Activity and Travel Survey. In this survey, there are four elements that are significant to the composition of household activity pattern:

1. activity and trip diary,
2. household information,
3. person information, and
4. vehicle information.

The activity and trip diaries for the two-day period are recorded completely by listing the start time and location, and end time and location of each trip and activity. Information on the usage of each available vehicle and number of persons in that vehicle is also recorded.

All vehicles available for use by members of the responding household are recorded. Vehicles include cars, trucks, vans and motorcycles. Any company vehicles for personal use and garaged at home are also included in the vehicle survey. The information provided for each vehicle are: owner of the vehicle, year, make, model, type, fuel type, and reading on odometer for the beginning of the first day and the end of the second day.

The household information supplied includes: household size, household income, type of dwelling unit and length of ownership, number of phones, number of vehicles, number of activities and trips made each day, and the day that the survey was conducted.

The survey on household members extracted such personal information on each member

in that household as: age, gender, race, home language, employment status, occupation, student status, and holder of driver license.

The diaries associated with the information on vehicle, household, and members in the household constitute a unique household activity pattern for that household. They also provide the data is needed by the proposed model system.

#### **5.4 SUMMARY STATISTICS**

There are 2,232 households and 5,125 persons involved in this survey. The total number of activities and trips made is 67,016 and 37,965, respectively. Some basic summary statistics related to the activity and trip diaries are listed in Table 2.

The range of household size of all households is from 1 to 7 with an average household size of 2.29 and a standard deviation of 1.23. Average household annual income level is "10" which represents the range between \$50,001 and \$55,000. The average number of vehicles possessed by a household is 1.85 with standard deviation of 1.18, and the average number of vehicles for each person is 0.81. The total number of activities performed is 67,016, comprised of 33,881, and 33,135 for the first and the second day, respectively. The average number of activities for each household is about 15, with about 6.5 for each person in the household. The total number of trips is 37,965, distributed as 19,487 for the first day and 18,478 for the second. The average number of trips made is around 8.5 and 3.7 for each household and person, respectively.

Some statistics derived from the person survey are depicted in Table 3. The

average age of the sample respondents is 37. Forty eight percent of the participants are male and 74% own driver licenses. Most have only one job, and relatively few are afforded a flex-time working schedule.

**Table 2 Summary Statistics on Household Information**

Characteristics	Average	Std Dev.	Maximum	Minimum
Household Size	2.29	1.23	7	1
# Vehicles	1.85	1.18	9	0
# Day 1 Activities	15.18	6.62	62	1
# Day 1 Trips	8.73	6.49	44	0

\* Sample size=2232

**Table 3 Summary Statistics on Person Information**

Characteristics	Average	Std. Dev.	Maximum	Minimum
Age	37.16	21.03	91	0
Male	48%	NA	NA	NA
Driver License	74%	NA	NA	NA
Multi-Job	3%	NA	NA	NA
Tele Comm.	1%	NA	NA	NA
Flex Time	13%	NA	NA	NA
Length of Work (Yrs.)	2.32	2.60	6	0

\* Sample size=5125

## 5.5 REDUCTION OF DATA SET

In the application, some specific assumptions and simplifications associated with the Portland data set are made. First, the complete data set containing 2232 households is broken down into seven groups (see Figure 18), which are classified strictly by household size. Three (2-member, 3-member and 4-member) of the seven groups were selected for further analysis; the full sample size of 2-member, 3-member and 4-member household groups contain 866, 325, and 265 households respectively. Detailed analysis was performed on the subset of these that were headed by adult couples; thus the final subsamples of 2-member, 3-member, and 4-member households were comprised of having none, one, and two children, respectively. The stratification of the data set into these subsamples makes the sample simply organized and facilitates explanation of results. It is also helpful in simplifying the relationships between increased accessibility (reduced travel time) and the independent variables considered in the analysis that follows. In the current application of the proposed model, both in-home activities and non-auto related travel activities are excluded. Based on these criteria and on that of completeness of data, the total observations selected for analysis for the 2-member, 3-member and 4-member households (having zero, one, and two children, respectively and headed by adult couples) comprise 402, 193, and 153 households, respectively.

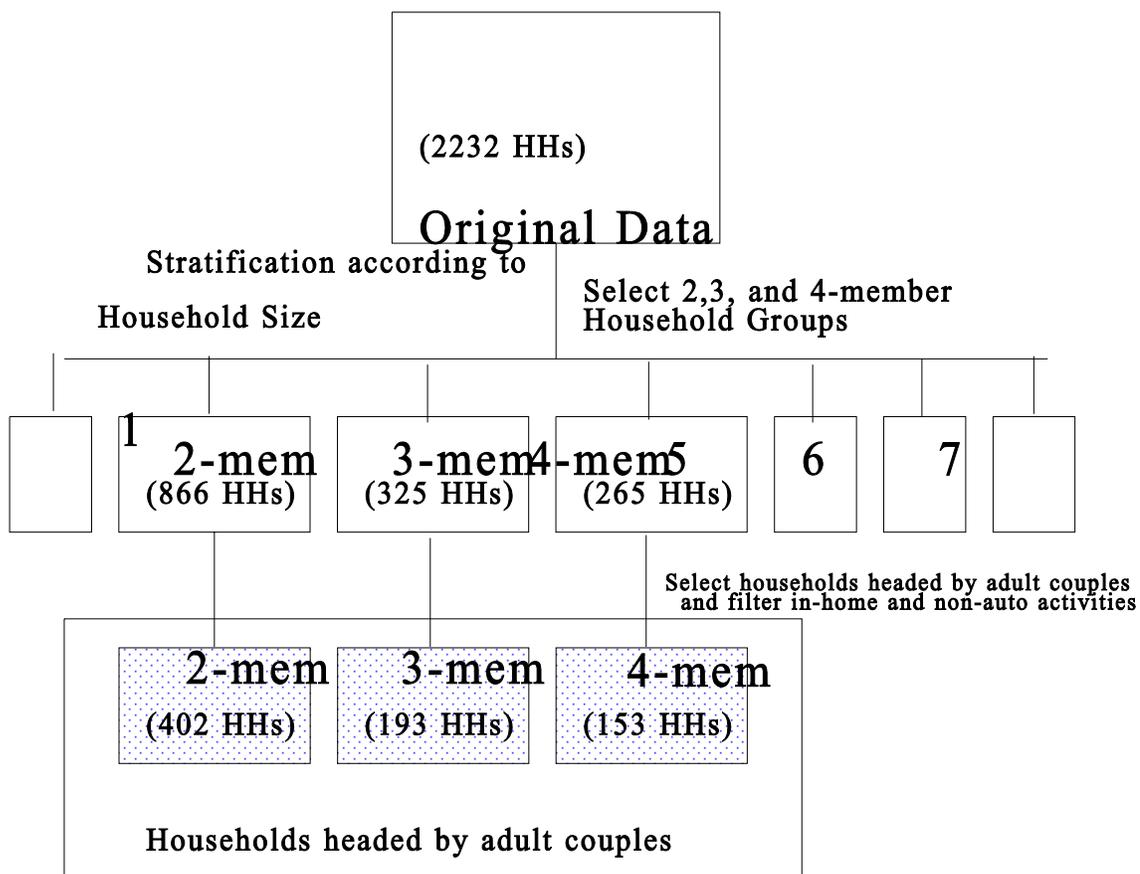
Table 4 displays summary statistics associated with the full three household groupings (i.e., without filtering for adult couples) by household size. The average

income level is around 10 (with the range of \$45,001-\$50,000) for each group, and average number of vehicles ranges from 1.91 to 2.32. Expectedly, the average number of activities and trips increases with respect to the size of the household. These same statistics are displayed for the selected data set (Table 5), part of the original 2-member, 3-member and 4-member groups in which all other households that do not contain working couples are neglected. The basic trend is similar to the original household groups but slightly different in magnitude. The income level of the selected data set is slightly lower than the income level of each group. On the contrary, the average number of vehicles is slightly higher for the selected data set. The numbers of activities and trips also have higher magnitudes.

Person information is depicted in Table 6. The mean age of respondents varies markedly between the subsample of 2-member households (53 years) and the other two (33 and 37 years for 3 and 4-member households, respectively). The percentage of household members owning a driver license also has a wide variation ranging from 97% for 2-member households to 55% for 4-member households, the latter figure obviously somewhat related to the presence of children. The proportion of respondents with multiple-job and tele-communication options is quite limited. Similarly, the proportion of persons with a flex-time work schedule is considerably small.

Statistics related to the activity diaries are presented in Tables 7 and 8. Table 7 shows trip purpose classification; "meal" trip is the most frequent trip category (almost twenty percent of all trips) followed by working trip category (about fifteen percent of all trips). In all, trips with relatively fixed time windows (e.g., meal, work, medical care

and



school trips) occupy almost one third of the trips made by the sample. Travel time, waiting time and activity duration are displayed in Table 8. The average travel time is about 16 minutes for 2-member and 3-member households, and 18 minutes for 4-member households; the waiting time ranges from 10 to 19 minutes for all cases for which a "waiting" component was indicated. The average activity duration has ranges from 120 minutes for 4-member households to 200 minutes for 3-member households. The average numbers of trip chains are 2.46, 3.35, and 3.24, respectively for 2, 3, and 4-member households. The average number of trips in a trip chain are 1.66, 1.67 and 2.57 for each group.

