The Development of a Household Travel Resource Allocation Model for Kitchener – Waterloo

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is the true copy of my thesis, including any required final revisions, as accepted by my examiners. I understand that this thesis may be made electronically available to the public.

Kevin Yeung

September 21, 2015

Abstract

Cities are dynamic and complex. Changes within cities are a result of actions of decision makers – governments, businesses, and households – and interactions within urban systems. An integrated land use - transport model is being developed to estimate the change in residential location choice and travel behaviour in the cities of Kitchener and Waterloo, Ontario, Canada. Within this model, there must be a representation of the daily travel decisions made by households to determine when and how people travel to activities. This decision is constrained by the availability of travel resources, such as vehicles or chaperones (for households with members that cannot travel on their own) This research proposes a model for these daily travel decisions that allocates travel resources to household members so that they are able to achieve their desired activities in a day. The output of the model is a set of scheduled tours and activities for each member of the household. The model is informed by a survey of 14 households within the Region of Waterloo, and tested against 9 household schedules that are located within the cities of Kitchener and Waterloo. The result of the model tests show that it performs relatively well in the scheduling of activities and the creation of tours if there is some level of time constraint associated with the discretionary activities. As well, the model is able to predict the mode choice for most tours, but some mode preferences are not entirely captured. Furthermore, this model is able to complete the travel resource allocation in an average time of 36 milliseconds per household. This research serves as the foundation for a model of household transport decisions that may be incorporated into the broader integrated land use - transport model for Kitchener and Waterloo.

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1.0 INTRODUCTION

1.1 Research Motivation

People around the world are increasingly choosing to live in cities and urban regions. While just over half of the world's population lived in urban areas in 2014, this proportion is expected to grow to two-thirds of the world's population by 2050 (United Nations, 2014). As the population within cities grow, urban planners and engineers are presented with several challenges. The first of these challenges is in the management of land use. Population growth could lead to the physical expansion of city boundaries as new homes and businesses are located on previously undeveloped land. In contrast, this growth could be directed to areas within the existing city boundary that may be redeveloped to have higher population and activity densities.

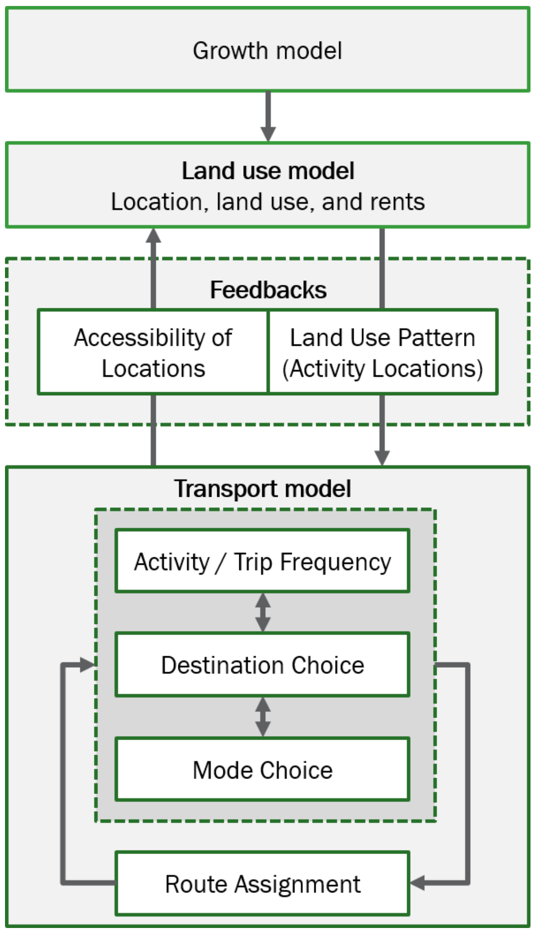
In any case, the growth of population leads to the second challenge: the efficient movement of people and goods in urban regions. The demand for travel will increase as the number of people and activities grow within urban areas. This demand emerges from a desire to complete activities - such as working, studying, shopping, and relaxing - in different locations. Planners and engineers have a role in shaping how people travel by planning and designing a transportation system that appropriately satisfies existing and future travel demand. Transportation systems may include infrastructure to support trips by walking, by cycling, by transit or by car.

These two challenges – the management of land use and the efficient movement of people and goods – and their associated solutions are intricately connected. The locations of activities and developments are dependent on the relative access and mobility provided by the transportation network. Residents may wish to live in areas with good access to employment, schools, stores and recreational opportunities. Businesses and firms may desire to locate in areas with good access to markets and labour. At the same time, the type of transportation system that is able to provide this access and mobility is dependent on the location and density of activities and developments in an urban area. Cities that have dispersed populations and activities may be more reliant on transport modes, such as cars, which can cover longer distances. In contrast, cities with concentrated populations and activities may be more conducive to walking or cycling, but may also require higher-capacity transport modes such as bus or rail transit.

Based on the interaction between land use and transportation systems in a city, planners and engineers should therefore consider these two elements in conjunction with one another. Vuchic (1999) suggests that the transportation system should be planned in relation the location of residences, as well as economic and social activities. This type of integrated land use and transport planning requires coordination and collaboration between regional planning organizations and transportation authorities. Vuchic (1999) argues that this type of integrated planning is required in order to achieve transportation systems that are efficient and cities that are livable; however, few cities are able to achieve this type of planning integration. While a transport network plan is often integral to a city or region's Official Plan, the transport plan is often based on aggregate forecasts of population, employment and land use; furthermore, the output metrics of accessibility and mobility within the city might not feedback to the land use planning process.

There have been some cases of improved integrated land use and transport planning coordination. In Canada, transit authorities in Toronto (Metrolinx, 2015) and in Vancouver (Translink, 2015), have provided leadership for integrated land use and transport planning by identifying guidelines and conducting planning studies for residential and commercial developments around its major transit corridors and stations. In the United States, Metropolitan Planning Organizations (MPOs) have jurisdiction over the regional land use and transport plans. Within these MPOs, such as in the Portland area (Oregon Metro, 2015) and the Philadelphia area (Delaware Valley Regional Planning Commission, 2015), there is a coordinated effort in the estimation and forecasts of regional land use and transport networks, often through the use of integrated land use - transport models.

An integrated land use – transport model is a tool that estimates change the spatial development of an urban region based on interactions between land use systems and transport networks (Martinez, 2000; Wegener, 2004). The outputs of land use models – typically the location of residences, employment, and activities, feed into transport models, which identify the accessibility of locations in the city. This output from the transport model is also fed back to the land use model, as illustrated in Figure 1-1. In this way, planners and engineers are able to improve their understanding of the complexities of cities. These models may be applied to explore potential outcomes of policy and infrastructure investment alternatives while considering different economic and demographic conditions.



(Modified from Martinez (2000))

Figure 1-1: General Structure of Integrated Land Use - Transport Models

These integrated land use - transport models approximate the behaviour and actions of various decision makers within cities. Households, businesses, developers, and government agencies are all examples of decision makers, which are also known in literature as agents. The outcomes in land use systems and transport networks are a result of the behaviour of individual agents (Bonabeau, 2002; Martinez, 2000). A good understanding of agent behaviour and decision making processes in the context of urban systems is the core of a successful integrated land use - transport model. One of the fundamental agents that is important to understand is the household. Households are a collection of individuals who live together in a dwelling. The decisions of households and the decisions of individuals in households are inter-related. These decisions have implications for both land use and transport systems. Consider the choices that are available to households in the context of land use and transport systems.

A household has choices in residential location and dwelling type. The household can choose to live in the city centre, where activities and buildings are located close together, and where population and employment densities are relatively high. Alternatively, the household can choose to live in a suburban neighbourhood, where activities and buildings may be located further apart. The residential location influences the dwelling types that are available to the household. Single detached dwellings are more prevalent in suburban neighbourhoods, while apartments and condominium units are more prevalent near the city centre. These decisions are influenced by the household's preferences for amenities within the dwelling, the price of the dwelling, and the access from the dwelling to work, school and other community activities. Household decisions in residential location and dwelling type ultimately shape the demand for housing and other amenities in different locations throughout the city.

A household's decision in residential location influences the transportation needs and resources for each person within the household. The location of the household in relation to the location of employment, school, retail and recreational activities shapes the length and cost of travel. Furthermore, a household's location influences the transport mode alternatives (e.g. walk, bike, transit or drive) that are available and feasible. Each person within the household is able to choose amongst the transport mode alternatives that allow them to travel to each of their activities. However, these choices are restricted by the independence of individuals – whether or not the person can travel on their own – and by the number of available resources – such as vehicles, time or travel budget – within the household. Individuals within the household, therefore, must schedule their activities and choose their transport mode in consideration with the other individuals of the household.

Given a set of travel demands and resources, the household needs to collectively make decisions that allocate its resources to meet the demand. These decisions are complex, and these decisions potentially occur as often as every week or every day. While in most cases households are thought to allocate their resources each day to minimize their overall travel cost and time, other factors may also influence this decision. In particular, there may be constraints in time that influence when activities may occur, and also constraints imposed by dependents, as an independent person must chaperone and accompany the dependent to his or her activity.

These day-to-day or week-to-week resource allocation decisions ultimately influence the demand for travel within the city's transportation network. Moreover, these regular decisions shape longer term household travel resource decisions. In cases where a household is not able to meet the demand with the given resources, the household has several options. In the short term, the household may reduce its travel demand by deferring or cancelling activities that are of lower priority. External resources, such as extended family members or neighbours, might also assist in the fulfilment of travel demands. Over the long term, the household may increase its available resources by purchasing a new vehicle or by moving to a new location with additional transport alternatives. The travel resource allocation decision is fundamental to broader transportation decisions, and therefore, is a core component of a successful integrated land use - transport model.

1.2 Research Objectives

The focus of this research study is on the short-term travel resource allocation decision of households. In particular this study focuses on the dynamics and complexities of the resource allocation decision. The ultimate objective of this research is to establish the logic and process for a model that is representative of household travel resource allocation decisions.

In order to achieve this ultimate objective, this research first seeks to understand the process that households follow to allocate resources to meet their travel demands. In particular, this study explores the following questions:

1. How do households allocate resources – vehicles, time, and supervision – to conduct travel for independents who are able to travel on their own and for dependents who require supervision or chaperoning from an independent?
2. How do households prioritize their various activities? In what order are activities are scheduled?
3. What factors do households consider when making travel decisions?
4. How much flexibility do households have in their household schedule?
5. What role do external resources, such as extended family or neighbours, have in satisfying household travel demands?
6. How do households respond when presented with an unexpected activity?

The answers to these questions guide the scope and development of the household travel resource allocation model. This research proposes and develops a model concept based on elements from existing literature and on the findings from the above questions. The model is also tested using activities and characteristics provided by households in this research study. In particular, these secondary questions are explored:

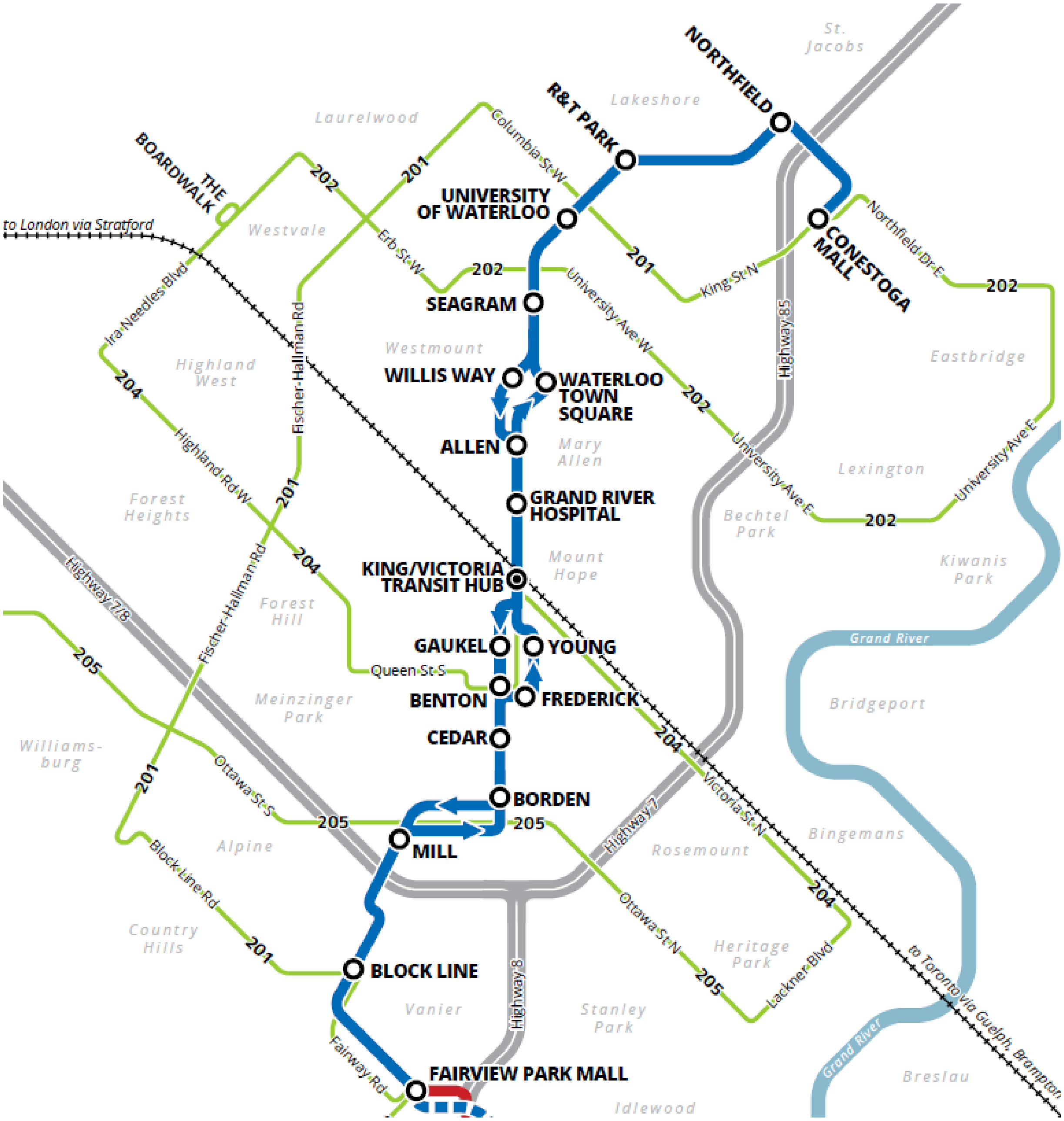
1. How well does the proposed model developed in this study replicate actual household activity and travel schedules?
2. What is the time required for the model to discover a solution?

1.3 Study Location and Significance

This proposed model focuses on the urban municipalities of the Region of Waterloo, Ontario, including the cities of Kitchener and Waterloo, which are located approximately 110 kilometres west of Toronto. The entire region, which also includes the City of Cambridge and four rural townships, currently has a population of 568,500 (Region of Waterloo, 2014). A substantial majority of travellers within the Region use the automobile as their primary form of transportation, with 90% of trips occurring by automobile, 5% of trips occurring by transit and 5% of trips by bicycle or foot (Data Management Group, 2011).

By 2031, the Region of Waterloo is projected to house a population of 729,000 (Region of Waterloo, 2014). This population increase will also have associated growth in employment and traffic demands. To accommodate this growth, the Region is proposing several land use policies and transportation infrastructure investments that will focus higher density development along transit corridors and will encourage a shift from automobile to alternative modes of transportation. One of the main initiatives is the construction of a 19 kilometre light rail transit line connecting the urban centres in Kitchener and Waterloo. The Region is also planning several high frequency bus routes that would connect to the light rail transit corridor, as depicted in Figure 1-2. By implementing these transportation initiatives, the Region will strive to achieve its goal to have 15% of trips occurring by transit in 2031 (Region of Waterloo, 2011b). In addition to

As the Region endeavours to implement these infrastructure investments and policies, a broader modelling and monitoring effort is being undertaken by the University of Waterloo to understand the actual impacts of these planning decisions on travel behaviour and residential location choice. In particular, this broader effort will model household location decisions and residential developer decisions, in addition to household transport decisions. Moreover, this effort will monitor changes in land use and travel behaviour once the light rail transit corridor is operational. Figure 1-3 illustrates the scope of the modelling and monitoring efforts in Kitchener - Waterloo and where this study fits within the broader research work. The outcome of the current research study may provide some contributions to existing land use - transport model and activity-based travel model literature. However, the primary intent of this research is to establish the logic of household travel resource allocation decisions, which can be combined with a route assignment algorithm that comprises the transport component for an integrated land use - transport model of Kitchener - Waterloo. Future research in household travel behaviour may build upon the work conducted in this study.



Light Rail (Blue) | iXpress Bus Routes (Green) | Map Source: (Region of Waterloo, 2012)

Figure 1-2: Map of Future Transit in Kitchener-Waterloo

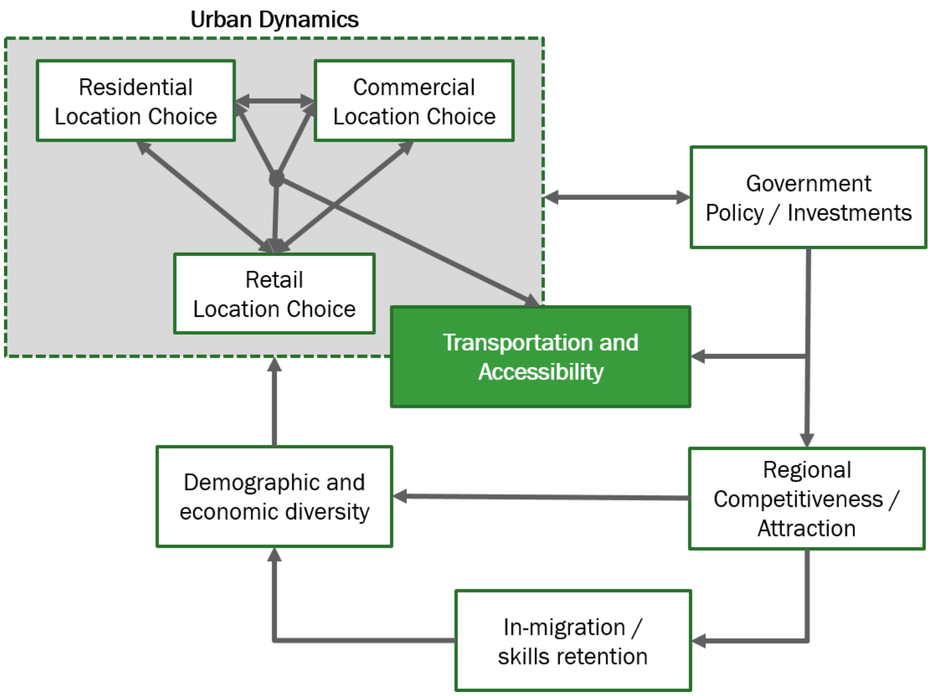


Figure 1-3: Scope within Kitchener - Waterloo Modelling and Monitoring Work

1.4 Outline of Thesis

This thesis details the motivation, methodology, and results of this research study. Chapter 1 provides an overview of the motivation for this research and outlines the specific research questions and objectives for the study. Chapter 2 provides a review of the existing literature on the relationship between transport and land use, as well as the literature on travel forecasting models, and activity-based transport models. Chapter 3 outlines an exploratory survey that is conducted to increase understanding of the process and the factors that influence household travel resource allocation decisions. Both the methods and results of the survey are discussed in that chapter. The results influence the development of the model concept, which is detailed in Chapter 4. Chapter 5 provides a discussion of the model testing methods and results. Finally, Chapter 6 outlines conclusions from this research and identifies areas and next steps for further research.