**Table 4 Summary Statistics on Segmented Household Groups**

Characteristics	Average	Std. Dev.	Maximum	Minimum
<b>2-member Household (N = 866)</b>				
Income Category	10.36	3.66	14	1
# Vehicles	1.91	0.91	9	1
# Day 1 Activities	13.49	4.46	27	2
# Day 1 Trips	7.56	4.16	23	0
<b>3-member Household (N = 325)</b>				
Income Category	10.62	3.41	14	1
# Vehicles	2.32	1.08	9	0
# Day 1 Activities	18.87	6.25	37	4
# Day 1 Trips	10.95	5.41	30	0
<b>4-member Household (N = 265)</b>				
Income Category	10.14	3.42	14	1
# Vehicles	2.25	0.95	9	0
# Day 1 Activities	26.86	7.40	62	4
# Day 1 Trips	15.81	7.05	41	0

**Table 5 Summary Statistics on Selected Households**

Characteristics	Average	Std. Dev.	Maximum	Minimum
<b>2-member Household (N = 402)</b>				
Income Category	9.30	3.20	13	1
# Vehicles	2.03	0.79	6	1
# Day 1 Activities	13.90	4.48	27	23
# Day 1 Trips	7.90	3.84	23	2
<b>3-member Household (N = 193)</b>				
Income Category	10.08	2.91	13	2
# Vehicles	2.52	0.94	7	1
# Day 1 Activities	19.05	5.91	36	6
# Day 1 Trips	11.36	4.97	27	2
<b>4-member Household (N = 153)</b>				
Income Category	9.43	2.95	13	1
# Vehicles	2.28	0.91	6	1
# Day 1 Activities	27.45	6.86	45	11
# Day 1 Trips	16.63	4.16	40	2

**Table 6 Summary Statistics on Selected Person Information**

Characteristics	Average	Std. Dev.	Maximum	Minimum
2-member Household (N = 804)				
Age	52.64	15.19	88	18
Male	50%	NA	NA	NA
Driver License	97%	NA	NA	NA
Multi-Job	2%	NA	NA	NA
Tele Comm.	1%	NA	NA	NA
Flex Time	15%	NA	NA	NA
3-member Household (N = 579)				
Age	33.52	18.14	88	0
Male	52%	NA	NA	NA
Driver License	78%	NA	NA	NA
Multi-Job	2%	NA	NA	NA
Tele Comm.	1%	NA	NA	NA
Flex Time	10%	NA	NA	NA
4-member Household (N = 612)				
Age	37.16	21.03	82	1
Male	47%	NA	NA	NA
Driver License	55%	NA	NA	NA
Multi-Job	5%	NA	NA	NA
Tele Comm.	2%	NA	NA	NA
Flex Time	13%	NA	NA	NA

**Table 7 Distribution of Main Trip Purposes on Selected Households**

Trip Purpose	Number of Observations Percentage(%)		
	2-member HH	3-member HH	4-member HH
Meal	491 ( 18%)	278 ( 16%)	592 ( 26%)
Work	419 ( 15%)	282 ( 16%)	269 ( 12%)
Medical Care	49 ( 2%)	25 ( 1%)	20 ( 1%)
School	23 ( 1%)	74 ( 4%)	181 ( 8%)
Other	1758 ( 64%)	1101 ( 63%)	1211 ( 53%)
Total	2740 (100%)	1760 (100%)	2273 (100%)

**Table 8 Summary Statistics of Trip Diaries on Selected Households**

Characteristics	Average		
	2-member HH	3-member HH	4-member HH
Sample Size	2740	1760	2273
Travel Time(min.)	15.68	15.35	18.36
Waiting Time(min.)	19.19	10.38	15.11
Activity Duration(min.)	185.48	201.08	119.09
# Trip Chains	2.46	3.35	3.24
# Trips/Chain	1.66	1.67	2.57

## CHAPTER 6

### EMPIRICAL APPLICATIONS

#### 6.1 INTRODUCTION

In this chapter, an application of the model system to real world conditions is provided using the data set from the Southwest Washington and Oregon Area Activity and Travel Survey of 1994, which is described in Chapter 5. The travel time matrix corresponding to these data, which is one of the required elements in the application, is obtained by using data geo-coded with TRANPLAN format. An adjustment procedure is used to establish congruence between reported travel times and geo-coded travel times. Calculations involving both travel time and the proposed accessibility measurement based on the concepts of space-time prism discussed in Chapter 2 are presented to measure the potential improvement over observed household activity patterns that may be achieved with optimal behavior. The results of this application of HAPP demonstrate the usefulness of the proposed model. Specifically, the distributions of the potential travel time savings and increase in the measurement of accessibility through optimal activity scheduling, trip chaining, and ridesharing for different household groups are presented. The factors that underlie these improvements are investigated by performing OLS (Ordinary Least Square) regression analyses between the potential reduction in travel time (increased accessibility) and life-style, socio-demographic, activity diary-related variables. The results of the estimations show that household size is not a significant determining factor; on the contrary,

the presence of trip chaining is very important in explaining the potential improvements in travel time and accessibility.

## **6.2 ESTIMATION OF TRAVEL TIME MATRIX**

The travel time matrix, which is a key component of HAPP, is estimated by first converting get-coded data into the standard coordinate format of TRANPLAN. Then the data are manipulated through TRANPLAN in order to get skim trees from which the travel time table for all O-D pairs is obtained. There are 1,260 TAZs (Traffic Analysis Zones), 21,868 links and 9,703 nodes associated with the Southwest Washington and Oregon Area (see Figure 19). The network travel times are obtained from TRANPLAN non-peak-hour travel times.

A comparison between the network travel time and the reported travel time is made in order to find the perceived difference between revealed and calculated travel time. The comparison indicates a tendency of the respondents to "round off" travel time into 5- or 10-minute categories for longer travel times, and, in most cases, to report a longer travel time (of 5 or 10 minutes) for trips with network travel times less than 5 minutes. Some adjustment on the network travel time is therefore necessary to reconcile network times with the diary information. Tables 9-11 list the reported and network travel times and the mean ratio between these two measures for 2-member, 3-member and 4 member household groups. Figures 20-22 illustrate the mean ratio within the range of one standard deviation from the mean. The diagrams indicate that the respondents consistently over-estimate low travel time values (relative to network travel

times), especially for the "below-10-minute" categories, and systematically round off to 5-minute or 10-minute categories. The network and reported travel times are brought into congruence by a two-step process. The first stage of the process involves multiplying the network times by the mean adjusted ratio; this global adjustment to network travel time is then further adjusted based on individual households' revealed differences in perception. In this way, any perceived differences between households can be accounted for rationally.

Specifically, network travel time is adjusted by the following process:

1. Adjusting by multiplying the mean perception ratio measured from each category in Tables 9-11, and
2. Multiplying the balance factor of individual revealed difference, which can be obtained from the ratio between the total individual reported travel time over the total adjusted network travel time.

An example is provided in the following table to demonstrate the process. In the displayed example, network travel times are generated from TRANPLAN, and reported travel times are obtained from survey data. The adjusted network times in Column 4 are obtained by multiplying the network time by the associated perception ratios. The final adopted network times are obtained by multiplying the individual balance factor of each household by the associated adjusted network times ( the balance factor is the ratio between total reported travel time and total adjusted network travel time).

Following this adjustment on travel time, the sum of the reported travel times will be equal to the sum of the corresponding network travel times for each household, providing the base for comparison between existing and normative behavior.

Network Travel Time	Mean Perception Ratio	Reported Travel Time	Adjusted Network Travel Time	Adopted*
5	2.88	13	14.4	12.12
8	1.72	13	13.76	11.58
12	1.37	15	16.44	13.84
17	1.29	15	21.93	18.46
Total		56	66.53	56

\* Obtained by multiplying the balance factor by the associated adjusted network time  
 Balance factor=Total Adjusted Network Time / Total Reported Time

**Table 9 Mean Adjust Ratio Between Reported and Network Travel Time  
(2-member Household)**

Network Travel Time (min.)	Mean Perception Ratio*	Standard Deviation	Number of Trips
0 ~ 5	2.88	2.63	766
6 ~ 10	1.72	1.12	806
11 ~ 15	1.37	0.71	534
16 ~ 20	1.29	0.80	264
21 ~ 25	1.10	0.57	182
26 ~ 30	0.97	0.44	92
31 ~ 40	0.91	0.47	70
41 ~ 50	0.62	0.41	17
51 ~ 60	0.36	0.30	9
TOTAL			2740**

$$* \text{ Mean Perception Ratio} = \frac{\text{reported travel time}}{\text{network travel time}}$$

\*\* The remaining trips were either non-automotive or outside of the study area

**Table 10 Mean Adjust Ratio Between Reported and Network Travel Time  
( 3-member Household )**

Network Travel Time (min.)	Mean Perception Ratio*	Standard Deviation	Number of Trips
0 ~ 5	2.75	2.33	418
6 ~ 10	1.54	0.88	545
11 ~ 15	1.44	0.73	316
16 ~ 20	1.24	0.72	210
21 ~ 25	1.12	0.60	118
26 ~ 30	1.19	0.51	63
31 ~ 40	0.88	0.46	64
41 ~ 50	0.89	0.30	17
51 ~ 60	0.87	0.29	5
> 60	0.23	0.00	4
<b>TOTAL</b>			<b>1760**</b>

$$* \text{ Mean Perception Ratio} = \frac{\text{reported travel time}}{\text{network travel time}}$$

\*\* The remaining trips were either non-automotive or outside of the study area

**Table 11 Mean Adjust Ratio Between Reported and Network Travel Time  
(4-member Households)**

Network Travel Time (min.)	Mean Perception Ratio*	Standard Deviation	Number of Trips
0 ~ 5	2.58	2.62	721
6 ~ 10	1.71	0.96	600
11 ~ 15	1.23	0.64	378
16 ~ 20	1.07	0.47	196
21 ~ 25	1.04	0.46	124
26 ~ 30	1.03	0.46	66
31 ~ 40	0.96	0.35	35
41 ~ 50	0.97	0.46	16
51 ~ 60	1.38	0.01	2
TOTAL			2138**

$$* \text{ Mean Perception Ratio} = \frac{\text{reported travel time}}{\text{network travel time}}$$

\*\* The remaining trips were either non-automotive or outside of the study area

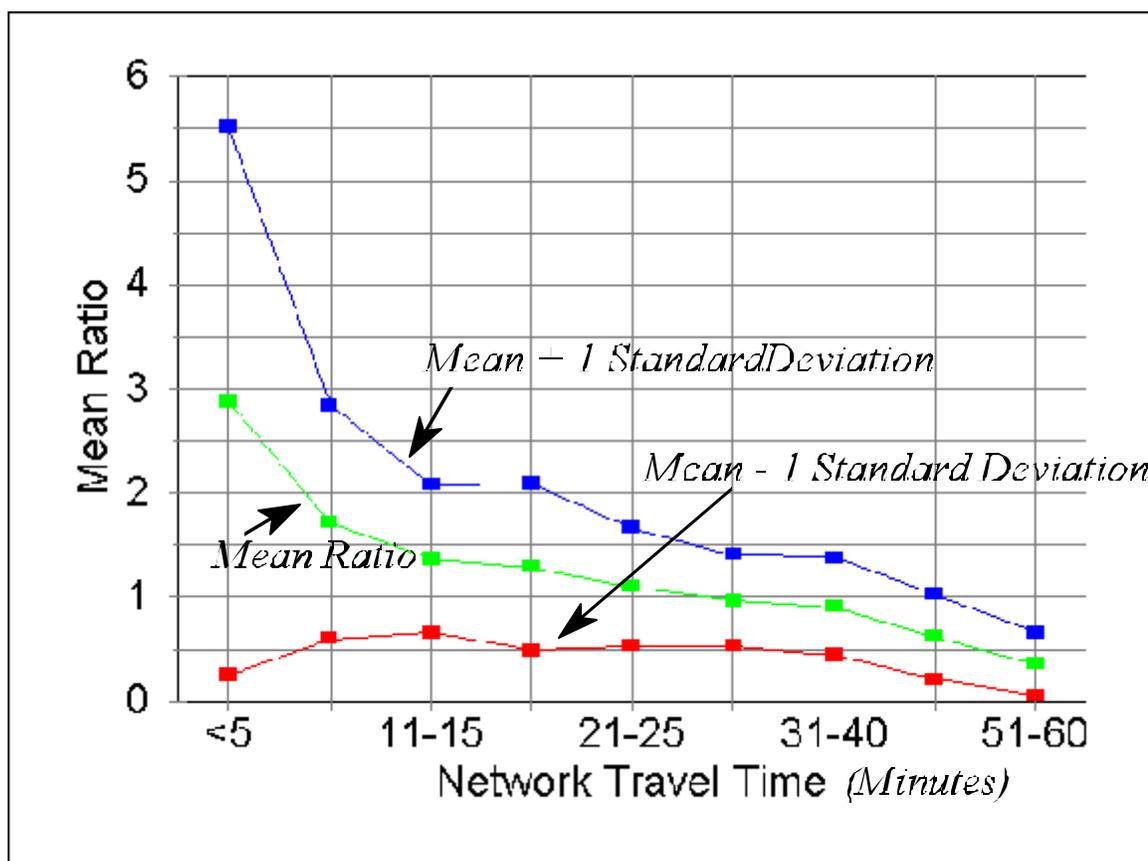


Figure 20 Travel Time Perception Ratios (2-member Household)

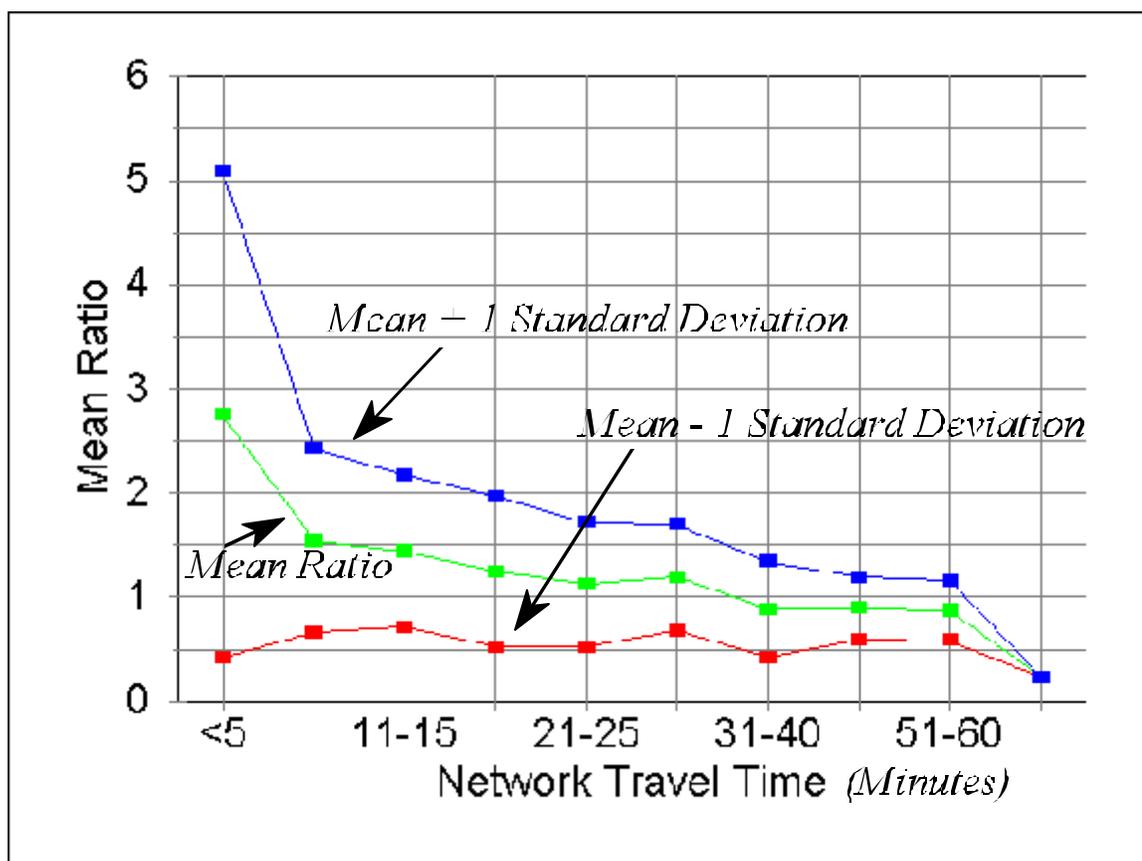


Figure 21 Travel Time Perception Ratios (3-member Household)

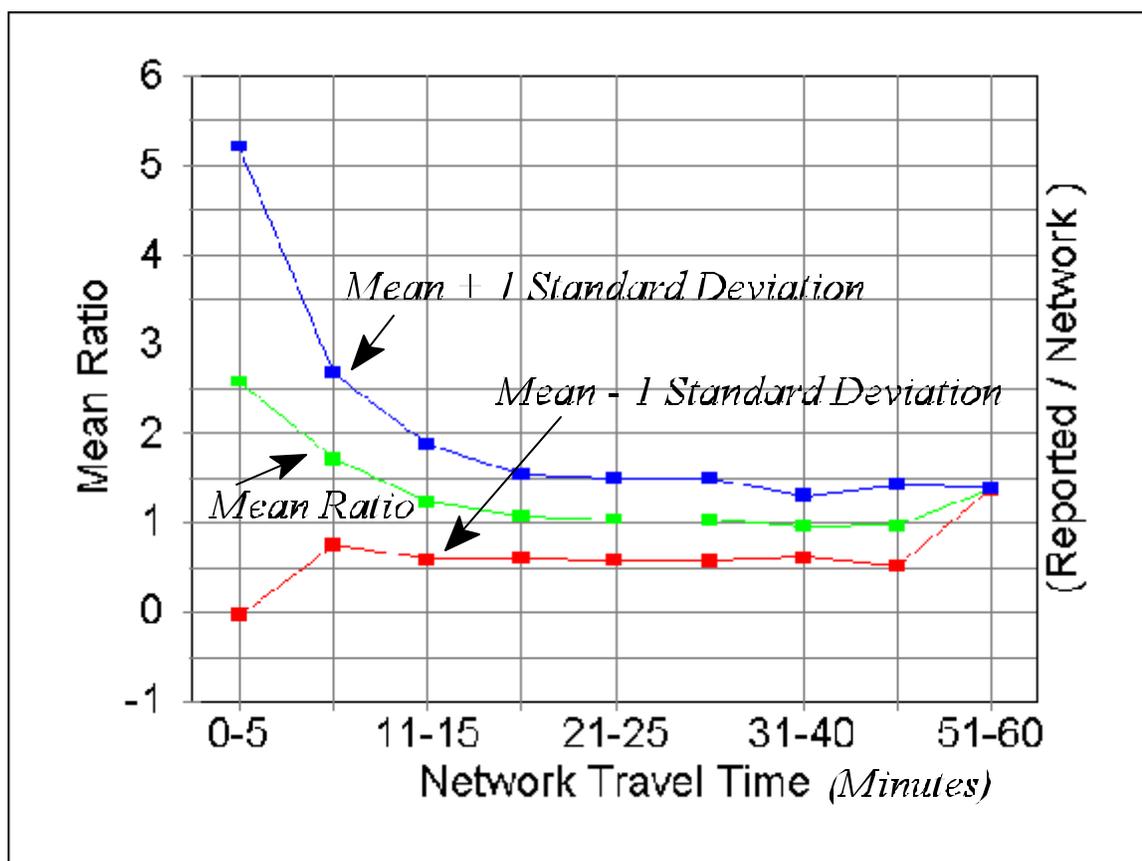


Figure 22 Travel Time Perception Ratios (4-member Household)

### **6.3 APPLICATION OF HAPP IN THE MEASUREMENT OF POTENTIAL ACCESSIBILITY IMPROVEMENT**

An application of HAPP is presented to evaluate the potential improvement in the measurements of travel time and household accessibility that may be achieved with "optimal" travel behavior. Observed activity patterns are the result of decisions made by households subject to restrictions placed either by the transportation supply environment or resulting from such other unobserved factors as imperfect information, household rules, etc. It is a description of the current household situation. Alternatively, optimal activity travel patterns are normative behaviors that are expected to exist under conditions constrained only by the spatio-temporal conditions described in Equations 1-37. The optimal activity pattern used in this analysis is based on minimizing the sum of travel times and waiting times in a daily household activity diary, and discouraging people from making unnecessary out-of-home trips. The selection of household travel times and activity waiting times as an objective is somewhat intuitive in nature, and the process of preventing people from making unnecessary trips can be achieved in the objective function by minimizing the number of persons going out-of-home with a large cost constant. The gap between these two situations (i.e., optimal and observed) can be construed to be the potential benefit that may be achieved through elimination of these unobserved restrictions. As such, it can play a positive role in evaluating the limits of the potential of policy alternatives to impact daily activity patterns.