2.0 LITERATURE REVIEW

2.1 Overview

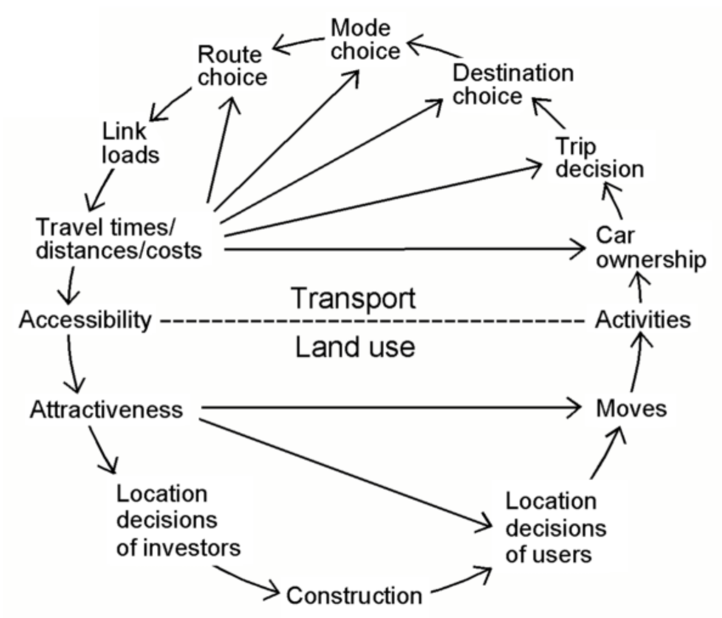
Extensive research exists on the relationship between land use systems and transport networks. A review of this literature justifies the need to undertake an integrated land-use transport modelling approach to understand the complexities of urban systems. Furthermore, as the focus on this research is on household transport decisions, this review compares the two main approaches for modelling transport within integrated land-use transport models. The first main approach – the classic four-step travel forecasting model – is prevalent in practice, but there are limitations in its ability to represent household travel decisions. The second approach – activity-based travel models – is not as widely used, but may provide a better representation of travel decision behaviour. Understanding these transport modelling approaches provides a basis for the development of the proposed household travel resource allocation model.

2.2 Transportation and the Built Environment

Societies rely on transportation to function, as it enables the movement of people and goods to economic and social opportunities. Throughout history, access to transportation infrastructure has significantly influenced city and land use planning. Cities have historically originated around rivers and lakes as marine transportation provided access to trade with neighbouring regions. Through the Industrial Revolution, cities expanded with the introduction of railroads, which could transport manufacturing resources over further distances (Abbot, 2013). Following the Second World War, the proliferation of the automobile coupled with extensive highway and bridge infrastructure investments championed in North American cities by Robert Moses amongst others allowed city limits and economies to expand (Larson, 2009). Automobile technology enabled urban form to be sparser, and in turn, required households to use automobiles to travel to destinations (Kennedy, 2011). Today, these same cities are challenged by the legacy of automobile-oriented development.

In response to automobile-oriented development, there have been efforts in the planning community to restrict development within existing urban boundaries, and to focus growth along corridors with transit to maximize the use of transport infrastructure. There have been many studies that attempt to establish the relationship between transportation and the built environment, yet these studies have had mixed results. Some, like Newman and Kenworthy (2006), have shown in a study of Los Angeles that there is a strong and significant relationship between population density and transit ridership. Cervero and Kockelman (1997) found that areas with higher densities, a diversity of land uses, and a grid patterned street network were moderately associated with higher transit, cycling and walking trips. However, a meta-analysis of travel and built environment studies by Ewing and Cervero (2010) showed that, in general, built environment variables have very marginal impacts on overall travel behaviour, but suggested that there may be some positive associations between transit use and combinations of built environment variables, such as proximity to transit, street network design and land use diversity variables. The challenge with these results is that while these studies focus on establishing a relationship between variables, they neglect the human behaviour and decisions that may motivate change.

Despite the mixed results of these studies, there is growing recognition of this intrinsic link between how people move in cities and where households and businesses establish in cities. Accessibility enabled by transportation infrastructure and the activities that arise from different land uses have an influence on each other. Land use influences the location of activities, which influences travel demand and the performance of the transport network. People's satisfaction with the current condition of the transport network affects where they choose to live and conduct activities. Throughout the American planning literature, the relationships and feedbacks between land use and planning were represented as a cycle, as illustrated in Figure 1 (Wegener, 2004). Moreover, there are broader factors such as the demographic and economic environment that influence the growth and decline of cities (Kennedy, 2011). There is a desire to better understand the interaction of these decisions and factors in order to make better policy and planning decisions.



(Source: Wegener, 2004).

Figure 2-1: The land use transport feedback cycle

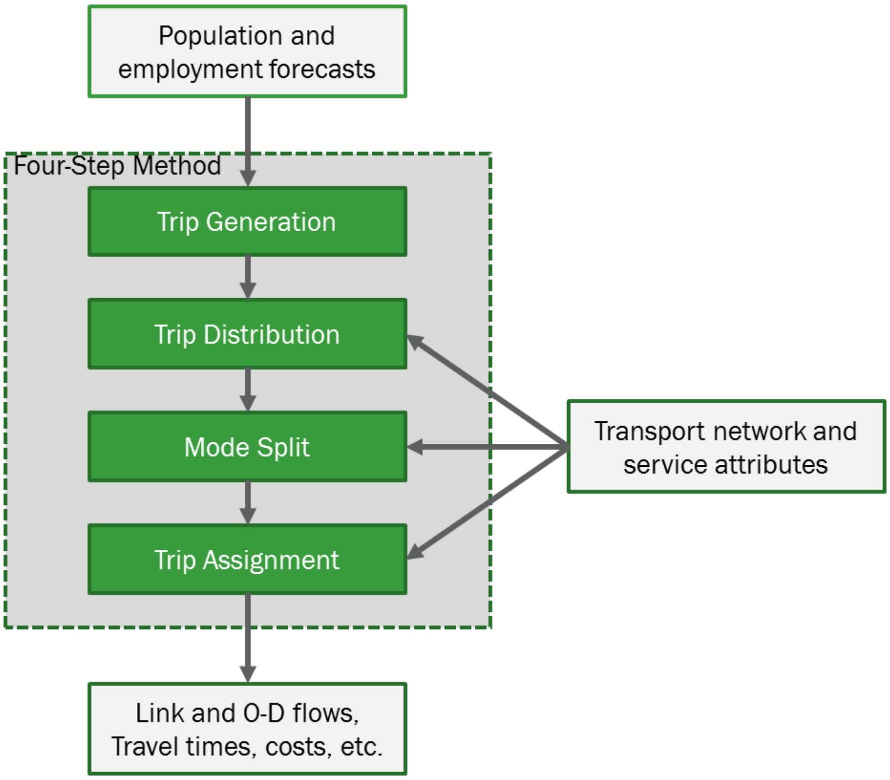
Integrated land use - transport models attempt to capture the complexities of change within cities based on the behaviour and interactions of various actors and stakeholders within the urban environment. Wegener (2004) compared 20 integrated land use - transport models that were calibrated and operational in urban regions around the world. This review identified the types of urban systems that are represented in these models, and also compared their ability to represent urban change in these systems. UrbanSim (Waddell, 1998) and ILUTE (Salvini & Miller, 2003) are two examples of such integrated land use - transport models that attempt to represent the relationships and processes between broad socioeconomic factors, transportation networks as well as land use and development. Travel forecasting models are an integral part of urban models as they determine the accessibility of a household to employment and commercial activities throughout the city. Furthermore, they also estimate the travel demand across transport networks.

The two main approaches for travel forecasting models is the classic four-step travel forecasting model, and activity-based travel models. Wegener (2004) noted that many of the models, like UrbanSim, use the classic travel forecasting approach. Few exceptions, like ILUTE, use an activity-based approach. Each of these approaches for travel forecasting is discussed in the following sections.

2.3 The Classic Travel Forecasting Model

A travel forecasting model is a fundamental tool within the transportation planning practice that estimates change in travel behaviour and transport system performance as a result of land development or infrastructure investments. These models are often used to determine the level of demand – in terms of trips – between origins and destinations in a city and the level of utilization – in terms of volume – for transport corridors in the network. The travel forecasting model of a city or region does not estimate trips for each specific address location as it would be too computationally intensive; rather, the model relies on a spatial representation known as the traffic analysis zone (TAZ), which is a collection of household and firm locations within an area that together act as origins and destinations (Ortuzar & Willumsen, 2011). Characteristics of these TAZs are collected from census data and local household travel surveys. These data are used to inform the travel forecasting model.

The traditional travel forecasting model typically consists of a four-step process that determine travel demand as illustrated in Figure 2-2 (Meyer & Miller, 2001). This modelling approach has been well documented in the literature and widely applied in practice. This section provides an overview of the concepts to provide the context of travel forecasting and is not intended to be an exhaustive detailing of the mathematical proofs for the model. Interested readers should refer to McNally (2000), Meyer & Miller (2001) or Ortuzar & Willumsen (2001) for further details on the traditional travel forecasting model.



(Modified from Meyer & Miller (2001))

Figure 2-2: The Four-Step Travel Forecasting Model

2.3.1 Step 1: Trip Generation

The first step – trip generation – estimates the number of trips that are produced from origins or attracted to destinations within the city. Zones with higher residential populations often produce trips, while zones with commercial activities (e.g. retail or office) often attract trips. Regression analysis is often used to determine number of trips generated by a TAZ as a function of independent variables that describe the TAZ. Models that estimate the number of trips produced from a TAZ often consider the following variables: population, household size, residential density, average income, and car ownership; moreover, models that estimate the number of trips attracted to a TAZ often consider these variables: number of employees, number of sales, gross floor area of office space or retail (Cambridge Systematics et al., 2012; Ortuzar & Willumsen, 2011). The following equations are examples of trip attraction models that have been calibrated for a specific municipality, which estimate the number of work trips and discretionary trips that a zone attracts each day based on its employment and household characteristics:

$$Daily\ Trips_{Work} = 1.45\ E_{Total}$$

Equation 2-1: Example Home-based Work Trip Attraction Model

$$Daily\ Trips_{Discretionary} = 9.00\ E_{Retail} + 1.70\ E_{Service}\ +\ 0.50\ E_{Other} + 0.90\ H$$

Equation 2-2: Example Home-based Discretionary Trip Attraction Model

… where E_{Total} is the total employment, E_{retail} is the amount of retail employment, $E_{service}$ is the amount of service employment, E_{other} is the amount of other miscellaneous employment and H is the number of households (Martin & McGuckin, 1998). All the values are aggregated to a zonal level.

As an alternate to the regression analysis apporach, cross-classification is another method that is used to generate trips produced from a zone based on the characteristics of households within a zone. In this method, households are stratified into different categories of characteristics, such as household income, number of vehicles, number of persons, or number of workers. Average trip rates are then established for each combination of characteristics based on the households within each category (Sopher, McDonald, Stopher, & McDonald, 1983). The number of trips produced is dependent on the types of households that are within each TAZ. In the United States, a number of state travel forecasting models use the cross-classification method, often classifying households by size, automobile ownership and income (Horowitz, 2006).

2.3.2 Step 2: Trip Distribution

Once there is an estimate of the trips produced or trips attracted by a zone, the travel forecasting model is then concerned with matching trip productions and attractions into origin-destination pairs within the city. Travel destination choice is the primary objective of trip distribution. Given a trip type and origin, this step determines the number of trips that travel to each TAZ within the city. Trip distribution typically relies on the gravity model, which estimates the travel demand between an origin and destination zone (T_{ij}). This estimation is based on the attractiveness of each zone (often represented by the trips produced by the origin TAZ (O_i) and the trips attracted by the destination TAZ (D_j), and based on an impedance function that represents the cost to travel between each zone (f (C_{ij})). The form of the gravity model is in Equation 2-3:

$$T_{ij} = \propto O_i D_j f(C_{ij})$$

Equation 2-3: Gravity Model

… where α is a proportionality factor (McNally, 2000b; Ortuzar & Willumsen, 2011). The output of the trip distribution step is a table that represents the number of trips for each origin-destination pair in the city.

2.3.3 Step 3: Mode Choice

Mode choice, the third step of the travel forecasting process, determines the travel mode of the trip models, which is typically either automobile or transit, but could also include cycling or walking (Vuchic, 2005). Mode choice models are applications of a disaggregate or discrete choice problem, in which an individual selects a solution from a set of alternatives (Ben-Akiva & Lerman, 1985). The basis of these models is in microeconomic theory and utility maximization, where individuals select the alternative that maximizes his or her benefit or value (Ben-Akiva & Lerman, 1985). Utility (U) is a measurement of the preference for a particular alternative (i) based on its characteristics, and usually consists of a measured, deterministic component (V) and a random component (ε).

$$U_i = V_i + \varepsilon_i$$

Equation 2-4: Components of Utility

In transport planning, the deterministic utility component (V) typically includes the travel time and cost associated with a particular travel mode for a trip (Ortuzar & Willumsen, 2011). However, there may be other attributes or characteristics of a travel mode that are related to utility. In the case of public transit, the travel time may be broken up into its various components including access time, waiting time, in-vehicle time, transfer time, and egress time (Vuchic, 2005). Furthermore, the cleanliness and comfort of transit vehicles and facilities also influence its utility (Dell'Olio, Ibeas, & Cecin, 2011). With respect to bicycling, the utility is sensitive to the amount of travel along on-road and off-road routes, and the provision of bicycle parking and shower facilities at the destinations (Hunt & Abraham, 2007). The utility of walking is related to the presence of sidewalks and the topography along the route (Rodríguez & Joo, 2004).

The random component of utility (ε) accounts for variations in preferences that are difficult to capture. Assuming that the random component of utility is independently and identically Gumbel type distributed, the probability (P) for an individual to select a particular mode (i) can be calculated with a multinomial logit model expression that includes only the measured component of utility (Ben-Akiva & Lerman, 1985):

$$P_i = \frac{e^{V_i}}{\sum e^{V_i}}$$

Equation 2-5: Multinomial Logit Model

In the above equation, the probability that an individual would select the mode, i, is a function of its measured utility, as well as all of the other utilities in the choice set. Based on the travel times and costs to travel between each origin and destination in the city, it is possible to determine the demand for trips by each mode.

2.3.4 Step 4: Route Choice

The fourth and final step of the travel forecasting model – route choice – determines the transport corridors a trip uses to travel between the origin and the destination zones. This step ultimately estimates the travel demand for the corridors within the transport network. Various methods are available to undertake this step of the travel forecasting process, but two of the common methods include all-or-nothing assignment and congested assignment. All-or-nothing assignment is the simplest algorithm that suggests that all trips between an origin and destination will take the shortest path to the destination, without regard for the effects of congestion (Willumsen, 2000).

With congested assignment, the determination of route choice typically follows a shortest-path approach with restrictions based on the capacity of the network. The shortest path is dependent on the average travel time (t) along a corridor, which is a function of the uncongested travel time (t_f), travel demand (V) and capacity (C) of the corridor. One classic example of a travel time function for a corridor is from the Bureau of Public Roads (BPR) (1964):

$$t = t_f \left(1 + \propto \left(\frac{V}{C}\right)^{\beta} \right)$$

Equation 2-6: BPR Function

… where α and β are parameters that capture the quality of the traffic flow on the corridor. Under congested assignment, travellers may switch their selected route on the network to find the most efficient route to their destination; however, there is an expectation that the network would reach a point of equilibrium (Willumsen, 2000). Wardrop (1952) defined the state of traffic equilibrium in two ways, either under user equilibrium where "no individual trip-maker can reduce his or her path costs by switching routes" or by social equilibrium where "the total travel cost (for all travelers) is minimized." These principles have been applied in the Frank-Wolfe algorithm, which determines the route choice and travel volumes on each corridor iteratively until equilibrium is achieved (Willumsen, 2000). While the Frank-Wolfe algorithm is most commonly applied in the literature and in practice, the Origin-Based Algorithm by Bar-Gera (2002) provides a method to assign traffic onto a network using less computational memory and processing time.

2.3.5 Behavioural Limitations of the Traditional Travel Forecasting Model

At the conclusion of the traditional travel forecasting model, transportation planners and engineers have an estimation of: the number of trips generated by an area, the distribution of the trips to destinations, the mode of travel for each trip and the route taken for each trip. This modelling approach has been widely accepted in practice; however, there also have been many criticisms of this traditional model because of its limitations in representing realistic travel behaviour (Boyce, 2002; Kitamura, 1996; McNally, 2000b; Recker, McNally, & Root, 1986a).

The sequential nature of the travel forecasting model, while it is a simplifying assumption, limits the model's ability to accurately represent travel behaviour. In this approach, land use is an exogenous static input into the model. The output of each step informs the next step of the model. Kitamura (1996) argues that travellers do not usually consider the choices of the number, location, travel mode and travel route of trips exclusive of one another; instead, each of these choices are related. For example, a person's selection of a location may be dependent on the available travel modes at each location and travel times along the route. Boyce (2002) supported this idea and extended further with a paradigm that a traveller will make the destination, mode and route choices in an integrated approach.

Spatial and temporal aggregation further limits the ability of the travel forecasting model. Spatial aggregation is applied during determine trip generation. Characteristics such as population, households and employment from associated land uses are aggregated at the TAZ level and used to estimate trip productions and attractions. This spatial resolution is not detailed enough to represent household travel behaviour (Wegener, 2004). In particular, trips are associated with TAZs and not with households. In this way, the model lacks detail to represent the fundamental motivation for travel, that is, trips are derived from the need to do activities in different locations (Recker et al., 1986a). Moreover, as this model considers aggregate periods of time (such as the morning or afternoon peak periods), Kitamura (1996) argues that this approach does not allow for the suitable analysis of congestion or shifts in departure times.

The final set of criticisms relates to how the travel forecasting model represents travel decisions. First, the traditional model misrepresents decisions, in particular location and mode choice, as a true choice process without consideration of constraints that might limit the choice set (Recker et al., 1986a). The constraint may be related to the availability of the transport mode. As an example, as the traditional model treats each trip from origin to destination as an individual entity, it ignores the possibility that these trips may be linked together in a trip-chain, also known as a tour (Kitamura, 1996). A tour is defined as a set of consecutive trips that starts and ends at the household's place of residence (Adler & Ben-Akiva, 1979). This may lead to separate modes being assigned to these linked trips through the model whereas in reality the same mode is used for the entire tour. Another example is in the availability of a household vehicle. The four-step travel forecasting model may assign a trip to use an automobile as its travel mode without regard for whether or not a vehicle is actually available for that trip.

Recker et al. (1986) also argues that the traditional travel forecasting model neglects alternate decision strategies as it relies on the utility maximization decision framework. The prevailing assumption in this framework is that individuals are rational decision makers who will always choose the best alternative given they have all the available information about their alternatives available (Ben-Akiva & Lerman, 1985). However, Simon (1957) argued that humans are not capable of processing all information regarding their alternatives and their rationality is bounded by this limitation.

Some have advanced proposals for alternate decision strategies. Mahmassani & Chang (1987) developed a rule-based model of departure time choice that incorporated the assumption of bounded rationality and suggested that individuals find an acceptable solution instead of the optimal one. Moreover, decision makers will not change their selection if they are already satisfied with their existing choice. Chorus & Dellaert (2012) suggest that travellers perceive and understand attributes of a mode through experience. Over time, the repeated utilization of a mode may eventually develop a habitual travel mode choice.

Throughout the literature, it is clear that there are concerns with the behavioural representation of the traditional travel forecasting model. Kitamura (1996) suggests that these limitations may over estimate shifts in mode (from automobile to transit) and may prevent the effective evaluation of transportation demand management policies (e.g. the introduction of new infrastructure or pricing policies). In addition to these concerns with respect to travel behaviour, the traditional travel forecasting model is also limited in its ability to represent the relationship between land use and transport. The representation of land use is typically restricted to aggregate statistics of population, employment and retail opportunities. The outputs of the model are also aggregated to the TAZ level. This model does not adequately represent the integrated relationship between land use and transport as illustrated in Figure 2-1, nor does it represent underlying behaviour that may motivate decisions. Much of the efforts in transportation planning have concentrating in improving the accuracy and validity of travel forecasting models through a better representation of behaviour.