In this application, accessibility is measured by the volume of the space-time prism

(shaded diamond area) indicated in Chapter 2. The results of the calculation of potential improvement through optimal behavior can be illustrated by measurements of both absolute and relative improved accessibility and travel time. The measurements are defined as:

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

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

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

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

where  $ACC_r$ : relative percentage change in accessibility measure with respect to the observed measure

$TT_r$ : relative percentage change in travel time with respect to the observed measure

$ACC_a$ : absolute change in accessibility measure

$TT_a$ : absolute change in travel time

$ACC_{obs}$ : observed accessibility measurement

$ACC_{opt}$ : optimized accessibility measurement

$TT_{obs}$ : observed travel time measurement

$TT_{opt}$ : optimized travel time measurement

In the results that follow, the "optimal" values for the various measures for each household were obtained using the solution procedure presented in Chapter 4 to solve the mathematical programming problem described by Equations 1-36. The "observed" values were simply calculated from the observed data contained in the activity diaries.

For all of the 402 households in the 2-member household group, the household travel time is reduced and household accessibility is improved. Figures 23 and 24 describe the distributions of the relative (in percentage) and absolute difference in accessibility. These distributions are seen to be similar and resemble negative exponential type distributions; a large portion of the households only have minor improvement. The distribution of the improvements in relative and absolute travel times with optimal behavior are illustrated in Figures 25 and 26; these two distributions differ from each other. The relative measurement is distributed with two peaks in the less-than-10% and 30%-40% ranges; while the absolute measure of potential improvement is similar to the distribution of accessibility improvement which has a relatively monotonically decreasing curve.

This procedure was also applied to the 3-member household group; results are displayed in Figures 27-30. The patterns of these distributions are somewhat similar to those in the 2-member household group (although there is difference in the magnitude) except for the measurement of relative travel time, which is much more uniformly distributed in the range from 20% to 70%.

Results for the same procedure is presented for 4-member households in Figures 31-34. The patterns of this group are substantially different from the previous two groups, which

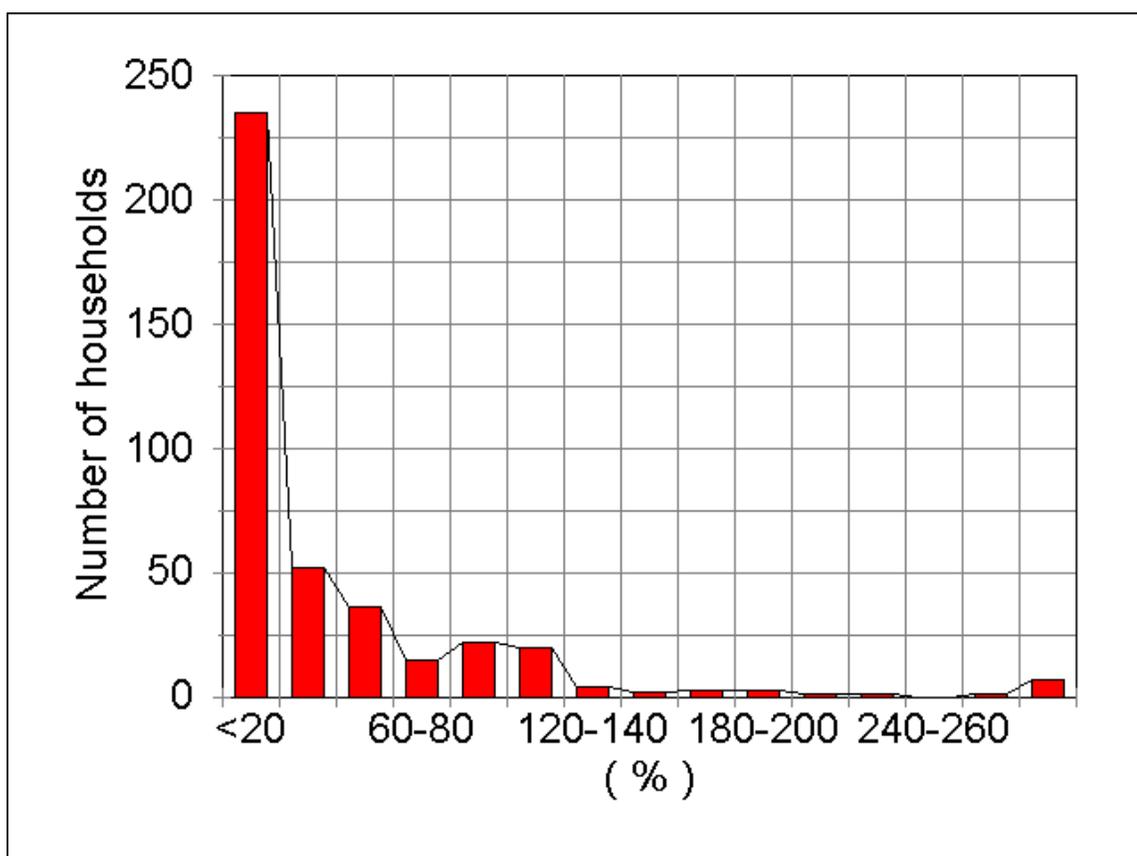
drop off dramatically from the smallest category of improvement and then tend to be smooth; the reason of these differences might be the presence of more children in this household group.

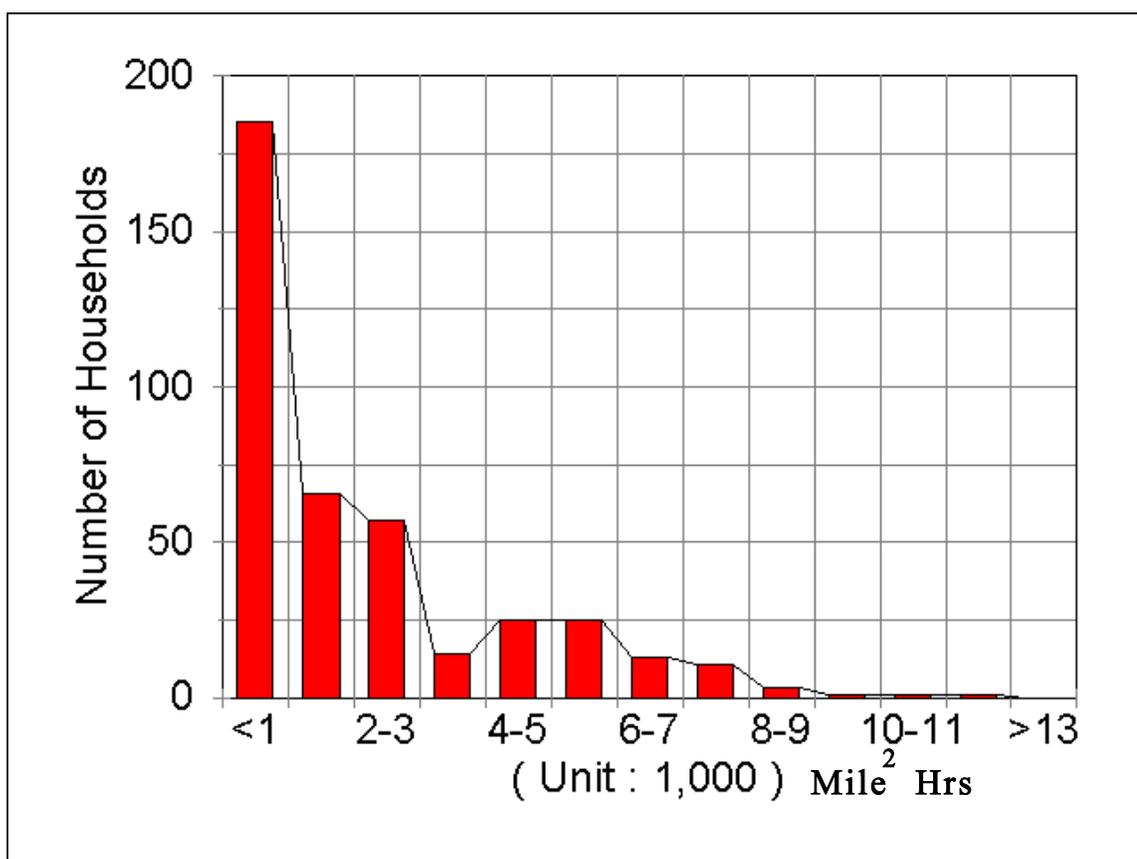
To summarize the comparisons among these patterns for different household groups, it is concluded that there is a tendency in which the presence of more children results in more smooth distributions from the beginning of the savings distribution achieved with optimal travel behavior. One possible explanation is that the presence of more children, especially for those under age 12, leads to a more complex activity diary, and thus results in a more likely inefficient arrangement of this diary.

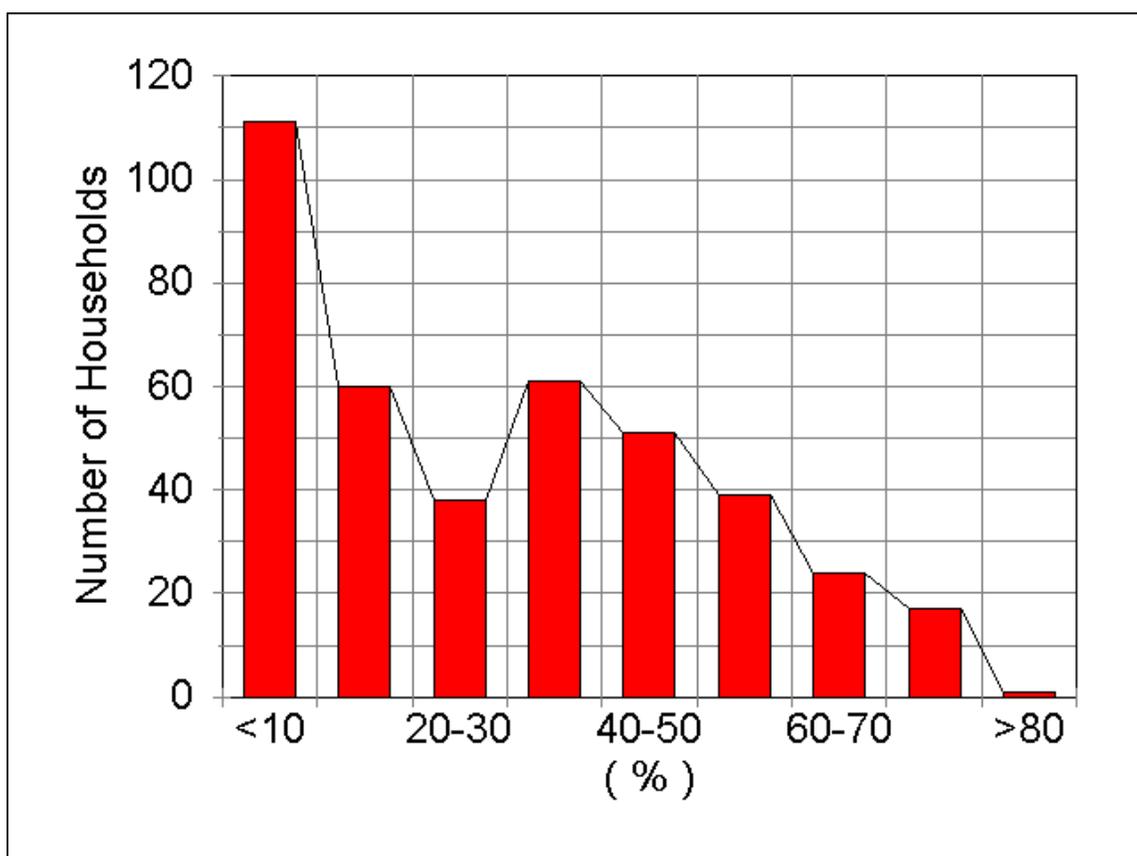
For all groups, the rearrangement of activity patterns through optimal behavior is shown to lead to potentially significant improvements in travel times and accessibility, and therefore can benefit to such aspects as savings of fuel consumption, efficient usage of household transportation supplies, and reduction of automobile usage with respect to ride-sharing behavior.

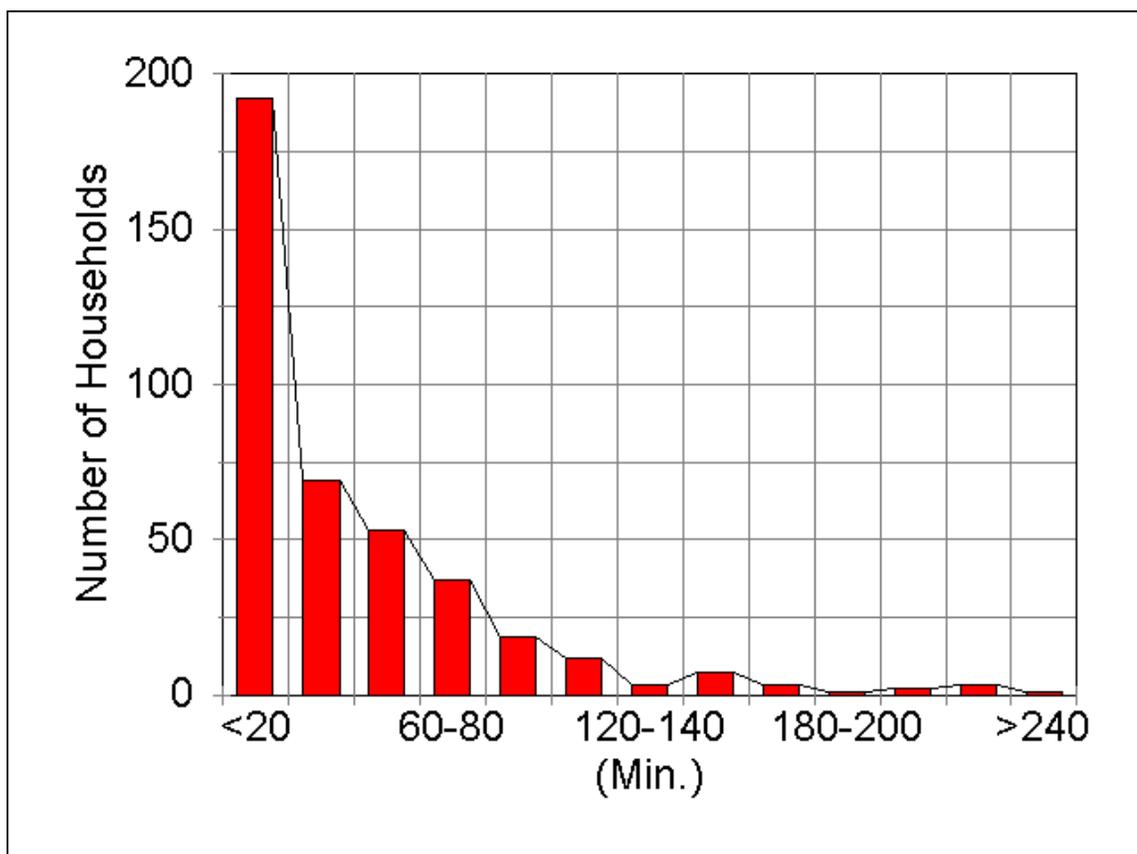
#### **6.4 RELATIONSHIP BETWEEN POTENTIAL IMPROVEMENT AND DEMOGRAPHIC CHARACTERISTICS**

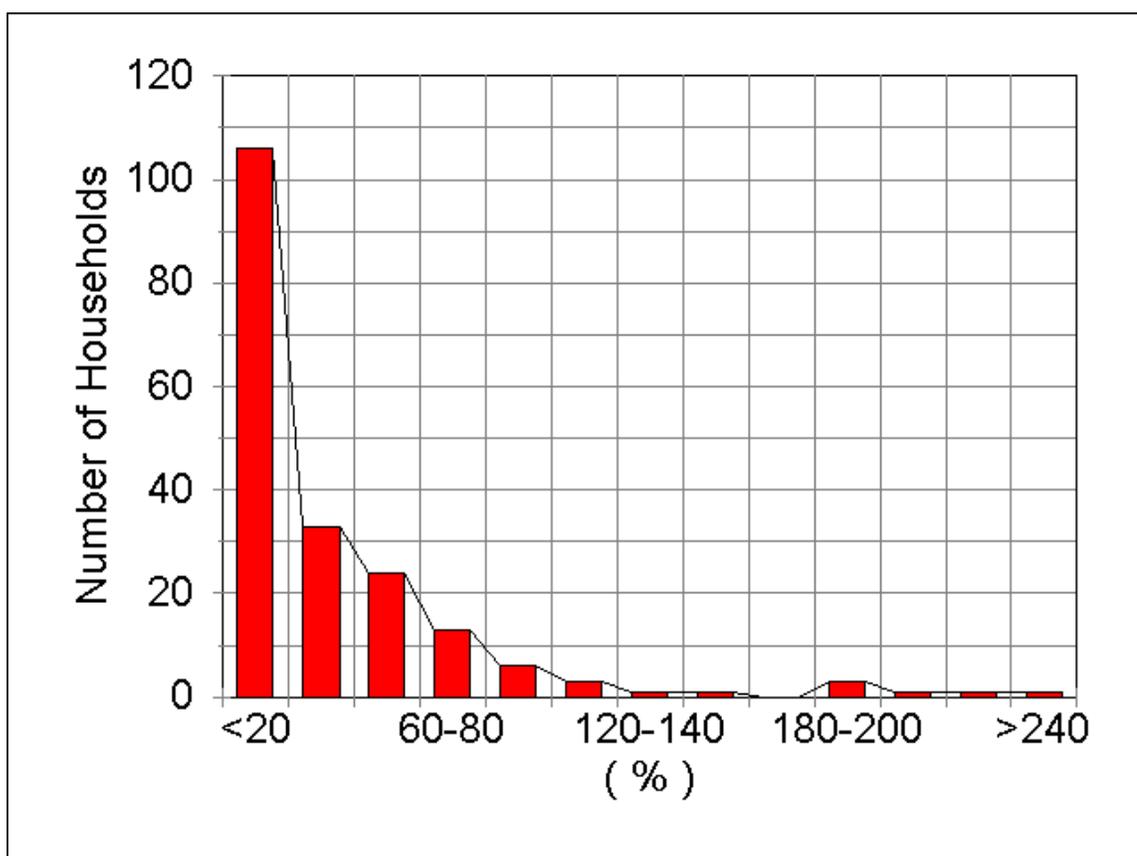
Such demographic variables as the existence of children under age 5, 12, 16, number of driver's license holders, and other household socio-economic variables, and such instrumental variables as the presence of ride-sharing and trip chaining are considered in regression analyses