2.4 Activity-Based Travel Models

Activity-based travel models have been proposed as an alternative to overcome the limitations of the classic travel forecasting model. The fundamental premise of activity-based travel models is to provide a better behavioural representation of transportation decisions. The roots of activity-based travel models can be traced back to the address by Hagerstrand (1970). In this address, Hagerstrand spoke broadly of the considerations that should be included in any models of human activity. By providing an initial definition of the considerations in activity-based models, the seminal address by Hagerstrand (1970) has inspired much of the research in activity-based travel models.

The foundation of activity-based travel models is the principle that travel demand is derived from the desire to conduct activities (McNally, 2000a). This principle was implicit in Hagerstrand (1970) as activities in different locations necessitate travel. Moreover, this has become one of the "most fundamental, well known and widely accepted principles" in travel forecasting (Bowman & Ben-Akiva, 1997). Within this approach, not all activities are the same and some activities are considered more important than others. Some activity-based models represent this importance through the use of utility, a measure of the benefit associated with completing the activity (Recker et al., 1986a). Other models identify a priority for activities based on the type of activity, and on level of required pre-planning (Roorda, Doherty, & Miller, 2005).

Another foundational element of activity-based travel models is a more comprehensive treatment of the temporal and spatial characteristics of activities and travel. Hagerstrand (1970) noted that human activities are conducted in specific locations for a certain duration, and he noted that time is a finite resource that cannot be saved for future use. Hagerstrand postulated that these considerations of space and time are fundamental to the understanding and modelling of human activity. Based on this work, a common theme in activity-based approaches is the scheduling of activities at a particular time and location (McNally, 2000a).

A final key theme for activity-based travel models is that there are constraints that limit the ability for a person to achieve activities. These constraints may be related to spatial, temporal, transport or interpersonal considerations (McNally, 2000a). Hagerstrand (1970) defined three categories of constraints that should be considered in activity models. First, there are *capability* constraints, which are biological demands, such as sleeping or eating, or physical restrictions, such as the duration or travel time for activities, which limit a person's time to conduct desired activities.

Second, there are *coupling* constraints, which is the requirement for at least two people to be in the same location at the same time in order to undertake certain activities. This constraint holds true especially for activities where a particular contract or transaction occurs between two individuals. Moreover, Hagerstrand specifically notes the lack of autonomy for children to travel, and this requires a parent to partner with a child in order to travel to activities. This idea is supported further by Chapin (1974), who observed that children place a significant demand and constraint on others in the household.

Finally, there are *authority* constraints, which are regulations that restrict access to a particular location or activity. An example of this constraint is the consideration of the hours of operation for any business or institution. An activity may not commence if that location is not currently open (Hagerstrand, 1970). The definition of these constraint categories is significant in activity-based models, as it determines when activities may be scheduled. Moreover, the second category – coupling constraints – suggest that travel is not an individual decision, but instead, is a decision that requires consideration of the needs of the entire household.

From these foundational characteristics, there have been several activity-based travel models that have been developed and documented in the literature. These models generally fall under one of three main modelling approaches based on its approach to alternative generation and decision-making. Activity-based travel models may consist of several sub-components that use econometric models or simulation models to represent the activity generation and scheduling behaviour. These also have been identified in the following sections.

2.4.1 Global Selection Approach

The first approach suggests that the decision-maker selects an activity schedule after an exhaustive development and search of all potential activity combinations. This approach applies a utility maximization framework, hypothesizing that people select a schedule that maximizes the benefit derived from completing activities. The models in this approach rely on the use of the multinomial logit or nested logit formation (as defined by Ben-Akiva & Lerman (1985)) to calculate the probability of selecting a particular activity schedule alternative.

STARCHILD is one example of a simulation-based model that follows this global selection approach. In STARCHILD, the locations and durations of individual activities are assumed to be planned in advance and are used as inputs into the model (Recker, McNally, & Root, 1986b). Using restrictions on activity start times, the model generates all feasible combinations of activities and tours. The model then identifies distinct and unique activity patterns and removes any schedules that share similar characteristics in order to reduce the number of feasible schedules into a manageable choice set. STARCHILD assigns a schedule to the person based on a multinomial logit formation that calculates the probability of a person to choose a particular schedule based on the utility of schedules in the choice set. The components of utility that are considered in STARCHILD include the utility of activity participation, the expected utility of participating in unexpected activities and the utility of remaining at home. This model was tested using a small set of sample data (Recker et al., 1986b).

A more recent example of the global selection approach is an econometric-based model for the Boston area. Using data from the 1991 Boston Travel Survey, Bowman and Ben-Akiva (2000) identified a model that represents the selection of a daily activity travel pattern. Each pattern alternative has an associated utility derived from different pattern characteristics including: the location of activities, the number of activities on each tour, the time of day of travel, and the mode choice for travel. This model assumes that the decision-maker considers all potential combinations of characteristics, and then selects an alternative based on the probability derived from the utility of the alternatives.

One major critique of this global selection approach is that people are typically not capable of perceiving all potential alternatives, and that an exhaustive search is not completely representative of behaviour. Moreover, a purely utility maximization decision framework also does not represent other influences that may affect the choice process (Gärling, Kwan, & Golledge, 1994a).

2.4.2 Sequential Development Approach

This alternative approach for activity scheduling responds to the notion that people cannot perceive all possible alternatives and are not able to identify the optimal solution that maximizes utility. Instead, the activity scheduling process is thought to be a step-wise approach. While each of the following modelling approaches focus on a different aspect of activity scheduling, each share a similar outcome. The models produce activity schedules that may be sub-optimal but acceptable (as in it meets the spatial-temporal constraints).

SCHEDULER is a rule-based simulation model that focuses on the selection of activities, as well as their locations and start times for an individual's activity schedule (Gärling et al., 1994a). In this model, various activities that may be scheduled are stored in what is known as a "Long Term Calendar". Each of these activities has a priority and duration, as well as a list of feasible locations and known open hours. Activities that will be completed by the individual are placed in the "Short Term Calendar". The SCHEDULER will sequence the activities and select activity locations by using a heuristic that identifies the closest activity in terms of location as the next activity (Gärling, Säisä, Book, & Lindberg, 1986). If there are any conflicts with the activities that are selected, the SCHEDULER may reorder the activities or select a lower priority activity from the Long-Term Schedule to replace the conflict. Once a feasible "Short Term Calendar" is created, the SCHEDULER then executes the activities in this schedule.

SMASH (Simulation Model of Activity Scheduling Behaviour) is also a rule-based simulation model that builds upon the work in the SCHEDULER, and focuses on the decision to include, delete or substitute activities (Ettema, Borgers, & Timmermans, 1993). The premise of SMASH is based off of the theory from Root & Recker (1983) that suggests that while individuals may generate activity patterns to maximize utility, there are decreasing marginal returns for each additional activity in a tour, as the additional burden from scheduling a complex trip may eventually become greater than the utility derived from achieving that activity. In SMASH, the utility of an action (e.g. add, delete or replace an activity) is calculated at each step of the scheduling process. This utility is a function of the number of actions performed, and various schedule attributes. These attributes allow the decision-maker to select an activity based on certain heuristics or objectives, which include:

- Minimizing the distance traveled to activities;
- Maximizing the time spent on activities;
- Maximizing the amount of high priority activities completed;
- Maximizing the attractiveness of the locations visited;
- Minimizing the travel time in the schedule;
- Minimizing the amount of waiting time; and
- Maximizing the chance of executing the schedule.

Both SCHEDULER and SMASH contribute to the literature by identifying models that focus on the decision-making process. However, these two models are limited to individual decision making. These models do not take into consideration the interactions that may take place in the household, in particular, the need to chaperone children, which was highlighted as an important constraint by Hagerstrand (1970) and Chapin (1974). Furthermore, both SCHEDULER and SMASH neglect mode choice in their models.

2.4.3 Household Heuristic Approach

This third approach for modelling activity and travel behaviour suggests that travel decisions are made at the household level. This approach attempts to address the constraints that may be imposed by other individuals within the same household. Moreover, these models postulate that household travel is also a result of many other broader long-term household decisions such as the decision to marry, have children, settle in a particular neighbourhood, work at a particular company or purchase a number of household vehicle (Arentze & Timmermans, 2000). These models do not necessarily estimate these decisions, but they may be determined in a broader modelling effort. In order to capture the complexity of these decisions, models within this approach are typically simulation based, in which the actions and characteristics of the household are simulated over time (Miller, 2005). Moreover, this approach is an application of agent-based modelling, implemented through object-oriented programming, are a common method for this approach. Agent Based Models (ABM) consist of a system of individual entities that represent decision-makers, which interact in the system based on specified rules which determine results within the given environment (Bonabeau, 2002).

One example of this approach is Albatross: 'A Learning-Based Transportation Oriented Simulation System' (Arentze & Timmermans, 2000). One fundamental difference in this model is that the choice behaviour is not purely based on utility maximization. Instead, Arentze & Timmermans (2000) suggest that individuals learn about different attributes of choices based on previous experiences or through social interactions with others. As a basic example, a person does not simply select an activity location based on minimizing travel time to an activity, but it also considers the attractiveness of a location (similar to a gravity model). The search of a feasible location continues until a satisfactory location is found, consistent with the literature that the optimal solution is not necessary.

The scheduling algorithm for Albatross is capable of scheduling the activities of up to two household members. The presence of children can influence household decisions, but they are not specifically modelled in Albatross. The algorithm first schedules the work activity (as it is hypothesized that this has the highest priority) and determines the travel mode for this trip. Then, the algorithm alternates between each household member to determine if, and when, any flexible activity should be added to the person's schedule. Once the activities have been included into the schedule, the algorithm creates trips to link the different activities into a tour, and then selects a mode for each tour. One stipulation in this model is that the mode must stay the same for the entire tour. Finally, the locations of activities are selected based on a heuristic that considers travel time and the attractiveness of a location (Arentze & Timmermans, 2000).

Another example of this approach is the Travel Activity Scheduling Model with Household Agents (TASHA), which is a simulation-based household travel model of the Greater Toronto Area (Roorda et al., 2005). TASHA is part of a broader integrated model of land use and transportation in the Greater Toronto Area (Salvini & Miller, 2003). In TASHA, the demand for a particular activity arises from the need to accomplish a project, which is a coordinated set of tasks with a common goal or outcome (Miller, 2005). Furthermore, Miller (2005) suggests that activities may be completed together with more than one household member as a joint activity.

Roorda et al. (2005) outlines the first implementation of TASHA, which creates a 24-hour household schedule. The scheduling algorithm first identifies the activities that should be included in the schedule based on distributions of activity frequencies in the Transportation Tomorrow Survey (TTS) conducted in the Greater Toronto Area. The algorithm then attempts to schedule each activity and its associated travel based on the priority of the activity. The algorithm is capable of adjusting the start and end times of activities in order to resolve any conflicts with overlapping activities. Once a schedule is finalized, the algorithm then assigns the mode choice for each tour of each person. The initial implementation of TASHA did not consider the activities of dependent household members that cannot travel on their own.

A subsequent paper introduces household interactions within an updated tour-based mode choice model for TASHA (Roorda, Miller, & Kruchten, 2006). This econometric model takes into account the need to chaperone dependents to activities. Moreover, it also considers the allocation of vehicles within the household, and also models ridesharing (Roorda et al., 2006). The model first identifies the mode choice for any independents and allocates the vehicles to the tours that maximize household utility. Following this allocation, the model attempts to join together individuals on existing tours for ridesharing if it will increase household utility. Ridesharing is undertaken if the utility of the passenger from travel cost or time savings is higher than the disutility imposed on the driver serving the passenger. If opportunities to rideshare on existing tours are not available, new tours to serve a passenger’s activity are considered only if it will increase the household utility. As this model considers several concurrent decisions, a genetic algorithm is employed to estimate the parameters of this complex mode choice model (Roorda et al., 2006).

Other examples of household heuristic models include CEMDAP (Bhat, Guo, Srinivasan, & Sivakumar, 2004), FAMOS / PCATS (Pendyala, Kitamura, & Akira Kikuchi, 2005) and ADAPTS (Auld & Mohammadian, 2009). CEMDAP is a simulation-based model with three components that generate the characteristics of the daily schedule, tours and activities for adults in the household. Various econometric models are embedded within CEMDAP, such as discrete choice models to select activity types, and duration models to determine the length of a tour or activity. FAMOS is the Florida Activity Mobility Simulator, which is a simulation-based travel demand model that is being implemented for the state of Florida. Within FAMOS, there are two modules: the Household Activity Generation System, which synthesizes a population based on the local household travel survey, and the Prism-Constrained Activity-Travel Simulator (PCATS) (Pendyala et al., 2005). PCATS develops a daily activity schedule based on the spatial and temporal constraint principles first proposed by Hagerstrand (1970). Within PCATS, the model first inserts work or school activities into the schedule. It then determines within the open periods of the day if there is any time to conduct an additional activity. If so, PCATS will identify the activity type, location and travel mode using two discrete choice models, plus it will determine the activity duration using a hazard-based model (Pendyala et al., 2005). ADAPTS is also a simulation-based model that generates activity schedules based on three key sequential steps: activity generation; activity planning; and activity scheduling (Auld & Mohammadian, 2009). Within each of these steps, there are econometric models that determine the characteristics of the planned activities (e.g. activity time, participants, location and travel mode), as well as a rule-based model to resolve any scheduling conflicts (Auld & Mohammadian, 2009). Each of these three models provide another approach to representing household travel decisions; however, each of these lack the explicit representation of children (dependents) and their activities within the model.

2.5 Chapter Summary

In the literature, it is recognized that there is a relationship between land use and transportation. Changes in one system ultimately has an effect on the other system. Integrated land use - transport models have been developed to estimate these interrelated urban changes. With respect to the representation of transport, one of two main approaches are used in integrated land use - transport models: the classic four-step travel forecasting model and the activity-based travel model.

The four-step model is widely used in practice and within integrated land use - transport models. This approach relies on several assumptions that simplify the analysis process but may not be necessarily representative of travel behaviour. The assumptions and limitations include the following:

- An approach that solves the decision of location, mode and route of trips in a sequential method whereas these decisions are often related;
- The aggregation of input characteristics and output trips to a TAZ level;
- The misrepresentation of mode choice as an unrestricted process that is not constrained by resource or location limitations; and
- The treatment of trips as an independent unit without regard for trips that may be linked together.

The combination of these assumptions and limitations restrict the ability for the four-step model to reflect underlying behaviour that ultimately influences household transport and location decisions.

The development of activity-based travel models has emerged in the literature to address the original concerns of the classic four-step model and to improve the representation of travel behaviour in models. As the name suggests, the focus of the model is on the activities that motivate travel. The common approach for activity-based travel models is to organize activity and trips into tours. The timing of activities and the mode choice of the tour are based on temporal and resource constraints. Early activity-based travel models, such as STARCHILD, determined all possible tour options and assumed that a person would select a tour under the approach of utility maximization. A second group of activity-based models challenged the assumption that individuals have perfect knowledge of all possible tour options and suggested a sequential approach to developing tours. In this way, the model is more reflective of actual human capability. SMASH and SCHEDULER are examples of such models, however, these models only focus on the timing and location of activities for individual tours. These models do not consider mode choice, nor do they take into account travel decisions based on interactions with other household members. A third group of activity-based models, including Albatross (Arentze and Timmermans, 2000) and TASHA (Miller et al, 2005), among others, addresses this limitation by incorporating interactions among household members.

The model that is proposed in this thesis builds upon the literature by adding to the collection of household heuristic models that are able to represent the interactions of household members in their regular transport decisions. This proposed model is similar in principle to the most recent household heuristic activity-based travel models, such as Albatross and TASHA. Both of these models consist of algorithms that follow a sequential process to construct tours and to select the transport modes for each tour. As well, the decision making agent in these models is the household, which also has influence on broader transport and housing location decisions. However, this proposed model differs from these existing models through the following contributions. First, this model improves upon Albatross, CEMDAP, FAMOS and ADAPTS by explicitly representing the travel demand and behaviour of dependents such as children, whereas in Albatross only the presence of children is considered in the model. As well in this proposed model, activities are scheduled in terms of priority, whereas in Albatross, the model alternates between household members to schedule activities. Second, this proposed model uses a rule-based approach to mode choice, which is a simpler alternative to the genetic algorithm used to develop the mode choice component in TASHA.

Finally, from the perspective of the broader research goals to understand the influence of household decisions on land use and transport systems, there is the need for a model that is able to efficiently find a solution for the short-term transport decision challenge. The model does not need to be as robust as what has been previously proposed in the literature. Instead, the proposed rule-based model in this thesis is meant to quickly arrive at a solution that can be input into a broader model. This work addresses a need to have a working household-level transport model that can be used to explore the relationships and changes within land use and transport systems in Kitchener and Waterloo.

The following chapter seeks to understand existing travel behaviour for households, which will inform the concepts and development of the proposed household travel resource allocation model, outlined in Chapter 4.

3.0 EXPLORATORY SURVEY

3.1 Overview

One of the key objectives of this research is to increase understanding of the actions and behaviour of agents within households as they undertake travel decisions. An exploratory survey was developed and implemented to accomplish this research objective. This exploratory survey is meant to describe general patterns and insights that will inform the development of a household-based activity travel model. Some of the results from this exploratory survey are used to justify model design decisions, while other results are used in the testing of the model (in Chapter 5). This chapter provides the details for the method of the exploratory survey, and discusses the insights that can be derived from this survey.

3.2 Methods

A household travel survey is the main survey instrument that is employed in this study. This type of survey is commonly used in transportation planning to collect both travel demand data, as well as attitudes and opinions of households (Stopher, 2000). In this study, this survey is used to gather information on household activity-travel patterns and behavioural motivations. This survey requires the participation of at least one member of the recruited household.

3.2.1 Study Sample

Representatives of households for this exploratory survey were recruited to participate using the convenience sampling technique. The study sample includes 14 households: six of these households have identified that at least one member of their household is dependent on others in order to travel to and from some activities. All participants in this sample that were recruited are affiliated with the University of Waterloo, either as a student, faculty or administrative support staff member. Emails were sent by the researcher to staff members in the School of Planning and the Department of Civil and Environmental Engineering at the University of Waterloo. Faculty and student colleagues of the researcher were also recruited in-person.

This non-random sampling technique and recruitment approach was chosen for this exploratory survey because of its ease of implementation and due to time constraints for the completion of the study. This chosen sampling technique is in contrast to a random sampling technique that is typically undertaken in household travel surveys. Random sampling methods strive to minimize bias in order for the sample to be generalizable to the population (Stopher, 2000). As a result of this survey design decision, there may be a potential bias as all representatives of the households participating in the survey have some affiliation to the University of Waterloo. This bias means that at least one member of each household in the sample may travel to the University of Waterloo for either work or school. The results of this survey cannot be generalized to the entire Kitchener - Waterloo study area; however, the survey provides some preliminary insights of how different households make travel decisions and achieves the objectives set out for this study. In order to extend the applications of the study to the broader Kitchener - Waterloo area, a more comprehensive survey of households recruited through a random sample is required.

3.2.2 Data Collection

Recruited participants were invited to participate in the survey and to respond on behalf of each member of their household. While some traditional household travel surveys may be conducted by mail, over the phone, or on the web, a computer-aided personal interview was employed as the preferred survey method. In this method, the survey questions were provided to participants in advance through email, and then the answers to each question were directly entered into a computer database by the interviewer during the survey. This method can expedite the processing of survey data as answers are entered immediately into the system, but the process of interviewing requires a large amount of time (Stopher, 2000). This method was selected for two main reasons. The first reason is that this method allowed the interviewer to assist participants when they were asked to provide a postal code that represents the location of each activity. The second reason is that an in-person survey also provided the flexibility for the interviewer to understand travel decision motivations that were not originally captured within the closed-ended survey questions. Any additional insights on household travel behaviour from the participants was also be entered into the electronic spreadsheet.

A set of questions were developed specifically for this household travel survey. These questions provided the base structure for the survey, but allowed the flexibility for the interviewer to explore other motivations for household travel behaviour. As with more recent surveys of this type, the approach of the questions focused on gathering information on the activities in a household as opposed to specific trips (Stopher, 2000). This household travel survey consisted of two main sections, which are discussed below. A copy of these questions has been included in this thesis as Appendix A.