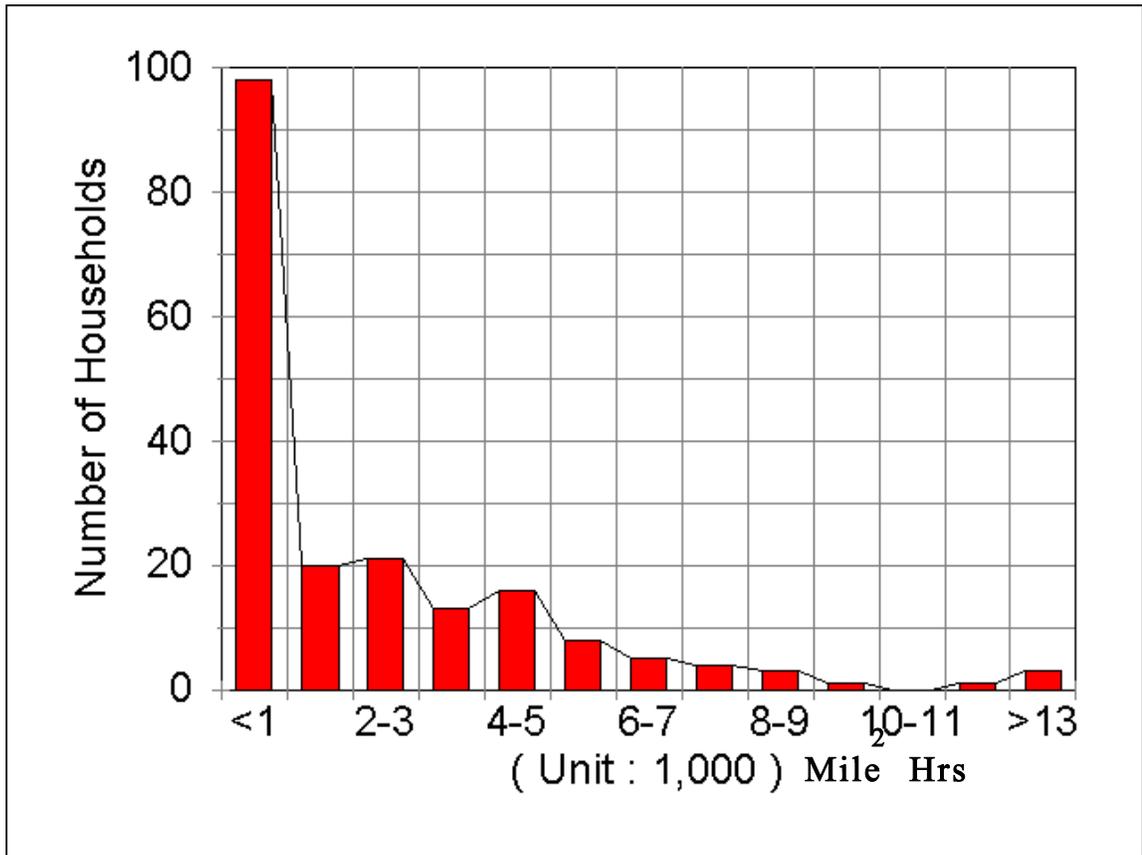


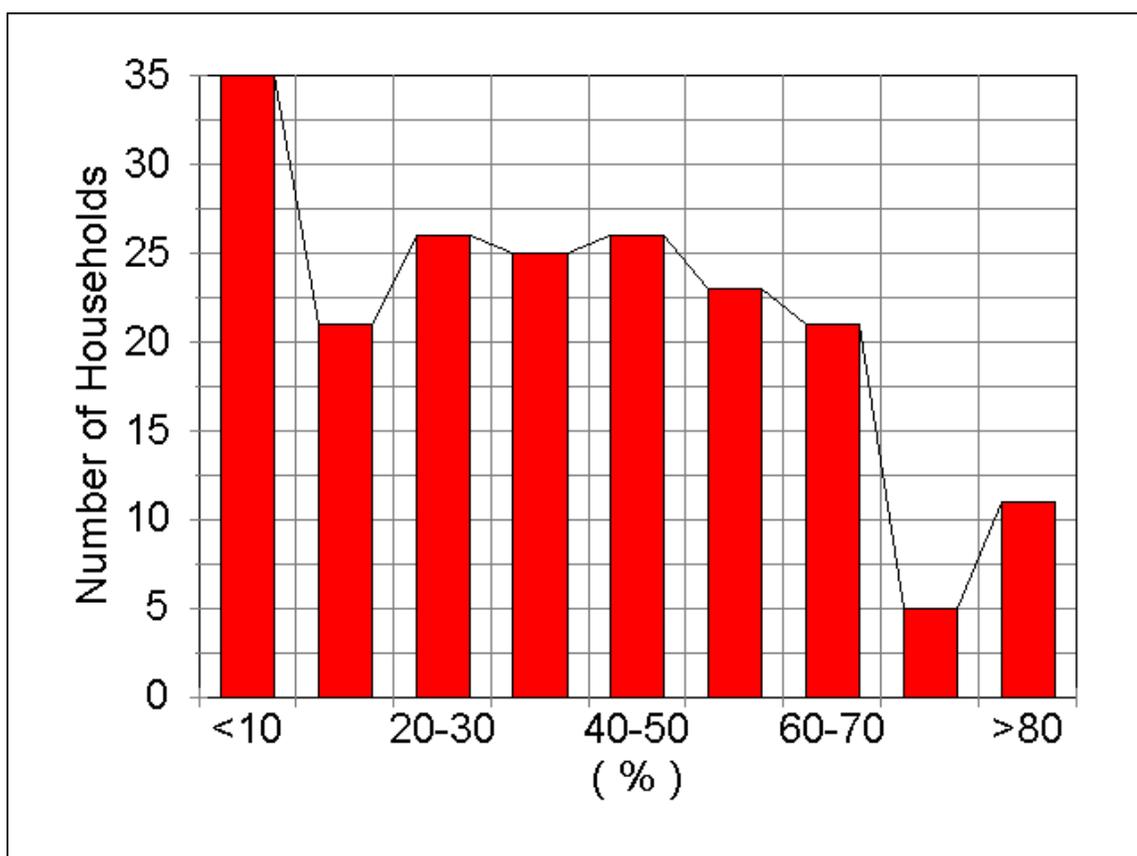


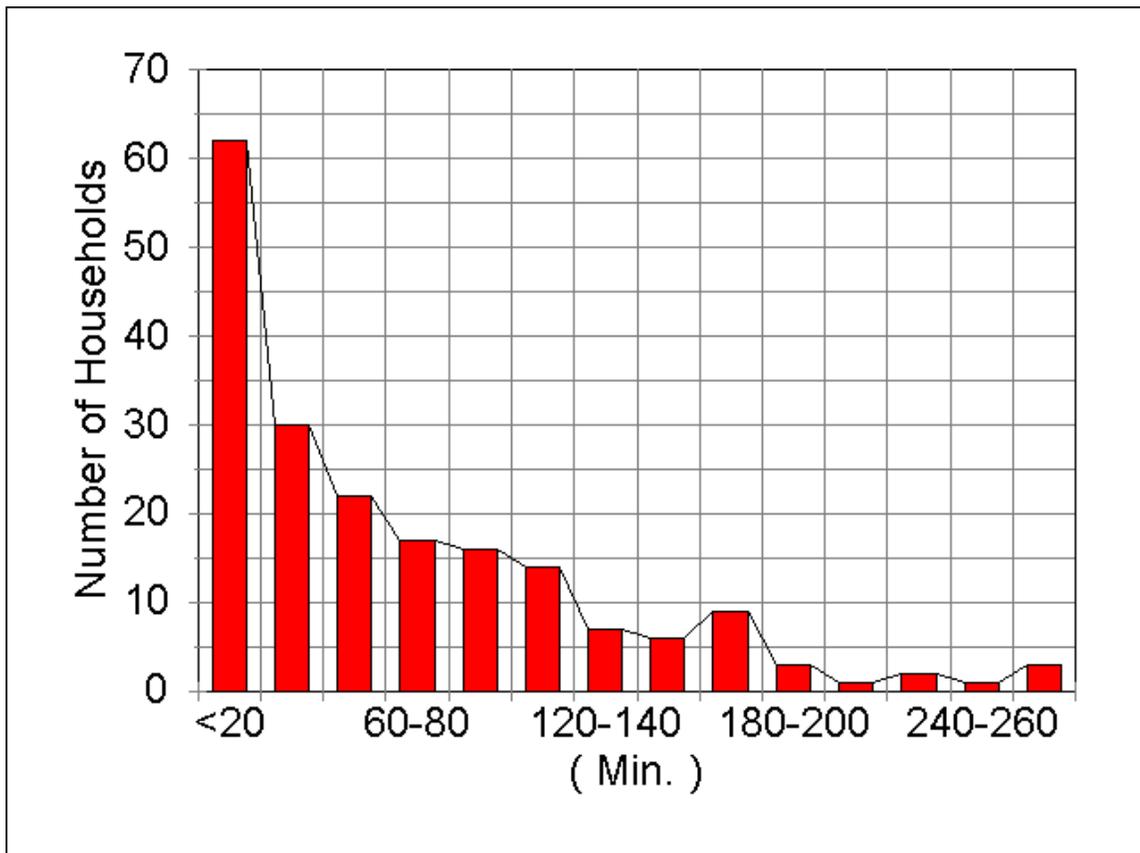


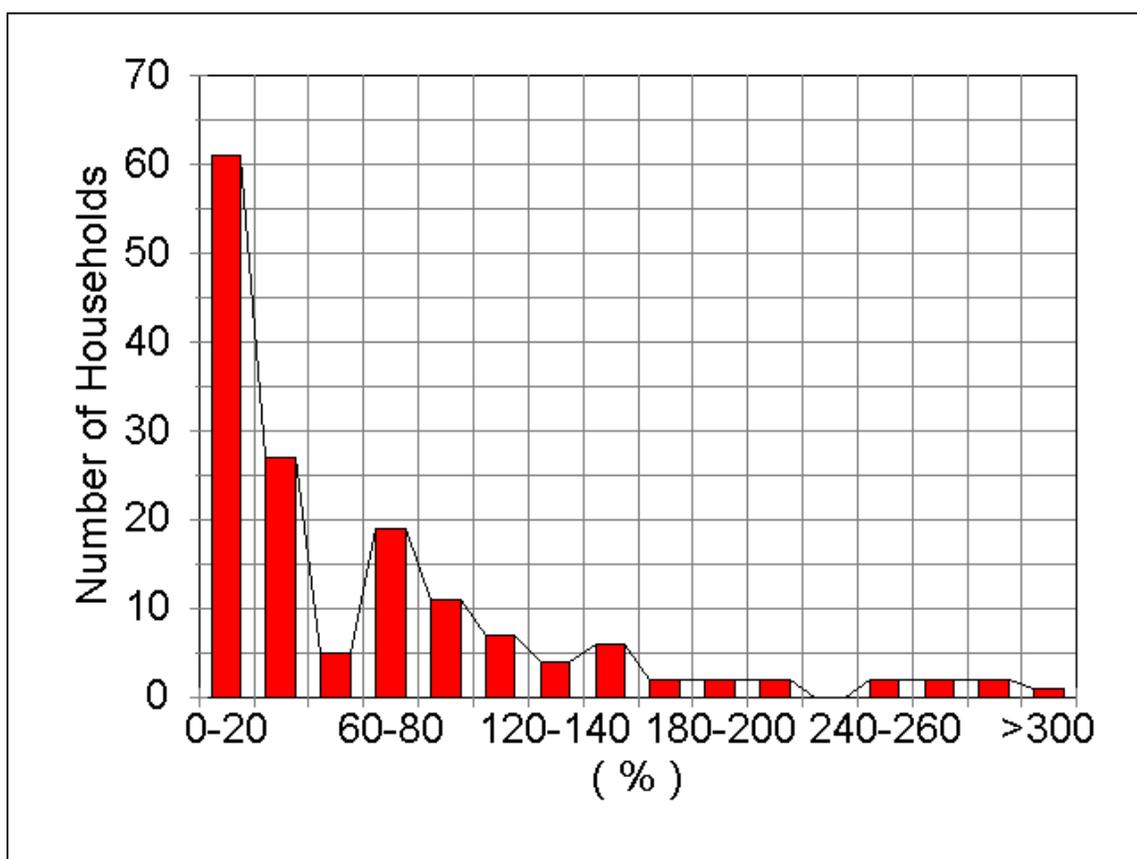


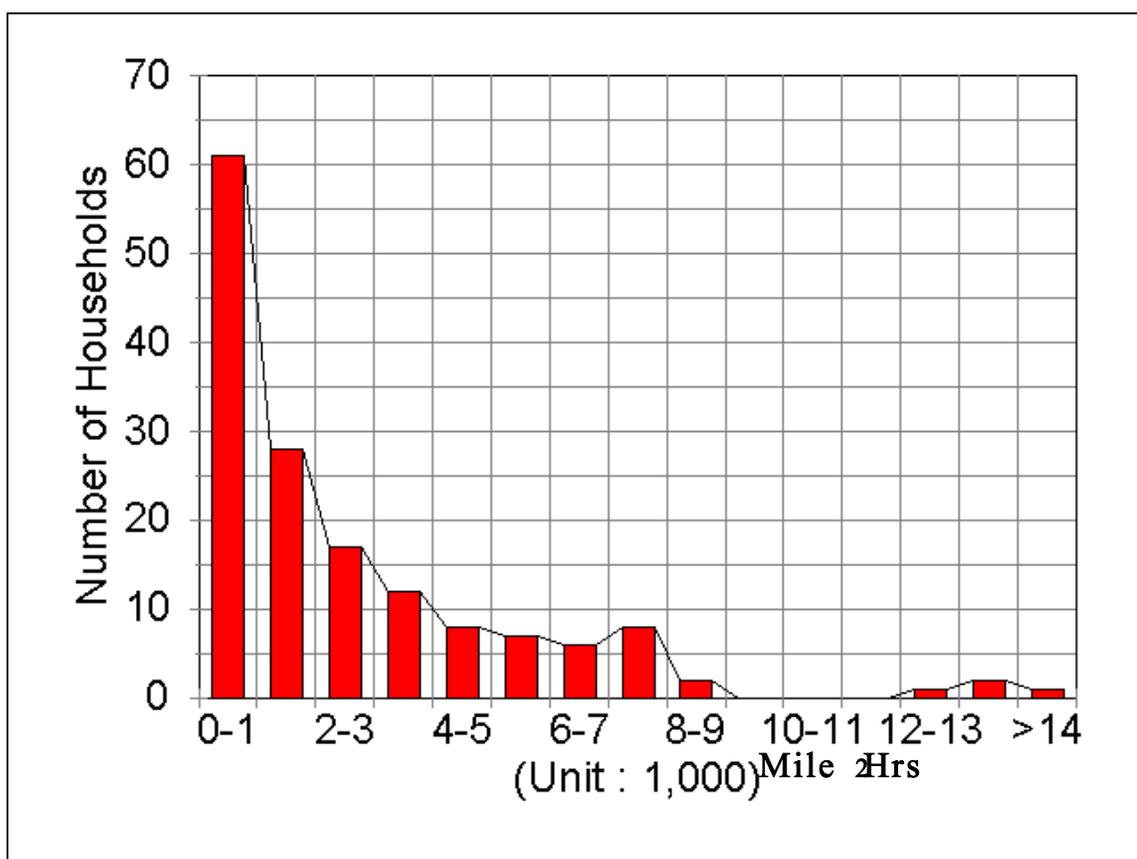


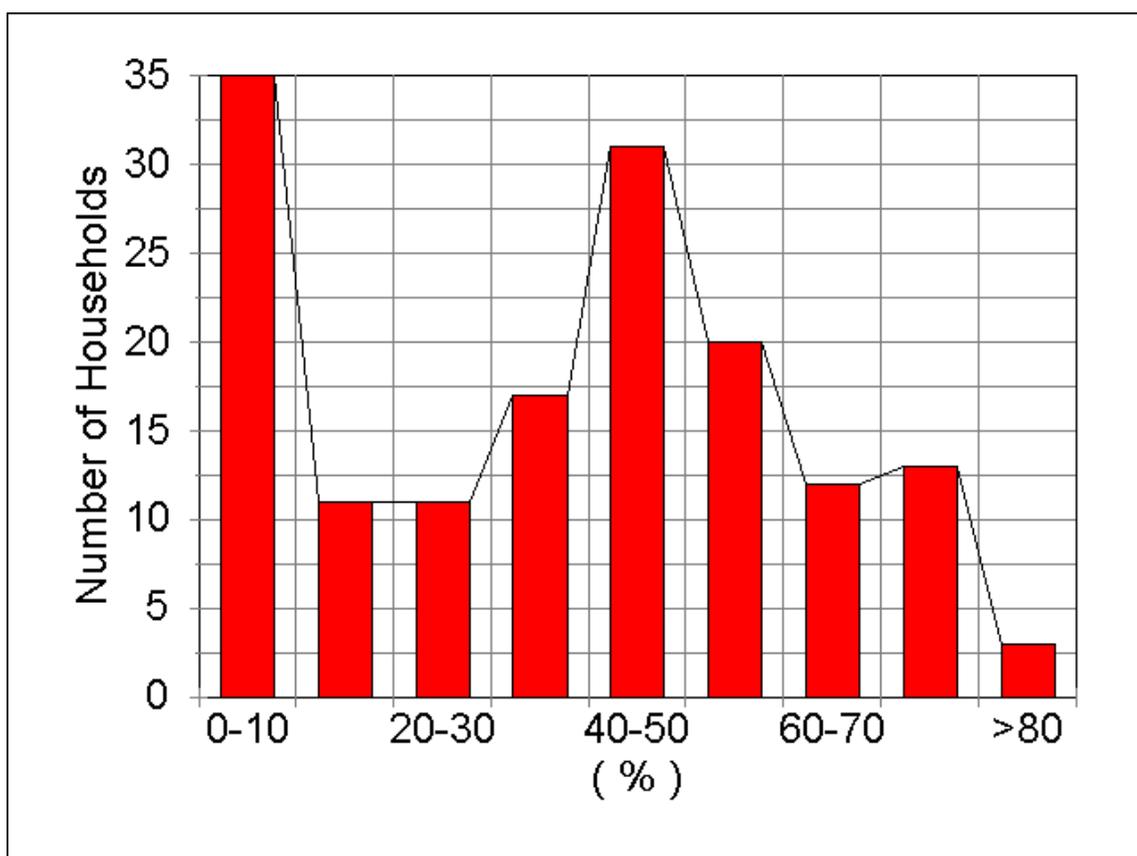


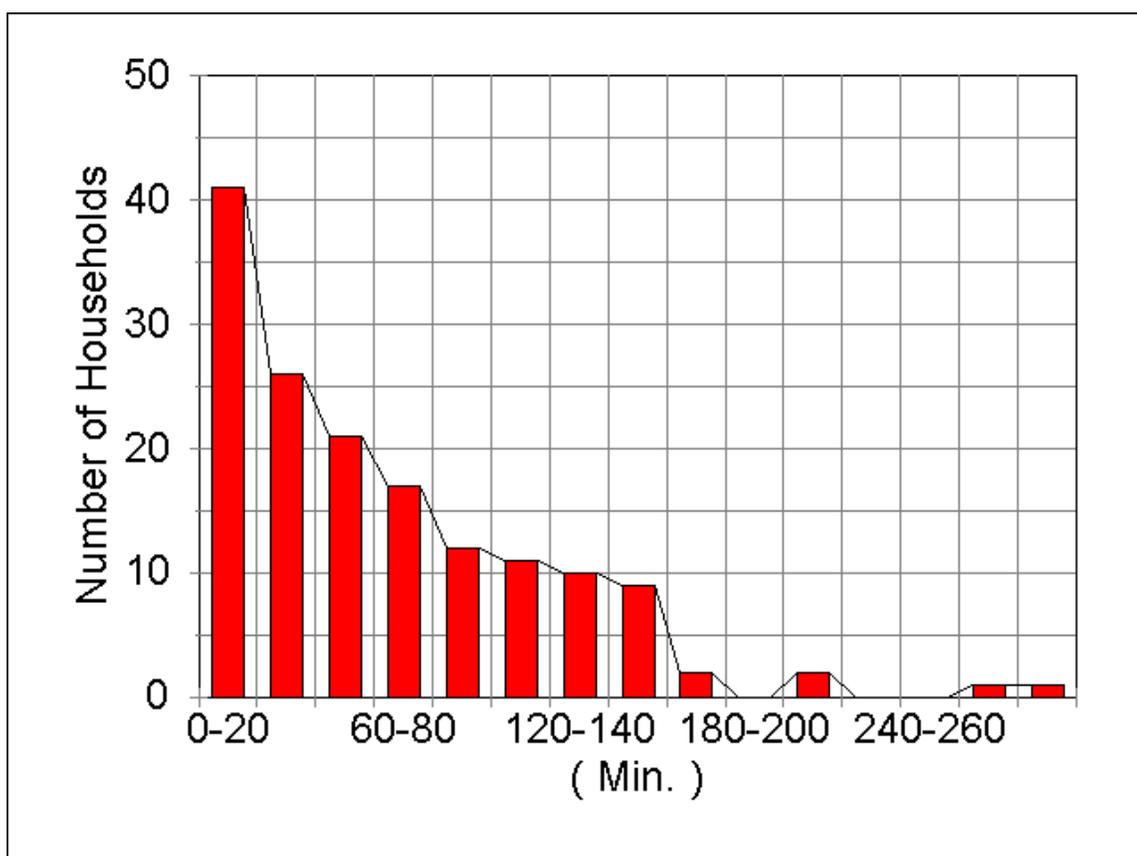












in order to explore their possible relationship with the potential improvements in the accessibility and travel time variables noted in the previous section. The notation and definition of the variables used in regression analyses are listed in Table 12. The estimation results are indicated in Tables 13 to 16 for relative and absolute accessibility (travel time) improvement, where the relative measurement is described as the relative change in the percentage improvements, while the absolute measurement is the difference between these variables for the observed and optimal household activity patterns.

In Table 13, the regression results on relative accessibility with respect to 2, 3, 4-member households, and the combination of the 3 groups are presented. The estimations are significant in terms of F value (all have more than 95% significance level). For 2-member households, only NO-VEH and TP-DIF are significant. NO-DRV and TP-DIF are the only significant variables in 3-member households; FLEX-TIME, NO-VEH, NO-TRIP, TP-DIF, and RIDE-SHARING are all significant in 4-member households. TP-DIF has an important role in all of these estimation results, and it can be concluded to have a major positive effect on increasing accessibility. In the case involving the grouping of all households, all of the variables are highly significant in terms of T value and all the signs of these variables are correct. To summarize the estimation result, it shows that ride-sharing behavior, the presence of more trips and more vehicles, and an increase in trip chaining (TP-DIF) all have positive effects. The magnitude of the ride-sharing effect is greater than that of the trip chaining variable.

In the case of absolute accessibility, TP-DIF still plays an important role. In addition, such socio-demographic variables as MULTI-JOB, FULL-STU, and LATE are also critical.

The F-values for all of these estimations are better than those associated with the relative accessibility, and all of the variables have significant T-values.

As to relative travel time improvement, the trip chaining variable (TP-DIF) as well as ride-sharing variable (RIDE-SHARING), as expected, always have a positive effect. Other variables, including INCOME, LATE, MULTI-JOB, and NO-ACT all have negative effects. Confirming the results of the previous section, the HH-SIZE 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 are both significant in terms of T test and F test, and are somewhat self-explanatory. The HH-SIZE, as in the case of relative travel time measurement, has a positive effect. Such variables as FLEX-TIME, INCOME, LATE, and NO-VEH all have positive effects. The same result is found in such variables as RIDE-SHARING and TP-DIF.

The OLS (Ordinary Least Square) estimation results indicate that some socio-demographic variables and activity pattern-related variables (e.g., NO-ACT, LATE, FLEX-TIME) do affect the potential for improvement in accessibility and travel time. The household size variable (HH-SIZE), 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 ride-sharing variable in terms of BETA value is greater than that of

**Table 12 The Notation and Definition of Variables in Regression Analyses**


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Notation	Definition