The first section of the survey asked the respondents to create a household travel profile by providing demographic and travel information for each person of the household. Respondents were then asked to provide the activity schedule for one weekday of the household. While it is recognized that not all days within the week have the same level of household activity and that a week-long household activity diary would capture these differences, an activity schedule for a single day was requested to minimize the survey burden on respondents. As a counterbalance to this survey design decision, the respondents were asked to outline a schedule that is representative of the busiest day for the household. This busiest day is assumed to be the worst case scenario in terms of travel resource allocation and is expected to provide some insight regarding the flexibility of the household in terms of activity scheduling. Table 3-1 lists out the information collected in the first section of the survey.

Table 3-1: Information Collected for Each Person in the Household

Demographic Information	**Travel Information**
- Age - Gender - Employment Status - Student Status	- Possession of a Driver’s License - Possession of a Transit Pass - Ability to Travel Independently - Number of Vehicles in the Household - Money Spent on Transportation
Activity Schedule of Busiest Day For each activity in day: - Activity Type - Location - Start Time - End Time - Travel Mode to Activity - Trip Start Time prior to Activity	

The second section of the household travel survey explored the factors that influence household activity and travel scheduling decisions. It focuses on gathering household-level information as opposed to individual person-level information. Ten questions were asked in this section to provide insight on the original questions that motivate this research.

Respondents were first asked in this section to provide a ranking of activity categories in the order from most to least important to accomplish. A person of a household may engage in many different activities over the course of the day or week, but often these activities fall into common activity types. The definition of these common activity types range across the literature. As an example, Recker, McNally, & Root (1986) categorized activities into three major types: subsistence (e.g. work or school), maintenance (e.g. shopping or business), and leisure (e.g. social or entertainment). Miller (2005) suggested a more disaggregate list of 10 activities including entertainment/recreation, formal group activity, household maintenance, information gathering, personal business, personal maintenance, serve-dependent, shopping, socialise with friends and relatives, and work. Furthermore, the activities may be conducted within the household’s residence or outside the home (Miller, 2005). The types of activities included within this survey falls between this aggregate list of Recker et al. (1986) and Miller (2005) and focus on the activities that require travel. The activity categories and definitions included in the survey are:

- Chaperone activities (e.g. accompanying others to their own activities)
- Grocery shopping activities
- Other shopping activities (e.g. shopping for housewares, clothing or other personal items);
- School or work activities;
- Service activities (e.g. attending medical appointments, visiting banks, or other services);
- Social activities (e.g. meeting with friends or family, attending events, or helping others); and
- Recreational activities (e.g. exercising, playing team sports, or visiting parks).

Participants were asked to rank these activity types in the order of its priority in the household travel schedule, from the most important activity to accomplish in a given day to the least important activity that may be deferred to another day. The answers from this question (#1) informed the order in which activities should be scheduled in a household activity-travel model.

A second set of questions (#2 - #6) asked respondents on the level of flexibility for the household in the context of its busiest travel day. In Question 2, participants were asked to select the maximum duration possible for any activity that would be added to its busiest travel day. The possible answers to this question include an activity duration of: at least 2 hours, at most 2 hours, at most 1 hour, and at most 30 minutes. Participants may also indicate that they have no flexibility in the household schedule for an additional activity. The results from this answer, in conjunction with an analysis of the duration of activities and travel from the household schedule, were expected to provide insights on the maximum amount of time household's expend on activities.

Questions 3 through 6 then explored when households would schedule unexpected activities depending on the priority and the person (i.e. independent or dependent) assigned to the activity. The participants were asked for each situation if they would schedule the activity: during the busiest day, during another weekday, or during the weekend. Participants were also able to state that they would not schedule the hypothetical activity. The answers to these multiple choice questions were expected to be indications of the actions that households undertake when the duration of activities exceeds the time available within a given day.

A third set of questions (#7 - #8) focused on the household's ability to conduct activities with their current household travel resources. Respondents are asked if their household is able to accomplish all of their desired activities with their existing transportation resources in Question 7. If not, the respondents were invited to identify the types of activities that they are unable to accomplish. In Question 8, the respondents were asked to indicate how often their household relied on external resources to fulfil activities and travel demands.

The final set of questions in this section (#9 - #10) focused on the motivating objectives and factors for household travel decisions. Respondents were asked to rate a set of factors and objectives based on their level of importance in influencing chaperone decisions and overall household travel decisions. Respondents were also able to provide additional factors and objectives that were not originally listed in the survey.

From this survey, general descriptive statistics (e.g. averages and ranges) and specific insights are determined and discussed in the following section.

3.3 Survey Results

Based on the outlined survey methods, 14 household travel surveys were completed for this study. This section describes the results and discusses the implications for a household activity-travel model. The first sub-section will describe the characteristics of respondents that are included in this study. The subsequent subsections will then discuss the results of the second section of the survey that explored the factors, attitudes and preferences that influence household travel decisions.

3.3.1 Distribution of Household Characteristics

Key characteristics of participating households were derived from the data collected in the survey. These characteristics describe the location of the household's residence and employment, as well as the composition of the household in terms of travel independence status and travel resource availability. A summary of this information is given in Table 3-2, while the following subsections provide a further discussion of these characteristics. Specific characteristics of the persons in each household are provided in Appendix B.

Table 3-2: Characteristics of Households in Sample

Household	**Location (TAZ #)**	**# of Persons**	**Work Status**			**Traveller Independence**		**Travel Resources**	
			Full-Time	Part-Time	Student	# of Dependents	# of Independents	# of Drivers	# of Vehicles
1	7247	5	1	1	3	1	4	2	1
2	7281	3	2	0	1	1	2	2	2
3	7292	2	0	0	2	0	2	2	1
4	7039	2	1	0	1	0	2	0	0
5	7291	2	1	1	1	0	2	1	0
6	7263	1	0	0	1	0	1	1	1
7	7116	2	2	0	0	0	2	2	0
8	9888	3	1	2	1	0	3	3	3
9	7151	4	2	0	1	2	2	2	2
10	9888	5	1	1	3	3	2	2	2
11	9888	4	2	0	2	2	2	2	3
12	7177	2	2	0	0	0	2	2	2
13	7254	1	1	0	0	0	1	1	1
14	7281	2	1	1	0	0	2	2	3

* **Note**: Zone 9888 represents a zone external to Kitchener - Waterloo.

Residential and Employment Locations

The majority of households in this survey reside and work within Kitchener - Waterloo. This survey has participants from both the central areas (near Uptown Waterloo and Downtown Kitchener) and the suburban areas (in the west end of the cities). Figure 3-1 is a map that depicts the location of households and employment for participants of this survey. This map shows that participants' household and employment locations are distributed across the study area. The number of respondent households in each of the identified 'Location of Household' TAZs is equal to one, with the exception of TAZ #7281 where there are two respondent households. The number of persons that are employed in each of the identified 'Location of Employment' TAZs is equal to one, with the exception of TAZ #7042 where there are nine employed persons, and TAZ #7153 where there are two employed persons. The Location of Employment does not include the location of schools for those persons identified as students.

Some of the households surveyed in this study may have members that either reside or work outside of the study area. Of the 14 households in the survey, four households reside outside of Kitchener and Waterloo. Similarly, one household has a member that works outside the study area in Cambridge, and another household has an individual that works outside of the Region of Waterloo. The data of these households have been kept within the survey results as their priorities and motivations for travel decisions are still informative to the development of a household activity-travel model. The diversity in household and employment locations is important for this study as these locations influence the distance to activities and the proximity to transport mode alternatives, which in turn may affect household travel patterns and mode choices.

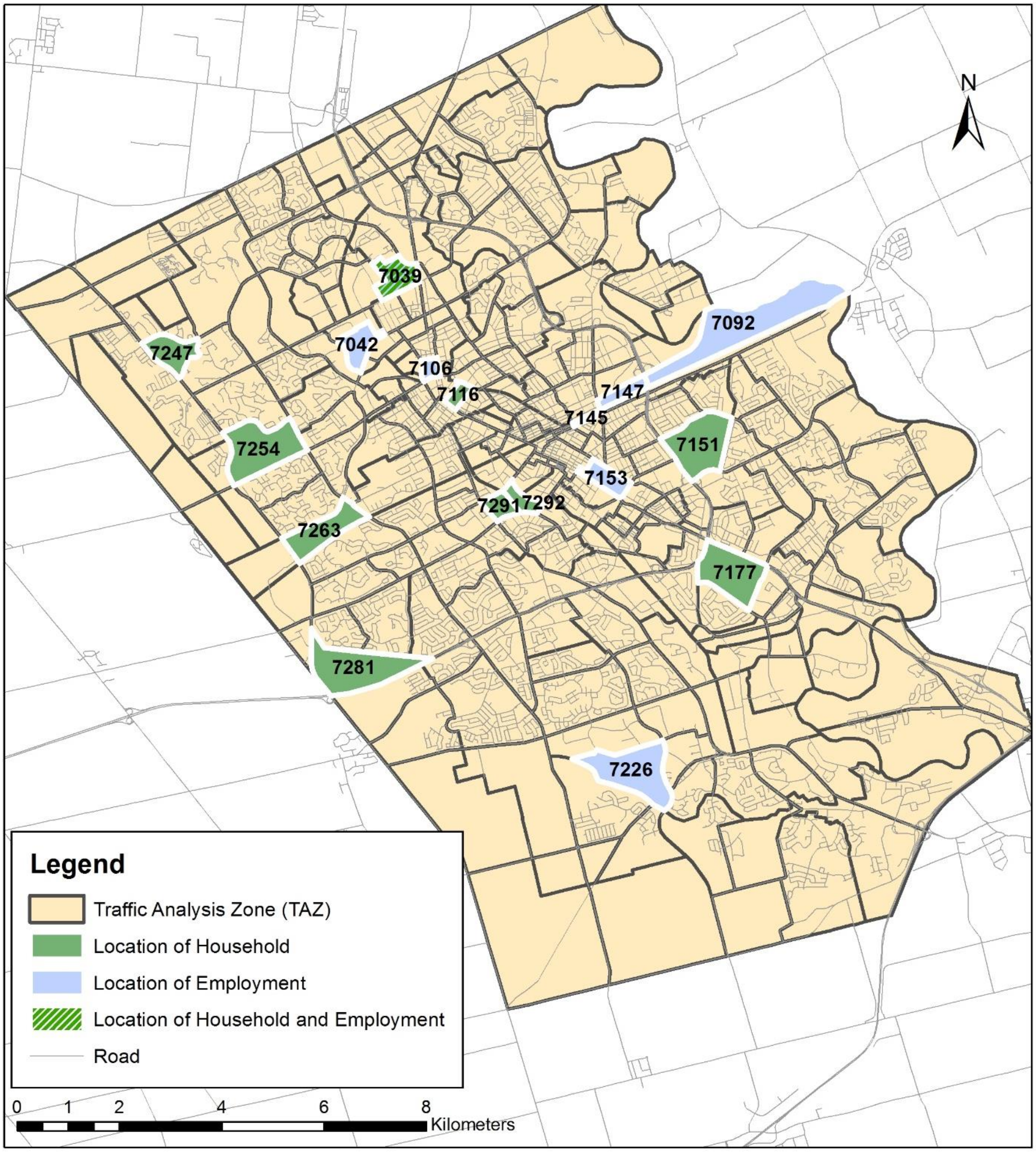


Figure 3-1: Location of Households and Employment for Participants in Kitchener-Waterloo

Household Composition by Travel Independence

Each of the households in this survey comprise up to five individuals. The individuals in each household have different demographic characteristics such as age, gender and employment status. The majority of households in this survey have at least one person who is employed. Two of the households consist of only students.

In the context of this study, it is important to consider whether or not the household has individuals who are dependent. Recall that within this study, independence refers to the ability for a person to travel to activities on their own. A person is considered dependent if he or she requires a chaperone to accompany him or her on a trip. In this survey, five households identified that at least one of their members was dependent. These members may be children or those who have physical or cognitive challenges. These households provided the circumstances in which these individuals require a chaperone to travel to and from their activities. The answers from these households reveal that there are varying levels of dependence. In some households, the dependents must be chaperoned by an independent for travel to and from *all* activities. Within this exploratory survey, two of the households stated that at least one member could be identified as fully dependent. In the three other households, the dependents may be described more accurately as 'semi-dependent' because there are particular circumstances where the individual can travel on their own to activities.

The circumstances that enable independent travel may revolve around the type of activity. Three of these four households noted that the semi-dependent individuals may travel to school and to recreational activities on their own. The fourth household stated that the semi-dependent is able to travel to the store on their own. The common theme across these households is the location and travel mode of these activities. The participants stated that the semi-dependents are allowed to travel to these activities on their own if they were within a walking or cycling distance. Furthermore, none of these semi-dependents were allowed to use transit on their own. In one case, however, the household identified their children as being independent as they were provided with a transit pass to travel to any of their activities.

Whether or not an individual is able to travel on their own to activities is often influenced by the age of the person. From this survey, children as young as nine years old were identified as semi-dependent and children as young as 15 years old were identified as independent. However, this definition of dependence is also subject to the comfort level of the independents (e.g. parents or caregivers) in the household. This comfort level may be a result of a number of factors that may include but are not limited to: activity locations, community safety, neighbourhood built form, parenting styles, and personal perceptions and preferences. This study was not intended to explore these factors, but further research may reveal the motivation and attitude of households on travel independence. What is evident from these results is that there are varying levels of dependence and that modelling efforts should reflect this diversity as the difference in dependence will affect the required household travel resources.

Availability of Travel Resources

The availability of travel resources – such as vehicles and chaperones – are important to household travel behaviour. When there are no available vehicles, individuals have to consider alternate modes such as transit, bicycling or walking to destinations. In the case where there are no available chaperones, dependents are not able to travel to their activities. Households are categorized based on a comparison of the available and required household travel resources. Households that have at least the same number of vehicles as licensed drivers are considered ‘adequately resourced’, while households that have fewer vehicles than drivers are considered ‘under resourced’. In this survey, 10 households are adequately resourced for vehicles, while four are under resourced. In the same way, households that have at least the same number of independents as dependents are ‘adequately resourced’, while households with fewer independents than dependents are ‘under resourced.’ Only one household is considered under resourced, while the rest of the households are adequately resourced in terms of chaperones; however, only four of these households have dependents that require a chaperone.

It is hypothesized that ‘under resourced’ households for either chaperone or vehicle resources have more complex travel behaviour than that of ‘adequately resourced’ households that rely more on mutual decisions and sharing of resources. As an example, a household with three drivers and two vehicles would have to determine which driver has access to the available vehicles, whereas if this household had three vehicles, all drivers do not necessarily have to consider the other individuals actions.

3.3.2 Activity Prioritization

Participants were asked to rank a list of seven activity types in the order of their priority in the household schedule. An activity type that is ranked 1 is the highest priority activity that is the most important to accomplish, while an activity type that is ranked 7 is the lowest priority activity that may be deferred to another day with more flexibility. In Figure 3-2, the average and range of ranks is presented for each activity type. All 14 households are included in these results; however, the ranking results of the chaperone activity has been disaggregated by whether or not the household has dependents.

From these results, it is evident that there is a most households consider school or work activities as their first priority. There is little variation in the ranking across the households for these activities. This supports the notion that school and work activities are considered mandatory activities that must be accomplished. The next most important activity type is to chaperone or accompany dependents to their activities; however, this is the case only for households with dependents. If the household does not have a dependent, chaperone activities are the least important. Of the remaining activities, which are often classified as discretionary, there is a wide range of ranks, which reflects the variation in household preferences for certain activity types to be prioritized over others. Even though there is this wide range, the average and location of these ranges indicate that households tend to prioritize these discretionary activities in this order: service, grocery shopping, social, recreational and other shopping. The result of this activity prioritization is used in the development of the household activity-travel model.

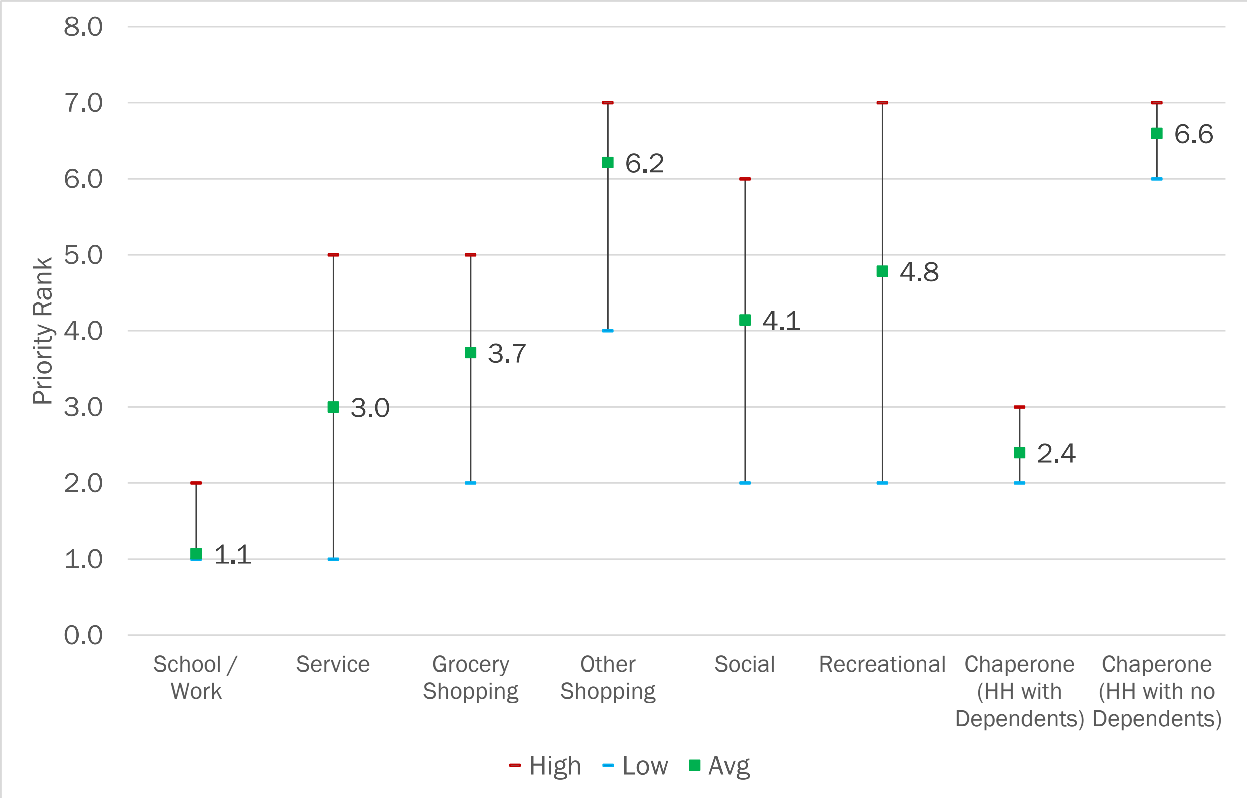


Figure 3-2: Priority of Activity Types

3.3.3 Flexibility of Household Schedule

In the survey, each household was asked to identify the household's busiest travel day and then provide the schedule for each person in their household on this day. This schedule included the start and end times of each activity, as well as the start time of the trip preceding each activity. From this information, the duration of activities and travel was calculated. The remainder of the time in the day is assumed to be spent at home. The average durations for each of these categories is depicted in Figure 3-3.