HH-SIZE	Household size
INCOME	Household yearly income level
AGE<12	Number of children less than 12 years old
FLEX TIME	The presence of flexible working schedule
MULTI-JOB	The presence of multiple-job option
FULL-STU	Number of persons being full time student
LATE	The presence of late activity schedule (with activity schedule fallen within the period of 12:00 AM and 6:00 AM)
NO-DRV	Number of persons with the ownership of driver license
NO-VEH	Number of vehicles available in a household
NO-ACT	Number of activities performed in a household
NO-TRIP	Number of trips performed in a household
RIDE-SHARING	The presence of ride-sharing behavior in an activity diary
TP-DIF	The difference of average number of trips within a trip chain between optimal and observed activity patterns

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trip-chaining variable. It is conjectured that in the case with ride-sharing behavior, better trip chaining results an efficient arrangement.

## **6.5 SUMMARY OF RESULTS OF APPLICATION**

The application of this proposed model system, HAPP, provides an opportunity to assess potential improvements in an accessibility measurement based on the daily household activity pattern; it also provides an assessment of the potential for trip chaining to be an effective efficient method to facilitate these improvements; especially, when used in conjunction with ride-sharing behavior. The regression results also establish an evaluation of the importance of each variable toward the improvement of each measurement, and thereby provides important information in evaluating policy alternatives.

## CHAPTER 7

### CONCLUDING REMARKS AND FUTURE RESEARCH

#### 7.1 CONCLUDING REMARKS

Accessibility measures have played an important role in transportation planning since the 1960's. Yet, there is only limited research on this topic, and that has largely been confined to the use of aggregated data and average spatial distance to construct home-based measurements. These measurements exclude such activity-based constructs as trip chaining and temporal/spatial constraints on accessibility. As such, they are responsive principally to changes in the transportation/land use infrastructure. Activity-based analyses provide a new framework to explore alternative structures for accessibility measurements that remove these deficiencies.

The incorporation of activity-based concepts in the measurement of accessibility not only takes advantage of incorporating a temporal dimension in assessing the potential for spatial interaction but also expands the applicability of accessibility consideration to real-world planning. The new measurement proposed in this dissertation is sensitive not only to changes in the transportation infrastructure, it is also responsive to such policy options as TDM and TSM, for examples; Increased accessibility resulting from trip chaining behavior, and effects on accessibility transference can be easily accounted for in the proposed measure. These are new aspects that can not be achieved with traditional accessibility measurements.

The contribution of this dissertation can be viewed from an other standpoint-the HAPP and its solution procedure. The core element of HAPP is extremely complex. Standard mathematical programming methods do not take advantage of the characteristics of the problem. Solution approaches by standard mathematical programming methods are both cumbersome and impractical. This research offers a new solution process based on dynamic programming methods and modified by developing opportunity cost from the saving matrix of the associated travel time and waiting time.