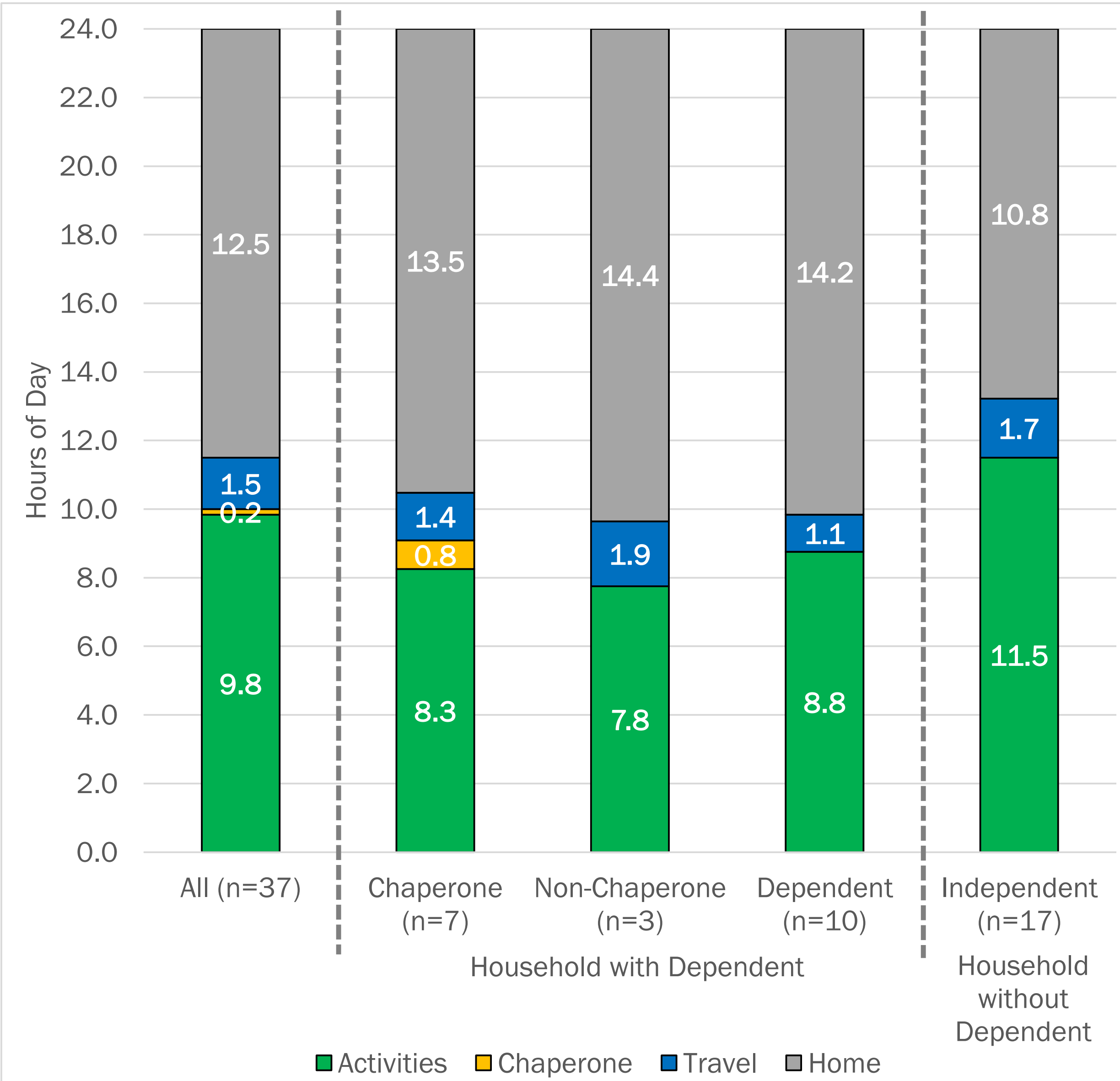


Figure 3-3: Average Time Allocation for a Person based on Travel Independence

The results show that on average each person spends approximately 10 hours conducting activities and 1.5 hours travelling to and from activities. The balance of the day is spent at home. These results have also been stratified by whether or not the household has a dependent, and also by the type of person within the household. There are substantial differences in these durations when the data are stratified by these categories. The average amount of time spent on activities is much higher in households without dependents than in households with dependents. Individuals in households without dependents spend on average approximately 3 hours more on activities outside of the house than their counterparts in households with dependents. This difference is potentially a result of the need to conduct some activities, such as preparing meals, taking care of children, or supervising studies, within the home. This study did not ask about activities within the home; therefore, further research on these home activities may provide additional insight into this difference.

Given the activity schedules of the busiest travel day of the household, the respondents were also asked to indicate the amount of flexibility their household schedule has to include an additional activity. The results of this question are provided in Figure 3-4. The majority of responding households indicated that there is some flexibility to add an additional activity even on its busiest travel day. However, households with dependents have less schedule flexibility than households without dependents. Approximately 40% of households with dependents indicated that they have no flexibility on their stated busiest travel day to add additional activities, and of those that do have flexibility, the duration of this additional activity would be between 30 and 60 minutes. In contrast, the majority of households without dependents are able to add an activity between 60 and 120 minutes in duration.

Combined with the assessment of the activity schedules, the responses from this question provide insight into a time budget or the maximum amount of time that a household allocates to conduct activities. The factors that influence the size of the budget is an entire other subject of research. Mokhtarian & Chen (2004) summarized over 24 empirical studies of time and cost budgets. They found that time budgets are not constant but are context-specific, depending on the characteristics of the household, its members, and their activities. The findings of this survey confirm that there is a difference in time utilization based on whether or not there are dependents in the household. These findings also inform the activity-travel model on how much time may be allocated to activities.

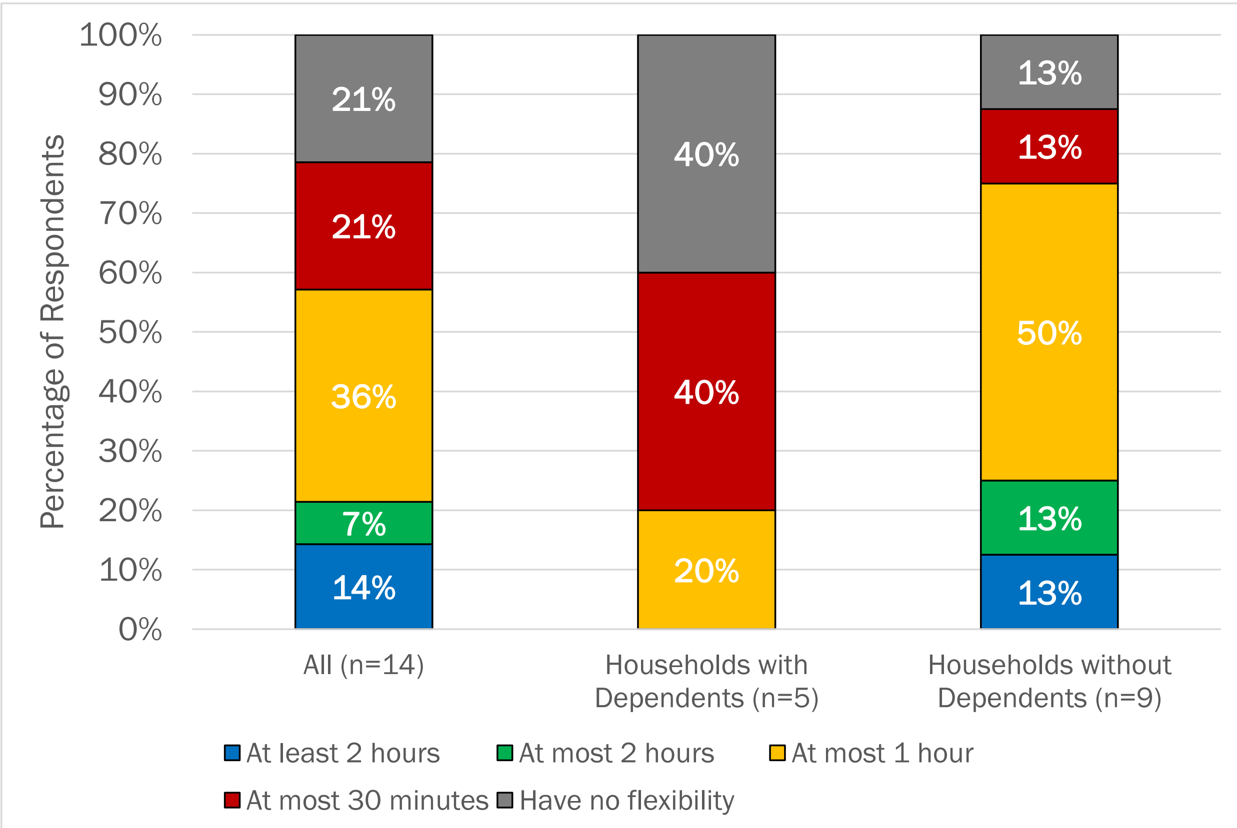


Figure 3-4: Duration of an Additional Activity that a Household is Able to Schedule in its Busiest Day

The final set of questions relating to schedule flexibility asked participants to determine when they would schedule an unexpected new activity in their schedule. The results of these questions are depicted in Figure 3-5. The results share many similarities across the types of activity scenarios. Based on these results, if any unexpected activity arose for a household, it will be scheduled. None of the participants selected that they would cancel the unexpected activity altogether, regardless of whether it was a high or low priority activity. The clear difference in these results is when an unexpected activity of different priorities would be scheduled. If the activity had a high priority, the activity would be scheduled during the same busiest day or on another weekday. Respondents appear to treat dependent high priority activities with more urgency than independent activities, as the majority of those households would try to schedule that activity on the same day. If the activity had a low priority, the activity would likely be scheduled on the weekend, regardless of whether the activity is for an independent or dependent person.

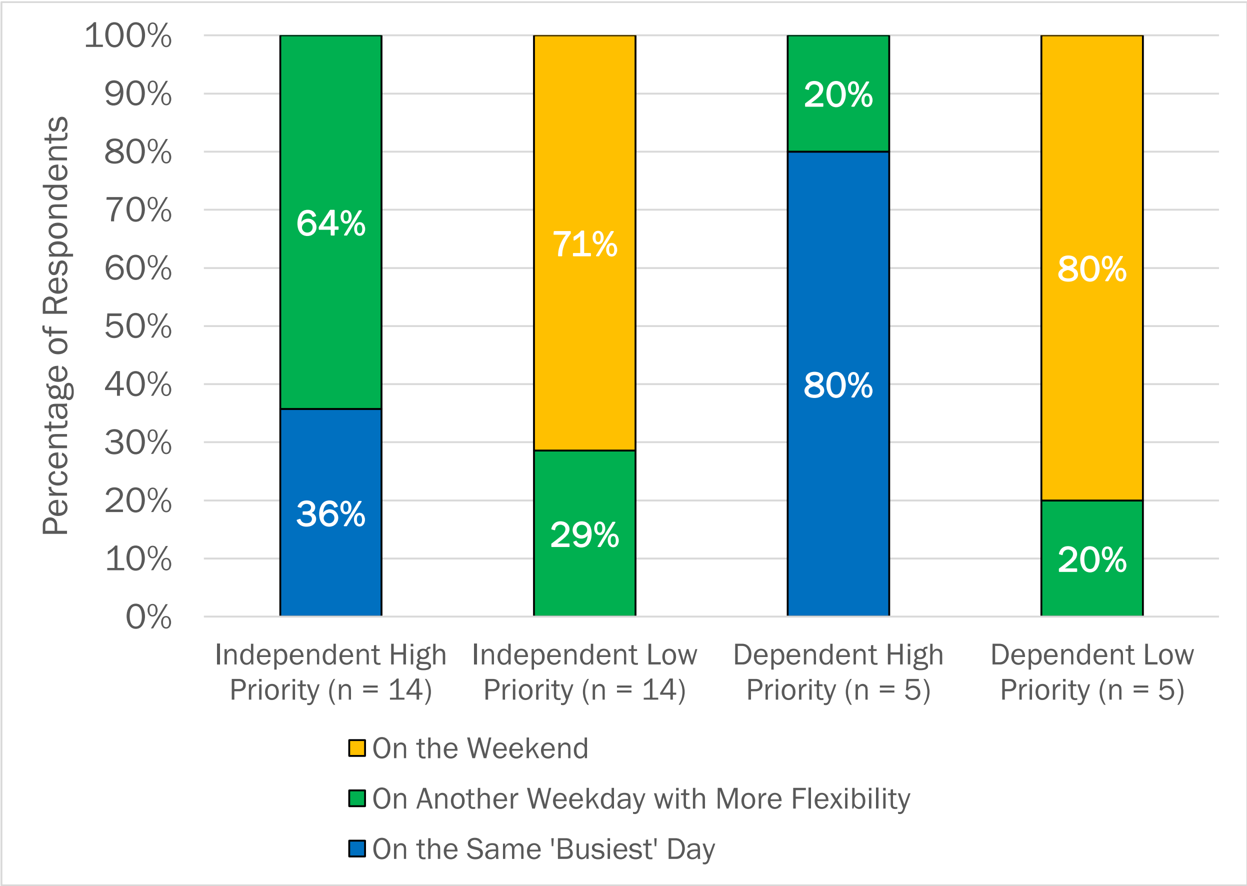


Figure 3-5: Household Preference to Schedule an Unexpected Activity

The interesting point to take away from the results in Figure 3-5 is that households tend to avoid placing an unexpected activity within the same busiest day. This preference is likely reflective of the effort to coordinate, readjust or reschedule other activities that have been preplanned and scheduled for the day. This result leads to an important assumption that is foundational to the proposed household travel model. It is assumed that for a given day, activities are scheduled in the order of priority (as indicated in Section 3.3.2). There is no readjustment of activity start times once it is placed in the schedule. Any subsequent lower priority activities will be placed in the remaining open schedule, or if it is not feasible to schedule, it would be deferred to another day. This assumption is a convenient simplification for this study, but it is supported by the results from the survey.

3.3.4 Ability to Conduct Activities

Households also responded to questions relating to their ability to achieve activities with their existing set of transport resources. Most households indicated that they were able to accomplish their desired activities; however, there were a few exceptions. The households that were not able to accomplish all of their desired activities did not have access to a household vehicle. In these cases, grocery activities that required shopping for larger items became more difficult. In one household, recent access to a local car-share has now enabled the accomplishment of these previously challenging activities.

Households were also asked to indicate how often they rely on external resources – extended family, coworkers or friends – to conduct travel. These external resources may chaperone dependents or offer rideshares and carpools to common activity locations. The results of this question are illustrated in Figure 3-6.

Based on these results, a significant majority of these households rarely use external resources to fulfil their existing transport demands. This result is expected as most of the households indicated that they were able to accomplish all desired activities with their own existing resources. Only 14% of responding households use external resources at least once a week. This result suggests that for this study external resources may be considered but do not need to be an integral part of the proposed activity-travel model.

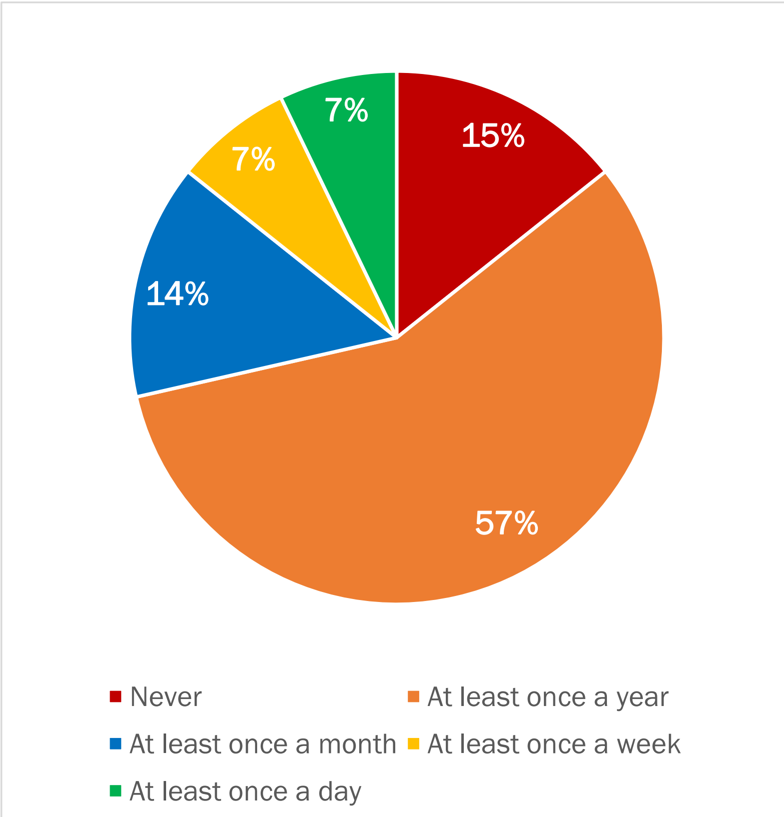


Figure 3-6: Proportion of Households that Rely on External Resources for Transport

3.3.5 Motivations for Household Travel Decisions

Each household rated several motivations based on their importance in influencing overall household travel decisions. A rating of 1.0 indicates that the motivation is very important to the household, whereas a rating of 5.0 indicates that the motivation is not very important to the household. Table 3-3 contains the result of this exercise. This table includes the average ratings for each motivation across the entire sample, as well as the averages for the households with and without dependents.

Table 3-3: Motivations for Household Travel Decisions

Motivation	Avg. Rating (ALL) n = 14	Avg. Rating (w/ Depend) n = 5	Avg. Rating (w/o Depend) n = 9
Maximizing Schedule Convenience and Flexibility	1.9	1.4	2.2
Maximizing the Benefit from Achieving Activities	2.0	1.8	2.1
Minimizing Household Travel Cost	2.9	3.6	2.6
Minimizing Environmental Impact from Travel	3.6	4.8	2.9
Achieving Fitness and Exercise	3.8	4.2	3.6

The results in Table 3-3 indicate that households seek to maximize schedule convenience and flexibility, as well as the benefit from achieving activities when making household travel decisions. These motivations are consistently important regardless of whether or not the household has dependents. An important insight from this result is that households value the ability to accomplish activities. While travel enables a person to conduct activities in different locations, the time associated with travel directly limits the amount of time available for activities. Therefore, in order to realize the above motivations, households likely consider travel time in household travel decisions.

The remaining motivations – minimizing travel cost, minimizing environmental impact and achieving fitness – are substantially less important for households with dependents. In contrast, minimizing household travel cost and minimizing the environmental impact from travel are secondary motivators for households without dependents. These results suggest that households with dependents will make mode choice or travel resource allocation decisions based on the ability for its members to accomplish their desired activities. Dependents add an additional constraint and demand in an independent's travel schedule; therefore, the remaining motivations have little to no influence in the travel decision. In contrast, a household without dependents do not have to consider this additional travel constraint, and the travel schedule for each independent may be more flexible. In this case, other considerations such as minimizing household travel cost and minimizing environmental impact may have a stronger influence on household travel decisions.

The six households that have dependents were also asked to rate the importance of various factors that specifically influence their decision on chaperone allocation. Table 3-4 provides the average rating of importance for each factor. A rating of 1 indicates that the factor is very important and a rating of 5 indicates that the factor is not very important in influencing this decision.

Table 3-4: Factors that Influence Household Chaperone Decisions

Factor	Average Rating n = 5
Travel Distance to Chaperone	3.0
Schedule Availability	1.6
Travel Cost to Chaperone	4.8

These results indicate that when households determine which independent that chaperones the dependent, the most important factor that is considered is schedule availability. Travel distance and travel cost to the chaperone are substantially less important in this decision. This result confirms the findings in Table 3-3, which suggests that households primarily make household travel decisions to maximize schedule convenience and flexibility, as well as the benefits from achieving activities. In this case, when a dependent desires to travel to an activity, the independent that is allocated to the dependent is the one that has available time in the schedule.

3.4 Chapter Summary

This chapter discussed the development, implementation and results of an exploratory household travel survey that is intended to inform the development of a household-based activity travel model. Fourteen participants were recruited for this survey from the University of Waterloo. These participants either worked or studied at the university, but this does not preclude other members of their household from working or studying in other locations. Each participant completed an in-person survey that asked about the activities for each member of their household on its busiest travel day, as well as the preferences and motivations for household travel decisions. The survey results revealed important insights including the following:

- While dependents are defined as an individual who is unable to travel to activities on their own, there is a range of dependence which is related to the travel mode and distance of the activity.
- Activities should be scheduled in this order: school/work, chaperone, service, grocery shopping, recreational, social and then other shopping;
- Individuals from households without dependents spend on average 11.5 hours on activities and 1.7 hours on travel, whereas individuals from households with dependents spend on average 8.0 hours on activities and 2.0 hours on travel;
- Households with dependents have less flexibility than that of households without dependents. A household with dependents may have flexibility to add an activity between 30 and 60 minutes in duration into the schedule, while a household without dependents may add an activity with a duration between 60 and 120 minutes.
- With the exception of dependent high priority activities, most other unexpected activities are likely to be scheduled by the household on another weekday or weekend that has more flexibility.
- Households primarily value the ability to achieve activities and to maximize schedule flexibility when making travel decisions. Households without dependents may also consider other factors such as out-of-pocket household travel costs, and the environmental impact of decisions.