In the proposed process, all of the possible candidates are considered and compared to each other and different selection criteria are applied to choose the best alternative from the candidates. Scheduling is handled by the so called "moving forward" method to find the first available time point; temporal variables related to the shift of route schedule are maintained and stored to check temporal feasibility. The wasting method also plays an important role in rematching person-vehicle-activity pairs in order to find the best pattern with ride-sharing options. Finally, the calculation is conducted by combining wasting on ride-sharing and savings on additional trip chaining behaviors.

The proposed solution process not only simplifies the complex formulation into a smaller context, it also quickens the required solution time. It is extremely fast in terms of computational time for the two-stage process. For a typical problem with 5 members and 20 activities, it is able to solve the solution in less than 5 seconds.

The results of the empirical application verifies that there is a gap in terms of accessibility and travel time between observed household activity patterns and optimal

behavior. Moreover, the causal relationships affecting increased accessibility (reduced travel time) can be estimated through OSL regression analyses. Among those variables, trip chaining variable is determined as the primary variable that affects the improvement. This observation is especially helpful in policy-making and decision-making-process for transportation authorities.

## **7.2 FUTURE RESEARCH**

There is room for substantial improvement in the scope of applications of the research presented herein. Specifically, some strict assumptions made in the analysis (compared to real world situations) need to be relaxed in order to make the approach more applicable. Three essential aspects should be taken into account in the modeling process for future research and studies: 1) behavioral aspects, and 2) uncertainty aspects, and 3) GIS environment. The first aspect is imperative to fully reflect real activity interaction situations, and the second is necessary to accommodate the inherent stochastic nature of activity participation and travel time variation. The last aspect is able to supply a better analysis environment.

The behavioral aspects which deal with user's responding behavior and habit are quite different. In this research, we assume that there is homogeneous behavior. It is suggested that research on user's adaptation and habit should be conducted and incorporated within the activity model. Activity participation is another issue for future study; it is uncertain in nature, especially for non-regular activities. Taking the stochastic nature into consideration will facilitate a solid foundation for demand analysis. It is also recommended that stochastic travel time be

considered in the future research to match the real world situations. Travel time varies daily, even hourly. It is important to include the stochasticity of travel time to reflect realistic traffic situations. The last aspect of incorporating GIS environment into the model system is useful in model expression, and can further provide choices on activity location (not only activity participation). The provision of this aspect will lead toward the completeness of this model in terms of its scope of applicability.

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