These insights are important to the development of a household-based activity-travel model for Kitchener Waterloo. The following chapter outlines the proposed model concept and its development. Chapter 5 then outlines the application and demonstration of the model.

4.0 MODEL CONCEPT AND DEVELOPMENT

4.1 Overview

Throughout the literature and in practice, it is widely acknowledged that travel demand is derived from the desire for an individual to complete activities in different locations. When a person considers to conduct an activity during a particular day, two basic questions must be answered:

1. When will the activity be accomplished?
2. How will the person travel to the activity?

The answers to these questions are dependent on the amount of free time that is available in a person's schedule, and also on the availability of travel resources, such as a vehicle or public transit. Furthermore, a person does not make these decisions in isolation, but in conjunction with other members of their household that share travel resources. In order to answer the two preceding questions, the household needs to collectively determine:

1. If it has vehicles: who will have access to a vehicle for their travel?
2. If it has dependents: who has the responsibility of accompanying the dependent to activities?

Determining the answers to these questions is the impetus for the household travel resource allocation decision. The primary objective of the household in this decision is for its members to achieve as many of their desired activities as possible given a set of travel resources. The proposed model is intended to represent this household travel decision.

This model takes the following household information as input:

- The number and characteristics of household members;
- The type and location of desired activities;
- The location of the household; and
- The number of vehicles available in the household.

Additionally, the model also requires a representation of the locations in the study area, which is accomplished using Traffic Analysis Zones (TAZs). Furthermore, the cost to travel between origin and destinations in the study area is dependent on these TAZs and the types of travel resources.

Given these inputs, the model undertakes the household travel resource allocation decision process. The model will sort all household activities by their priorities, and then will attempt to place activities into a person's schedule in order of priority. In this process, the model will also determine who is responsible to chaperone dependents, and who has access to household vehicles.

The output of the model is a set of tours for each person. Recall that a tour is defined as a set of consecutive trips that starts and ends at the household's place of residence (Adler & Ben-Akiva, 1979). Multiple activities may be conducted on a tour. With these tours, the model identifies for a 24-hour period when activities take place, when travel takes place and how trips are accomplished. Figure 4-1 provides an overview of the model concept and structure.

The following sections describe each of the components of the model. Section 4.2 describes the household inputs. Section 4.3 provides a brief description of the spatial representation, as well as the details of the calculation for travel costs by different transport modes. Section 4.4 discusses the logic of the proposed model through a couple of hypothetical examples. Section 4.5 summarizes the key principles that are integral to this model.

With the exception of the calculation of travel times and costs for the study area, the components of this model have been proposed and developed by the author of this thesis.

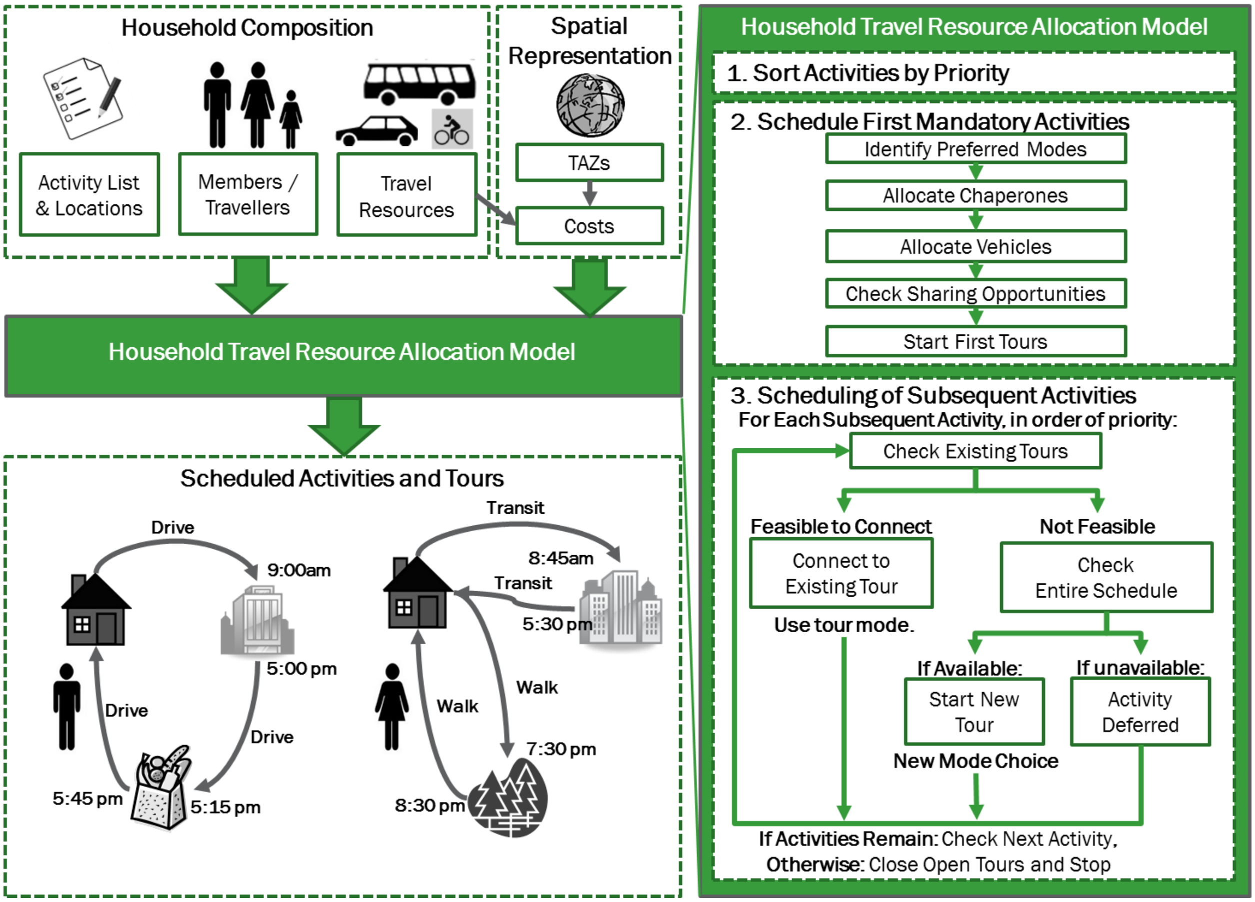


Figure 4-1: Household Travel Resource Allocation Model Structure

4.2 Household Composition

In this model, a household is defined as a collection of individual persons that live together within the same dwelling unit. The household is the fundamental decision maker within this model. Although travel can be undertaken by individual persons, these travel choices are influenced by the collective decisions of the household. Each household has a location, a set of persons or travellers, and a set of travel resources. Each person also has a set of desired activities. The following subsections provide details on each of these components, which are inputs into the model.

4.2.1 Household Location

Each household is associated with a physical location where each person must start and finish each day. All tours in the household originate and terminate at this location. It is represented by an address or six-digit postal code that is converted into a TAZ number. The household location is important in determining the travel costs and times to and from the household's activities.

4.2.2 Household Members

The members within a household are described by the following socioeconomic characteristics:

- Age (number);
- Gender (male or female);
- Employment status (full time, part time, or not employed); and
- Student status (yes or no).

These characteristics influence the types and locations of activities that may be undertaken by the person, which is discussed further in Section 4.2.3. In addition to these characteristics, the persons can be described by the following transportation characteristics:

- Travel independence status (independent or dependent);
- Possession of a driver's license (yes or no); and
- Possession of a transit pass (yes or no).

The travel independence status of the person is especially important in the utilization of travel resources. A person who is *independent* is fully capable of travelling to activities by him or herself using any of the travel resources that are available. A person who is *dependent* is not able to travel without supervision. A dependent requires an independent to chaperone him or her to activities.

In Section 3.3.1, the household travel survey revealed that there is a spectrum of travel independence, and a person may be considered semi-independent if he or she is able to travel to *some* activities on their own. The factors that determine travel independence was related to the travel modes and the types of activities that they are allowed to travel to on their own. In this model, this spectrum of travel independence has been simplified with the following criteria. If a semi-independent person is able to travel to his or her mandatory activities on their own, then they are classified as being independent. This simplified classification means that the model will not automatically assign a chaperone to the semi-independent, but it does not preclude the individual from sharing a ride with a driver to their activities.

4.2.3 Household Activities

Each person within the household has a set of activities that he or she may accomplish during the course of the day. Some of these activities may be considered *mandatory*. These mandatory activities must be accomplished at regular intervals (i.e. every weekday). Examples of mandatory activities include work activities or school activities. Other activities may be considered *discretionary*. These discretionary activities may occur with less frequency and may have less importance, which allows them to be accomplished when there is available time.

The types of discretionary activities follow the categories that were defined in the household travel survey for this study. These activity types include:

- Grocery shopping activities (shopping for food and drinks)
- Other shopping activities (shopping for homewares, clothing or other personal items);
- Service activities (attending medical appointments, visiting banks or other services);
- Social activities (meeting with friends or family, attending events, or helping others); and
- Recreational activities (exercising, playing team sports or visiting parks).

Each activity can be described with the following characteristics:

- Activity type and priority (mandatory or discretionary);
- Location (the TAZ where the activity takes place);
- Start time range (the earliest and latest time that the activity can begin); and
- Duration (the amount of time required to complete the activity).

These activity lists are currently assumed to be exogenous inputs into the model. These lists have been developed based on household surveys, described in Chapter 3. The application of these lists are discussed further in Chapter 5.

4.2.4 Household Travel Resources

Each household has a set of resources that enable the members of the household to travel to activities. These resources include a set of transport modes and a group of chaperones.

In this model, a person may drive, share a ride, use transit, bike or walk as the transport mode to his or her activities. This set of transport modes may be limited further based on the characteristics of the person and on the available vehicles in the household. While each person is able to consider transit, bike or walk in the model, a person may consider the drive or share transport modes if certain conditions are met. A person may drive if he or she possesses a driver's license and if a vehicle is available. A person may share a ride if there is both a driver and a vehicle available. Each transport mode has an associated travel time and cost to travel from the origin TAZ to the destination TAZ. The travel times and costs are calculated for each origin-destination pair and for each mode. The details of these calculations are discussed in Sections 4.3.1 and 4.3.2.

If there is at least one dependent within the household, then a new set of resources is required to fulfill the dependent's activities. This set of resources is the group of independents who are able to chaperone the dependent. Each independent person in the household is automatically considered as a chaperone. With each additional dependent activity, there are schedule and travel cost demands that must be considered for both the dependent and the chaperone. The household must decide which independent will chaperone the dependent for each activity.

4.3 Spatial Representation

This model relies on a Traffic Analysis Zone (TAZ) system to represent locations within the study area. A TAZ system is often used within transportation planning and analysis as the level of spatial resolution that provides a balance between high accuracy and fast processing speed. Specific addresses and locations, which would provide accurate, but slow results, are aggregated to the TAZ level. Each location within Kitchener - Waterloo is represented in the model by a number corresponding to a Traffic Analysis Zone. The entire area of Kitchener-Waterloo has been divided into 270 TAZs. These TAZs correspond to the zones used in the Transportation Tomorrow Survey, which is a household travel survey for municipalities in the Greater Toronto and Hamilton Area, as well as the Region of Waterloo (Data Management Group, 2011).

This spatial representation is critical to the generation of travel times and travel costs across the Region for each of the different modes and travel resources included in the model, as shown in Figure 4-1. The calculations of these travel times and costs are detailed in the following sections.

4.3.1 Calculating Travel Times

Travel times – for drive, share, transit, bike, and walk modes – are determined from the centroid of the origin zone to the centroid of the destination zone for each TAZ origin - destination (OD) pair in Kitchener - Waterloo. These travel times are calculated using an open-source trip planner known as OpenTripPlanner, which relies on open data for transport network and transit schedule information. OpenTripPlanner calculates the shortest path for each OD pair on the street network for trips that use Drive or Share modes. It also calculates the shortest path using the street and pathway network for Bike and Walk modes. For Transit, OpenTripPlanner uses the General Transit Feed Specification (GTFS) to determine which transit routes are taken for each OD pair (OpenTripPlanner, 2013). A batch process was used to calculate the travel times for each mode for each of the OD pairs in Kitchener - Waterloo. This process was developed by a postdoctoral fellow – Dr. Xiongbing Jin – who is coordinating the broader integrated land use - transport model for Kitchener - Waterloo. These travel times were stored in a table that is accessed by the model algorithm.

4.3.2 Calculating Travel Costs

The travel costs associated with a trip depends on the travel mode. The costs included in the model reflect what a person would pay "out-of-pocket" for each trip. There are no associated out-of-pocket costs for each trip that is accomplished on foot or by bicycle. The following sections discuss the travel costs for auto and transit trips.

Travel Costs to Drive or Share

The travel cost for any trip using an automobile typically include fuel and maintenance, which vary depending on the distance of the automobile trip, as well as user charges such as road tolls or parking fees (Vuchic, 1999). In this model, the travel costs that are considered only include fuel and maintenance. Based on an average price for regular gasoline in the Toronto area of $1.281 per litre (Statistics Canada, 2013) and an average fuel consumption of 8.34 litres per 100 kilometres for a mid-size vehicle (Canadian Automobile Association, 2013), the average variable costs associated with fuel is 10.7 cents per kilometre. Maintenance costs for a mid-size vehicle are estimated at 5.7 cents per kilometre (Canadian Automobile Association, 2013). Together, the out-of-pocket cost for auto travel used in this model is 16.4 cents per kilometre. At this time, data related to the average parking costs for each TAZ in Kitchener - Waterloo are unavailable and as such, these have not been included in the model; however, the model is capable of incorporating these costs if data are available.

There are also fixed costs of automobile travel related to vehicle ownership, insurance and depreciation (Vuchic, 1999). These fixed costs have been excluded from the model as these relate to a longer-term household decision on vehicle ownership, whereas this model is concerned with the day-to-day decision on mode choice. These fixed costs should not influence day-to-day mode choice decisions as it is assumed that household that has a vehicle would have already accounted for and internalized the costs for vehicle ownership.

The travel costs for auto travel are associated with any person that elects to drive or share a ride to his or her activity. The average travel cost per kilometre is multiplied by the shortest path distance between the origin and destination TAZ. The shortest path considers the level of congestion on each corridor based on outputs from an existing Region of Waterloo travel model (Region of Waterloo, 2011a).

Travel Cost for Transit

Fares are the only out-of-pocket cost associated with transit. A person may pay a transit fare using cash or with passes. The typical cash fare for transit in Kitchener - Waterloo is $3 per trip. Adult transit passes may be purchased for $79 per month. There are several types of student transit passes (e.g. elementary / secondary or post-secondary passes) that can be purchased, but as a simplification, it is assumed that all student transit passes cost the same as the post-secondary transit pass (i.e. “U-PASS”), which is $80 per 4-month term (Grand River Transit, 2015). This simplification is justified as a significant majority (87.5%) of non-adult transit trips in the Region of Waterloo are made by post-secondary students (Canadian Urban Transit Association, 2011). If a person holds either an adult or student transit pass, the fare per trip is much lower than the typical cash fare as the cost of the transit pass is divided by an assumed average of 40 transit trips per month. The inclusion of these varied costs ultimately affects the attractiveness of transit as the preferred mode of travel. If an individual already holds a transit pass, then the reduced price per trip will increase the utility and probability of the transit mode choice. Table 4-1 summarizes the different types of fare classes and their associated values.

Table 4-1: Assumed Transit Fares

Fare Class	Fare Value per Trip
Cash	$3.00
Adult Transit Pass	$1.98
Student Transit Pass	$0.50

Both auto and transit travel costs are stored in a table that is accessed by the model algorithm.

4.3.3 Calculating Utility

This model follows the approach of utility maximization as a decision framework that is common throughout activity-based travel models (Arentze & Timmermans, 2000; Ettema et al., 1993; Miller, 2005). In this approach, households will make mode choice decisions that attempt to maximize the overall utility for the household. Recall that utility is a measure of the attractiveness of an alternative that is comprised of a deterministic, measured component (V), and a random component (ε) (Ben-Akiva & Lerman, 1985). In this model, a combination of travel time and cost is used as part of the measured component of utility.

Under the assumption that the random component is independently and identically Gumbel type distributed, the probability that an individual selects a particular alternative can be calculated using this multinomial logit model expression (Ben-Akiva & Lerman, 1985):

$$P_i = \frac{e^{V_i}}{\sum e^{V_i}}$$

Equation 4-1: Multinomial Logit Model

The estimated logit model will be used in conjunction with the model algorithm to determine the allocation of travel resources to members of the household. The following subsections discuss the estimation of the multinomial logit model and the associated utility functions for each mode.

Mode Choice Data

This mode choice model used 2011 data from the Transportation Tomorrow Survey (TTS). This survey sampled 5% of the households in these municipalities. Each participating household reported the trips that their household members conducted over the course of a day. The data from this survey revealed the actual mode selected by a person for each of their trips.

Travel time and travel cost data were not provided in the TTS; however, the origin and destination TAZs of each trip were known. Travel times and travel costs for each mode were calculated separately as discussed in Section 4.3.1 and 4.3.2. One simplification in the calibration of the model is that an average transit fare is used as the cost for transit for each trip. This average fare is the revenue that the transit agency receives for each trip, which includes revenue from cash fares and passes. The average fare used to calibrate this mode choice model is $1.32 (Canadian Urban Transit Association, 2011). By combining the mode choice data from the TTS with travel time and cost data for each origin-destination pair, a mode choice model was calibrated for Kitchener - Waterloo. (It is important to note that while an average fare is used to estimate and validate the model, the assumed transit fares in Table 4-1 are used in the application of the model.)

As this model focused on Kitchener - Waterloo, the TTS data set was limited to households that are located within these two cities. Any households located outside of Kitchener - Waterloo were removed from the data set. Of the households that were within the study area, two-thirds of these data were set aside for calibration, while the remainder were set aside for validation. Furthermore, this model is also restricted to trips that are completely within Kitchener - Waterloo, meaning that both the origin and destination need to be within the study area for the trip to be included in the data set. This model only considers trips that use Auto Driver, Public Transit, Bicycle or Walk modes from the TTS. All other modes, including Auto Passenger, School Bus, Taxi, Motorcycle, and Other, were excluded from this model and trips with these other modes were removed from the data set. After all of these steps to filter the data, the data set for calibration included 14,014 trips, and the data set for validation included 6,867 trips.

Mode Choice Model Specification and Estimation

The utility for each mode (m) is assumed to be a function of travel cost (c), travel time (t), and a mode specific constant as shown in Equation 4-2. The constant is intended to represent any other benefits or costs that have not been measured but influence the mode choice.

$$V_{ij}^{m} = \beta_{cost} C_{ij} + \beta_{time} t_{ij} + \beta_{mode}$$

Equation 4-2: Specification of Utility Function

Two specifications were tested for this model. Model 1 consists of generic travel time (β_{time}) and travel cost (β_{cost}) coefficients. Model 2 consists of mode-specific travel time coefficients and a generic travel cost coefficient. A generic coefficient suggests that a change in a particular parameter, such as travel time, is valued the same across all modes, whereas a mode-specific coefficient suggests that the change is valued differently for each alternative. In addition to travel time and travel cost, an additional mode-specific constant (β_{mode}) is included in the utility function to capture the elements of utility that are measurable but not explained by travel time or cost. As an example, the perception of safety or the energy expended for movement may be an additional cost or disutility to active modes such as walking and cycling. The mode-specific constants are relative to the cost of a reference mode. In this case, the drive travel mode is used as the reference and therefore, β_{drive} is equal to zero.

The coefficients for the utility functions specified for multinomial logit models are typically estimated using a maximum likelihood approach developed by McFadden (1974). In this approach, the coefficients of the utility functions (β_x) are selected to maximize the logarithm of the likelihood function. A full derivation of the mathematics behind this approach is provided in Ben-Akiva & Lerman (1985). The specification of these functions are difficult to compute without statistical software. In this case, the coefficients for these models were estimated using the 'mlogit' package in the statistical software R, which follows the maximum likelihood approach for estimation (Croissant, 2013). The results for the generic model are provided in Table 4-2, and the results for the mode-specific model are provided in Table 4-3.

Table 4-2: Results of Model 1 Specification (Generic)

Parameter	**Estimate**	**Standard Error**	$\mathbf{t_{statistic}}$	**Significance**
β_{time}	*-0.0935*	*0.0031*	*-29.7470*	***
β_{cost}	*-1.0698*	*0.0767*	*-13.9429*	***
$\beta_{mode, transit}$	*-0.5479*	*0.0812*	*-6.7465*	***
$\beta_{mode, bike}$	*-4.7574*	*0.0983*	*-48.3965*	***
$\beta_{mode, walk}$	*-0.7249*	*0.0536*	*-13.5150*	***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Log-Likelihood = -7008.2; $\rho^2 = 0.1046$

Table 4-3: Results of Model 2 Specification (Alternative-Specific)

Parameter	**Estimate**	**Standard Error**	$\mathbf{t_{statistic}}$	**Significance**
$\beta_{time,\ drive}$	*-0.1394*	*0.0101*	*-13.8413*	***
$\beta_{time,\ transit}$	*-0.0486*	*0.0055*	*-8.8997*	***
$\beta_{time,\ bike}$	*-0.1517*	*0.0128*	*-11.8412*	***
$\beta_{time,\ walk}$	*-0.0969*	*0.0034*	*-28.6956*	***
β_{cost}	+0.1624	0.1662	0.9771	
$\beta_{mode,\ transit}$	-2.9605	0.2555	-1.5864	
$\beta_{mode,\ bike}$	-3.5387	0.1457	-1.0595	
$\beta_{mode,\ walk}$	-0.5441	0.0622	-0.6652	

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Log-Likelihood = -6877.8; ρ^2 = 0.1213

If any single parameter estimate differs significantly from zero, it should be included in the model (Ben-Akiva & Lerman, 1985). A t-test is used within the mlogit package to determine significance. The results in Table 4-2 indicate that the parameter estimates in Model 1 are highly significant to a 0.001 significance level. However, the results of Model 2 in Table 4-3 reveal that the cost parameter, and the mode specific constants are insignificant, and may be considered from removal from the model.

If a parameter estimate fails the t-test, a second test should be conducted to determine whether the estimate should remain in the model. This test determines whether the parameter's inclusion in the model provides a significant explanation in the change of utility or choice. A likelihood ratio test is used to determine the significance. In this test, the likelihood ratio is calculated using the following Equation 4-3:

$$Likelihood\ Ratio = 2\ (logL_2 - logL_1)$$

Equation 4-3: Likelihood Ratio

… where $logL_2$ is the log likelihood of Model 2, or the model with more variables, and $logL_1$ is the log likelihood of Model 1, or the simpler model. The likelihood ratio is compared to the chi-squared critical value at a 0.05 significance level and at the degrees of freedom equal to the number of additional variables. If the likelihood ratio is greater than the critical value, then the more complicated model is significant enough to include the additional variables. In this case, the likelihood ratio is equal to 260.8, and the chi-squared critical value at a 0.05 significance level and 3 degrees of freedom is 7.815. Therefore, the parameter estimates in Model 2 should be included even though they initially failed the t-test. Moreover, Model 2 has a higher similarity ratio ρ^2 than Model 1, which suggests that the alternative-specific model has a better goodness of fit than the generic model.

However, the estimate for the cost parameter in Model 2 is positive, which suggests that the utility of a mode increases with cost. With this estimate, Model 2 is contrary to the expected behaviour of travellers, which is that they prefer to minimize the amount of cost for travel. The inclusion of mode-specific travel time parameters in Model 2 provides results that are against this intuition. Therefore, Model 1 with generic travel cost and travel time coefficients was selected as the preferred specification to represent mode choice decisions in Kitchener - Waterloo. This model is also simpler and easier to interpret.

Interpretation of Mode Choice Model and Utility Functions

The results of Model 1 are translated into the following utility functions for each mode.

$$V_{ij}^{drive} = -0.09358 * t_{ij} - 1.0698 * c_{ij}$$

Equation 4-4: Utility Function for Auto Modes

$$V_{ij}^{transit} = -0.09358 * t_{ij} - 1.0698 * c_{ij} - 0.5479$$

Equation 4-5: Utility Function for Transit

$$V_{ij}^{bike} = -0.09358 * t_{ij} - 4.7574$$

Equation 4-6: Utility Function for Bicycle

$$V_{ij}^{walk} = -0.09358 * t_{ij} - 0.7249$$

Equation 4-7: Utility Function for Walking

As this model includes generic coefficients for travel time and travel cost, the marginal change in utility is the same across all modes. Every additional minute of travel time leads to a decrease in utility of 0.9358.

Every additional dollar of travel cost leads to a decrease in utility of 1.0698 for modes with out-of-pocket expenses. Both of these interpretations follow the intuition that individuals desire to reduce travel time or cost, and any increase in these variables would make the alternative less attractive. (It is important to note that the out-of-pocket travel cost for bike and walk modes are zero, and these have been removed from the equation as a simplification).

A comparison of the coefficients for travel time and travel cost can provide insight on the value of time that is associated with travel. The value of time is calculated using the following equation:

$$VOT = \frac{\beta_{time}}{\beta_{cost}} = \frac{-0.9358\ U/min}{-1.0698\ U\ /\ \$} * \left(60\frac{min}{hour}\right) = \frac{\$5.25}{hour}$$

Equation 4-8: Calculation of Value of Time

The calculated value of time suggests that in Kitchener - Waterloo, every hour of travel is worth $5.25. This value represents a trade-off between time and money. It is the average amount of money one is willing to pay to save one hour of travel time. At first glance, this value of time may be considered low. Small (2012) suggests in a review of the empirical literature that the value of time is approximately half of the average hourly wage for commuting trips. Neudorf (2014), in a job accessibility study for Kitchener - Waterloo, compared average wages in the Province of Ontario and values of times identified by the Region of Waterloo and Metrolinx to specify a value of time of $12.00 per hour. However, Small (2012) also suggests that the value of time can vary depending on trip purpose, which is highest for business trips and lowest for discretionary trips. A lower value of time in this study, therefore, is not surprising as it was estimated using all trips and not just commuting trips to work. This value of time would change if the model was calibrated for trip purpose.

The additional mode-specific constants for transit, bike and walk travel modes represent some additional disutility that cannot be attributed to travel time or travel cost, but are measurable influences on an individual's mode choice. (Recall that the drive travel mode does not have a mode-specific constant as this mode was used as the reference to estimate the model.) Each of these mode-specific constants are negative, which suggests that there are real or perceived costs in addition to out-of-pocket cost and travel time that reduce the attractiveness of these modes related to driving. These costs may be related to safety, energy, reliability, weather, or convenience.

Mode Choice Model Validation Test

This model was tested against a set of data to ensure that the specified model provides reasonable estimates of mode choice. The data used for validation consisted of the 33% of the households from the Transportation Tomorrow Survey that were located in Kitchener - Waterloo and were not used in the estimation of the model. The validation test used the same travel costs and times as the calibration set for each mode and origin - destination pair in Kitchener - Waterloo. These costs and times were input into the specified utility functions. The probabilities for selecting each mode were calculated from these utilities. The mode for the trip was predicted using these calculated probabilities and recorded. As the mode choice selection is a random process, the validation process was repeated 100 times and then these results were averaged across the number of repetitions. Table 4-4 represents the results of the validation test in comparison to the actual mode that was chosen for each trip in the validation set.

Table 4-4: Results of Validation Test

Mode	**Predicted**	**Actual**	**Difference**
Drive	84.5%	84.7%	-0.2%
Transit	7.5%	7.4%	+0.1%
Bike	1.2%	1.3%	-0.1%
Walk	6.7%	6.6%	+0.1%

The results from Table 4-4 indicate that the specified mode choice model performs well and is able to replicate travel behaviour in Kitchener - Waterloo. There is negligible difference between the predicted mode choice and the actual mode chosen as recorded in the TTS. This model can be used with confidence to estimate mode choice behaviour.

4.4 Model Algorithm

Given the household composition and spatial representation inputs, the proposed household travel resource allocation model will produce a set of tours and scheduled activities for the members of the household. The model accomplishes this objective through a rule-based approach that attempts to mimic typical household travel decisions. Activity and scheduling decisions are made with consideration of the actions and activities of all household members.

The household travel resource allocation model follows these three main steps, as illustrated in Figure 4-1:

1. Prioritize Activities;
2. Schedule the First Mandatory Activities; and
3. Schedule Subsequent Activities.

The overall model structure is outlined as pseudo-code in Appendix C. The pseudo-code also has references to the sub-routines that have been developed for the model in object-oriented programming language Java.

The details of the model rules and processes are outlined in the following subsections. To assist in this discussion, two hypothetical households are used to describe the application of the model rules and process: one with dependents (Household A) and one without dependents (Household B).

The early and late start times have been assumed for each of the activities. For work and school activities, this range is assumed to be from 15 minutes prior to 15 minutes after a desired start time. For all discretionary activities, the start time range spans over a time when activities are assumed to be conducted. (These values have been selected to demonstrate the model concepts and do not necessarily reflect the values assumed in model testing).

Household A consists of four persons with the characteristics outlined in Table 4-5. This household is located in a suburban neighbourhood in west Kitchener (TAZ 7263). It has access to two vehicles. The activities associated with Household A are summarized in Table 4-6. Figure 4-2 illustrates these locations within the study area.

Table 4-5: Characteristics of Household A Members

Person	Age	Gender	Employed?	Student?	Independent?	Driver?	Has Transit Pass?
1	37	M	Yes, full time	No	Yes	Yes	No
2	35	F	Yes, full time	No	Yes	Yes	No
3	8	F	No	Yes	No	No	No
4	3	M	No	Yes	No	No	No

Table 4-6: Desired Activities for Household A

Person	Activity	Type	Location	Early Start Time	Late Start Time	Duration
1	1	Work	7020	8:45am	9:15am	7 hr. 30 min
1	2	Service	7105	10:00am	7:00pm	15 min.
1	3	Recreation	7036	9:00pm	9:30pm	1 hr. 30 min.
2	1	Work	7112	6:45am	7:15am	8 hr.
2	2	Grocery	7254	7:30am	10:00pm	30 min.
3	1	School	7265	8:15am	8:45am	7 hr.
3	2	Service	7248	12:00pm	7:00pm	1 hr.
4	1	School	7255	8:30am	9:00am	8 hr.

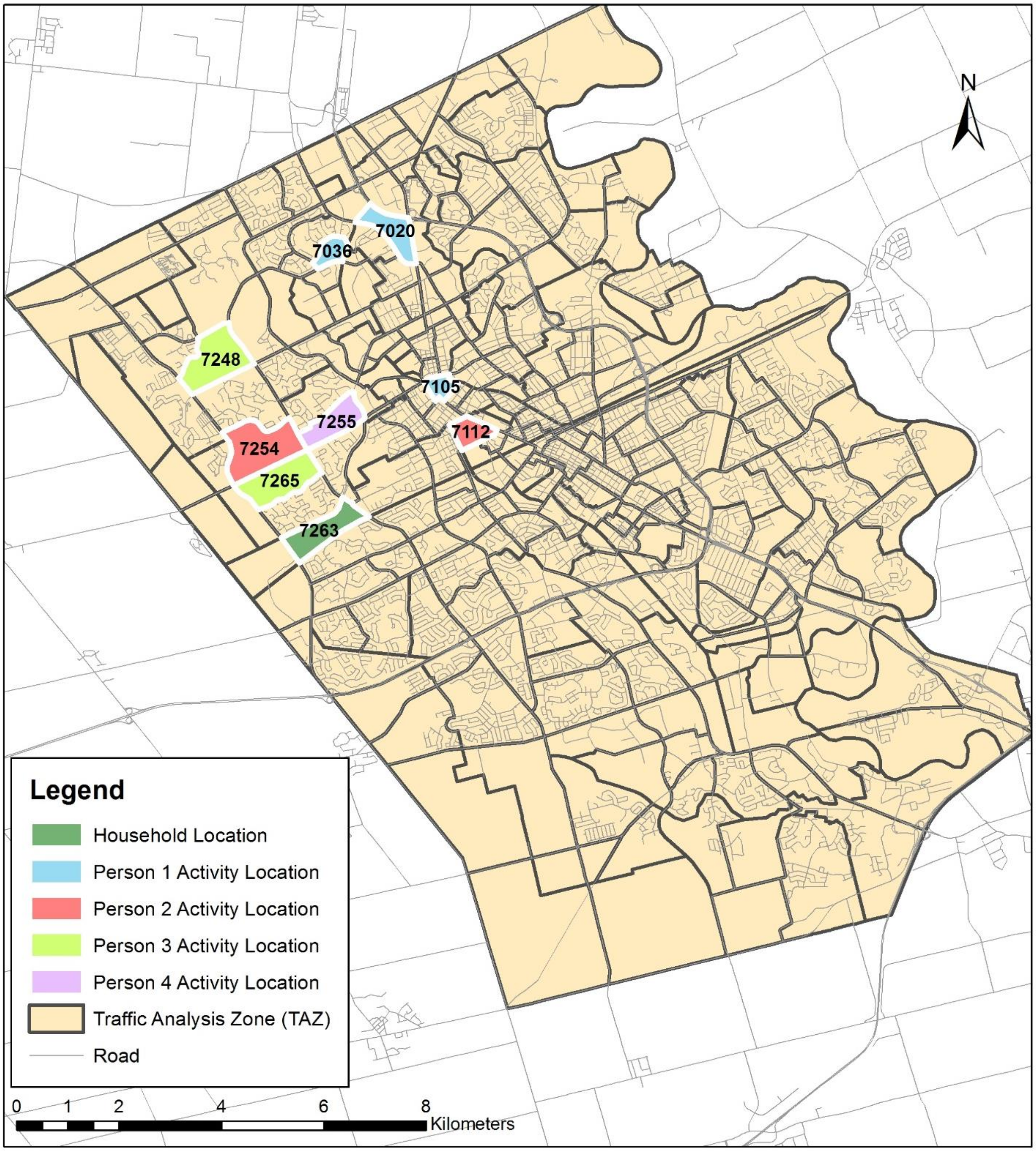


Figure 4-2: Map of Household A and Activity Locations

Household B consists of two persons with the characteristics summarized in Table 4-7. This household is located in an urban neighbourhood in Uptown Waterloo (TAZ 7106). It has access to one vehicle. The activities associated with Household B are summarized in Table 4-8. Figure 4-3 illustrates these locations within the study area.

Table 4-7: Characteristics of Household B Members

Person	Age	Gender	Employed?	Student?	Independent?	Driver?	Has Transit Pass?
1	31	M	Yes, full time	No	Yes	Yes	Yes
2	29	F	Yes, full time	No	Yes	Yes	Yes

Table 4-8: Desired Activities for Household B

Person	Activity	Type	Location	Early Start Time	Late Start Time	Duration
1	1	Work	7105	8:30am	9:00am	8 hr. 30 min
1	2	Service	7013	10:00am	7:00pm	1 hr.
1	3	Social	7117	2:00pm	8:00pm	1 hr. 30 min.
1	4	Recreation	7001	9:30pm	10:00pm	1 hr.
2	1	Work	7135	8:30am	9:00am	8 hr. 30 min
2	2	Recreation	7109	12:00pm	10:00pm	1 hr. 15 min.
2	3	Social	7141	4:00pm	10:00pm	1 hr. 30 min.

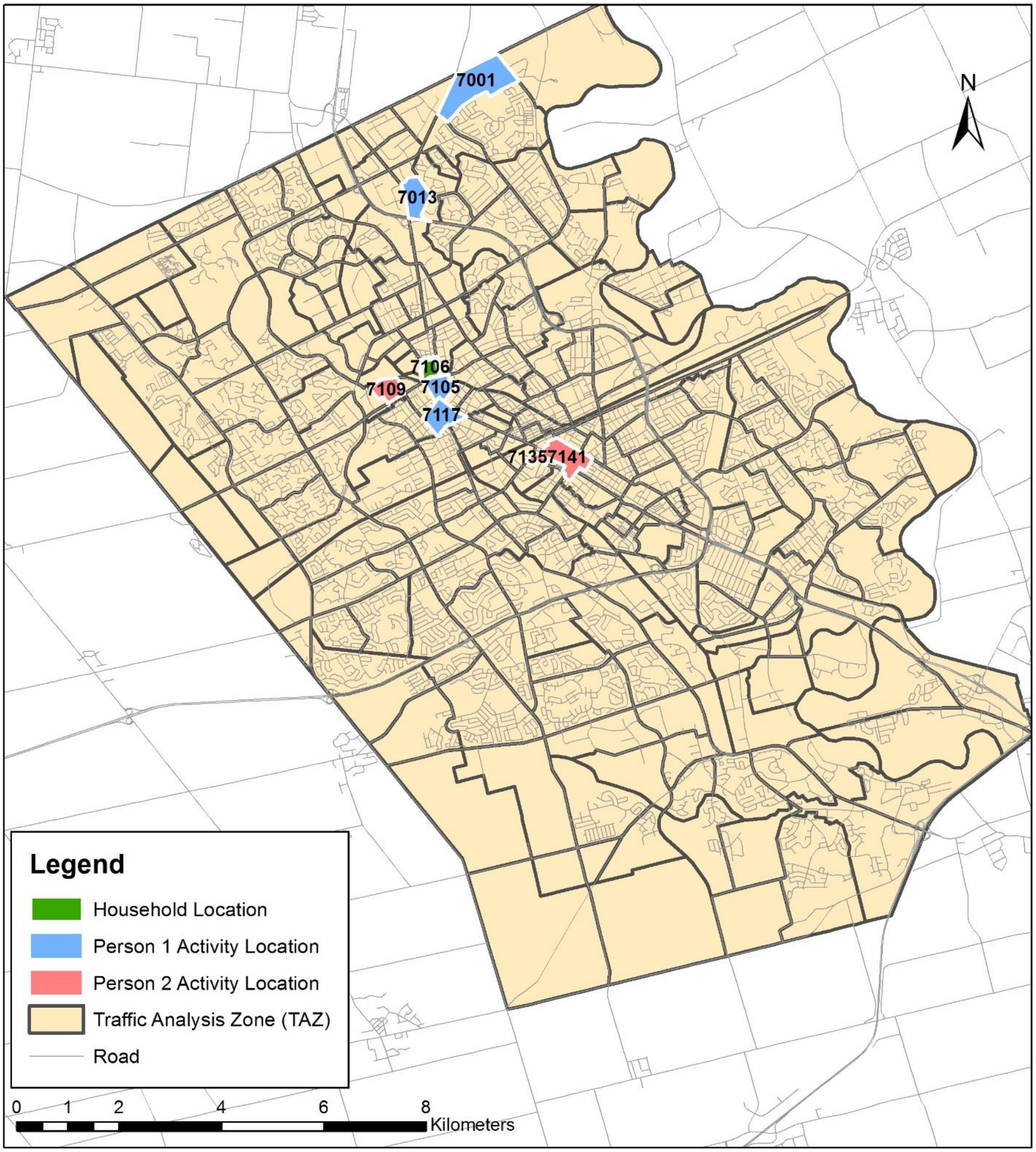


Figure 4-3: Map of Household B and Activity Locations

4.4.1 Prioritize Activities

This is the first step of the proposed model, as depicted in Figure 4-1. In this model, households schedule their activities in a sequential process in the order from highest priority to lowest priority. The notion that some activities take precedence over others and should be scheduled first is consistent throughout many of the activity-based travel models (Arentze & Timmermans, 2000; Gärling, Kwan, & Golledge, 1994b; Miller, 2005). Once an activity has been scheduled, this model prohibits the removal of the activity from the person's schedule. This rule assumes that households are unlikely to remove a higher priority activity in order to fulfill a lower priority activity.

From the survey results outlined in Section 3.3.2, the model prioritizes the activity types in this order:

1. Work or School Activities;
2. Service Activities;
3. Grocery Activities;
4. Social Activities;
5. Recreational Activities; then
6. Other Shopping Activities.

This order assumes that mandatory activities, such as work and school activities, take schedule precedence over discretionary activities, such as shopping, recreational or social activities. Furthermore, as chaperone activities were highly prioritized in the survey, the activities of dependent travellers take precedence over the activities of independent travellers. This assumption is consistent with the notion that dependents and their commitments often influence the scheduling of household activities (Chapin, 1974; Hagerstrand, 1970).

The activities that share the same priority are sorted further by schedule flexibility and then by start time. If any two activities have the same priority, the activity that has less flexibility, which is defined as the difference between the early and late start times, will be scheduled first. Finally, if any two activities have the same priority and the same flexibility, then the activity with the earlier late start time will be scheduled first.

Based on these prioritization rules, Table 4-9 is an ordered list of activities for Household A and Table 4-10 is an ordered list of activities for Household B.

Table 4-9: Ordered Activities for Household A

Person	Activity	Type	Priority	Flexibility	Late Start Time	Order
3	1	School	1	30 min.	8:45am	1
4	1	School	1	30 min.	9:00am	2
2	1	Work	1	30 min.	7:15am	3
1	1	Work	1	30 min.	9:15am	4
3	2	Service	2	7 hr.	7:00pm	5
1	2	Service	2	9 hr.	7:00pm	6
2	2	Grocery	3	14 hr. 30 min.	10:00pm	7
1	3	Recreation	5	30 min.	9:30pm	8

Table 4-10: Ordered Activities for Household B

Person	Activity	Type	Priority	Flexibility	Late Start Time	Order
1	1	Work	1	30 min	9:00am	1
2	1	Work	1	30 min	9:00am	2
1	2	Service	2	9 hr.	7:00pm	3
1	3	Social	4	6 hr.	8:00pm	4
2	3	Social	4	6 hr.	10:00pm	5
1	4	Recreation	5	30 min.	10:00pm	6
2	2	Recreation	5	10 hr.	10:00pm	7

4.4.2 Schedule First Mandatory Activities

Once all of the activities have been sorted, the model proceeds to initiate the first tours for each member of the household. This is the second step of the model as shown in Figure 4-1. It creates the tours using the first mandatory activity (with the earliest late start time) for each person. These activities have the highest priority in the household. The model conducts this step with the objective of minimizing the overall travel time and cost of travel incurred by the household. The model achieves this objective by first identifying the preferred travel modes for each person in the household, and then iteratively searching through alterative assignments of travel resources and modes until it finds a solution with the maximum utility.

Identify Preferred Modes of Independent Travellers

The model first identifies the preferred and alternate travel modes that may be used by each independent person to their first mandatory activity. These modes are identified without regard of household resource constraints. The choice set that each independent traveller can initially choose from is: Drive, Transit, Bike and Walk. These are the modes that may be used if the independent person does not need to accompany a dependent to their activity. The model determines these modes by calculating the utility of travelling from the household to activity location using Equation 4-4 to Equation 4-7. All of the utilities are input into Equation 4-1 to determine the probability of selecting the preferred mode. To select the preferred mode, the calculated probabilities are used to define a range of numbers between 0 and 1 that would select a particular mode. As an example, if the probabilities were 50% drive, 25% transit, 15% bike and 10% walk, then the model would define the following range of numbers: 0 - 0.499 would select drive, 0.500 - 0.749 would select transit, 0.750 - 0.899 would select bike and 0.900 - 0.999 would select walk. A random number generator method in Java is executed to select a number between 0 and 1. If the number falls between the ranges that are defined by the mode, that particular mode is selected. In order to determine the alternate mode, the probabilities are recalculated and the same random process is repeated without the preferred mode in the choice set. The results of this step are summarized in Table 4-11 for Household A and Table 4-12 for Household B.

Table 4-11: Preferred and Alternate Modes for the First Independent Activities in Household A

Person	**Option**	**Utility (Probability)**				**Mode**
		Drive	**Transit**	**Bike**	**Walk**	
1	Preferred	-3.27 (97.5%)	-8.43 (0.6%)	-7.28 (1.8%)	-9.42 (0.2%)	Drive
	Alternate	N/A	-8.43 (22.1%)	-7.28 (69.7%)	-9.42 (8.2%)	Bike
2	Preferred	-1.76 (95.1%)	-5.72 (1.8%)	-6.16 (1.2%)	-5.68 (1.9%)	Drive
	Alternate	N/A	-5.72 (37.2%)	-6.16 (24.0%)	-5.68 (38.8%)	Bike

Table 4-12: Preferred and Alternate Modes for the First Independent Activities in Household B

Person	**Option**	**Utility (Probability)**				**Mode**
		Drive	**Transit**	**Bike**	**Walk**	
1	Preferred	-0.27 (71.4%)	-3.03 (4.5%)	-4.94 (0.7%)	-1.38 (23.5%)	Drive
	Alternate	N/A	-3.03 (15.7%)	-4.94 (2.3%)	-1.38 (82.0%)	Walk
2	Preferred	-1.48 (90.1%)	-4.44 (4.7%)	-5.88 (1.1%)	-4.56 (4.1%)	Drive
	Alternate	N/A	-4.44 (47.1%)	-5.88 (11.1%)	-4.56 (41.7%)	Transit

Allocate Chaperones to Dependents

In households that have dependent travellers, the model determines which independent traveller has the responsibility of accompanying the dependent on the trip to his or her first mandatory activity. The model conducts this allocation with two main objectives. The first is to assign the chaperones such that members of the household are able to start their mandatory activities within their defined start time ranges, and the second is to maximize the total household utility associated with travel. Within the hypothetical examples, only Household A has dependent travellers, so it will be the focus of this section.

In Household A, there are two dependent travellers, and two independent travellers. By design, the model allows an independent traveller to chaperone up to two dependent travellers to their first mandatory activity. The model iterates through all possible combinations of chaperone - dependent pairings to determine the final chaperone allocation. In this example, there are four possible combinations, as outlined in Table 4-13.

Table 4-13: Potential Chaperone Allocation for Household A

Combination #	**Person 1 Chaperones:**	**Person 2 Chaperones:**
1	Person 3	Person 4
2	Person 4	Person 3
3	Person 3 and 4	None
4	None	Person 3 and 4

For each combination, the model determines if the chaperone activity is feasible, identifies the preferred modes of the chaperone, and calculates the overall household utility.

A chaperone - dependent pairing is considered feasible if the chaperone can begin his or her activity within the acceptable start time range, after dropping off the dependent(s) at their activity within their acceptable start time range. Consider Combination 1 and the chaperone - dependent pairing of Person 1 and Person 3. Person 3's mandatory activity must begin between 8:15am and 8:45am, while Person 1's mandatory activity must begin between 8:45am and 9:15am. The travel time between these two activity locations must be considered, which depends on the preferred mode of the chaperone.

The model determines the preferred modes by incorporating the total travel time and cost from the household to the dependent's activity, and then to the chaperone's activity. The utilities are calculated using Equation 4-4 to Equation 4-7. In this case, for Person 1, the preferred mode is to Drive, and the alternate mode is to Bike. As there are an equal number of drivers and vehicles in the household, Person 1 may use his preferred mode for this trip.

From the dependent's activity located in TAZ 7265 to the chaperone's activity located in TAZ 7020, the travel time by car is 22 minutes. As the model attempts to schedule activities at the earliest possible time, the dependent would start her activity at 8:15am. The earliest time that the chaperone could begin his activity is 8:45am, after arriving early at the activity at 8:37am. This pairing is considered feasible using the preferred mode. The utility that is associated with this trip is -5.10.

However, consider the other chaperone - dependent pairing of Combination 1: Person 2 and Person 4. The dependent's activity start time range (8:30am - 9:00am) begins after the start time range of the chaperone's activity (6:45am - 7:15am). As chaperoning Person 4 would cause Person 2 to be late to her mandatory activity, this pairing is considered infeasible, and an infinitely negative utility is assigned to this trip and combination. In fact, since Person 2 has such an activity start time range that is much earlier than the dependents, any combination with Person 2 as a chaperone will yield an infeasible result.

The only combination that is potentially feasible is the third combination, where Person 1 chaperones both dependents. When the model considers two dependents assigned to one chaperone, the order in which the dependents are dropped off becomes important. This order is dependent on the start time ranges for the dependents' activities. In general, the dependent with the earlier activity should be dropped off first. However, with start time ranges there may be overlap for when activities may begin. The model addresses this concern with the concept of time windows.

A time window is the amount of time between the early start time of a preceding activity and the late start time of a following activity (Equation 4-9). This time window represents the maximum amount of time that is available for travel between the activities. These time windows are calculated for Persons 1, 3 and 4 in Table 4-14. The calculation of the time windows help to determine which activities should be scheduled first. The dependent that has a larger time window between his or her activity and the following activities should be scheduled first as it allows for more flexibility in travel time for the following activities. In this case, placing Person 3's activity as the preceding activity allows for the most flexibility in travel time to the activities of Person 4 and Person 1. Therefore, Person 1 will drop off Person 3, then Person 4, prior to the start of his mandatory activity.

$$Time\ Window = Late\ Start\ Time_{Following\ Activity} - Early\ Start\ Time_{Preceding\ Activity}$$

Equation 4-9: Time Windows

Table 4-14: Calculation of Time Windows

Preceding Activity (Early Start Time)	**Following Activity (Late Start Time)**		
	Person 1 (9:15am)	Person 3 (8:45am)	Person 4 (9:00am)
Person 3 (8:15am)	60 minutes		45 minutes
Person 4 (8:30am)	45 minutes	15 minutes	

Given this order, the model determines the preferred mode for this tour using the total travel time and cost from the household to each of the stops on the tour. In this case, the preferred mode for Person 1 on this tour is to Drive, and the alternate mode is to Bike. The model will also check the feasibility of this tour with the associated travel times between each stop of the tour to ensure that no person will arrive late to his or her activity. Table 4-15 summarizes this check with the assumption that the trip starts from the household so that Person 3 will arrive by the early start time of his mandatory activity.

Table 4-15: Feasibility of Person 1 Chaperoning Persons 3 and 4

Person	**Activity Location**	**Travel Time to Location**	**Arrival Time**	**Early Start Time**	**Late Start Time**	**Feasible?**
3	7265	7 minutes	8:15 am	8:15 am	8:45 am	Yes
4	7255	7 minutes	8:22 am	8:30 am	9:00 am	Yes
1	7020	17 minutes	8:39 am	8:45 am	9:15 am	Yes

All trips of this tour are feasible with the preferred mode as the persons arrive prior to their early start time. Each person will start their activities at the early start time. The utility associated with this chaperone - dependent pairing is -6.82. As Person 2 does not have any dependents to accompany and there are enough vehicles in the household, she is able to use her preferred mode, which is to drive. The combined utility for the household is -8.58. Table 4-16 summarizes the results of the chaperone allocation process.

Table 4-16: Utility Summary of Chaperone Allocation Process

Combination #	Person 1 Chaperones:	Person 2 Chaperones:	Household Utility
1	Person 3	Person 4	Negative Infinity
2	Person 4	Person 3	Negative Infinity
3	Person 3 and 4	None	- 8.58
4	None	Person 3 and 4	Negative Infinity

Combination 3 has the highest utility; therefore, the model allocates Person 1 to accompany both dependents to their activities using his preferred mode, which is to drive.

Allocate Vehicles and Assign Mode

Following the allocation of chaperones, the model determines the allocation of remaining vehicles and assigns the mode for the first tour of independent travellers. In the case of Household A, this step is simple as there is one remaining vehicle left for Person 2, who prefers to drive to her mandatory activity. As there are no other independents requiring a vehicle, the second household vehicle is assigned to Person 2.

In the case of Household B, there are two independent travellers and both prefer to drive to their mandatory activities; however, there is only one vehicle available in the household. If there are more independents that prefer to drive to their first activity than the number of available vehicles, the model assigns the vehicles to maximize the overall utility of travel to the household. The model conducts a pairwise comparison of the systematic utilities (V). Given that both Person 1 and Person 2 prefer to drive to their activities, if Equation 4-10 is true, then the vehicle will be assigned to Person 1:

$$(V_{preferred}^{1} + V_{alternate}^{2}) \geq \; (V_{alternate}^{1} + V_{preferred}^{2})$$

Equation 4-10: Pairwise Comparison for Vehicle Allocation

Otherwise, the vehicle will be assigned to Person 2. If a vehicle has not been assigned to an individual, then the independent will use the alternate mode. Table 4-17 reviews the preferred and alternate modes, as well as its associated utilities for each independent person in Household B.

Table 4-17: Preferred and Alternate Modes for Household B

Person	Preferred Mode (Utility)	Alternate Mode (Utility)
1	Drive (-0.27)	Walk (-1.38)
2	Drive (-1.48)	Transit (-4.44)

If the vehicle is assigned to Person 1 and the alternate mode is assigned to Person 2, the total household utility is equal to -4.71. If the vehicle is assigned to Person 2 and the alternate mode is assigned to Person 1, the total household utility is equal to -2.86. The latter allocation has the higher household utility; therefore, the vehicle is assigned to Person 2, while Person 1 may use the alternate mode, which is to walk to his first activity.

Check Sharing Opportunities

Once all the vehicles are assigned, the model considers whether there are opportunities for independents to share a ride to their first mandatory activity. If a person using a mode other than Drive to his or her first activity, they may share a ride with a driver that is available and is not already chaperoning other people. In this case within Household B, Person 1 may share a ride as a passenger with Person 2, who is the driver. The model checks for sharing opportunities in an approach that is similar to the chaperone allocation process. The model will select Share as the travel mode for Person 1 if the trip meets schedule feasibility requirement and if it maximizes household utility.

In order for this shared trip to be feasible, the driver must not be late to her mandatory activity after dropping off the passenger at his mandatory activity. From the passenger's activity located in TAZ 7105 to the chaperone's activity located in TAZ 7135, the travel time by car is 10 minutes. After dropping off the passenger such that he begins his activity at the early start time (8:30am), the driver would arrive at her activity at 8:40am, which is within the activity's start time range. Therefore, sharing is feasible. The utility associated with sharing is calculated using the Drive utility function (Equation 4-4) and includes the total travel time and cost for the trip from the household to the passenger's activity location and then to the driver's activity location. The utility for this shared trip is -1.89. Sharing is selected for the first mode if it increases household utility. Recall that the total household utility for the independent trips in Household B was -2.86. As the utility of the shared trip is greater than the total household utility of the independent trips, Person 1 will share a ride with Person 2 for the first activity.

Start First Tours

Following each of these steps, the first tours for each person of the household is initialized using the chaperones, vehicles and modes assigned through the model. Each person that had a mandatory activity would have one initialized tour. The mandatory activities are also scheduled into the person's day based on the actual start time and the duration of activities. Subsequent activities may not be scheduled during the time these tours and activities take place. Furthermore, the model also protects an amount of time following the end of the last activity to ensure a person has enough time to return to home using the previous mode of the tour. Figure 4-4 summarizes the first tours for Household A. Figure 4-5 summarizes the first tours for Household B. Note that for each of these tours, the persons have not returned home. Subsequent activities and trips may be scheduled at the end of these tours, which is discussed in the following subsection.

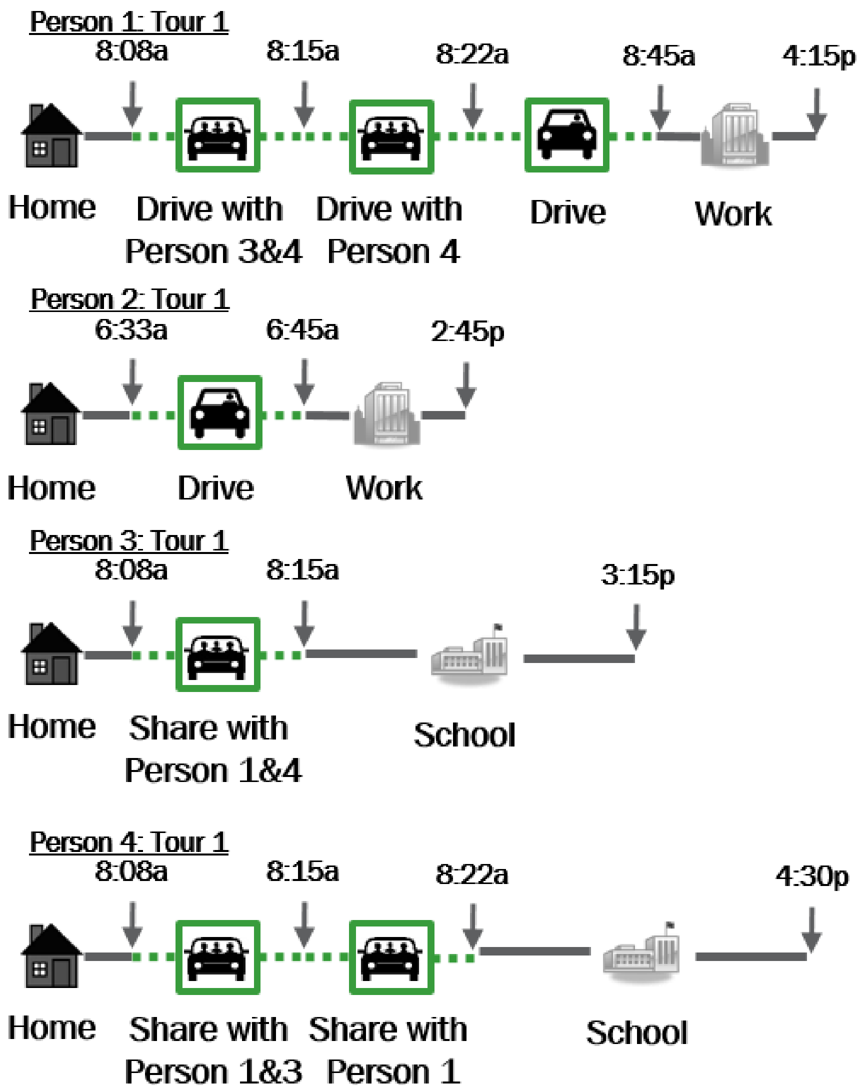


Figure 4-4: First Tours for Household A

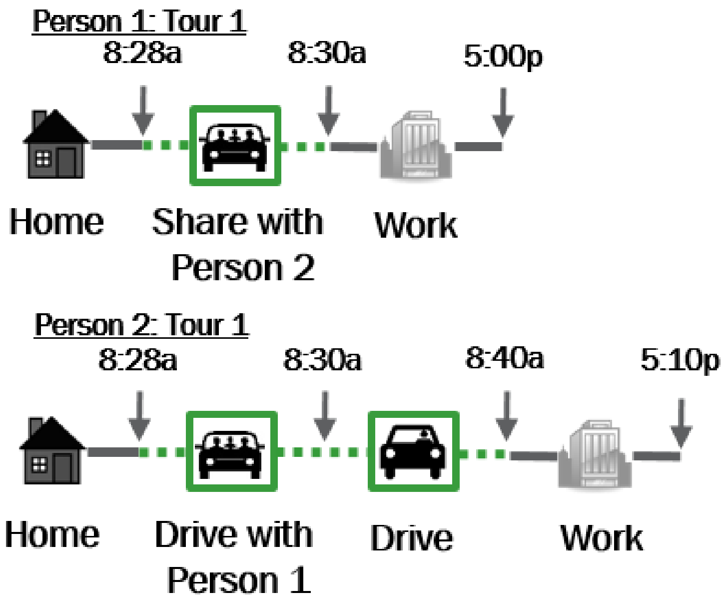


Figure 4-5: First Tours for Household B

4.4.3 Schedule Subsequent Activities

At the end of the second step in the household travel resource allocation model, the first mandatory activities are scheduled and the first tours are initialized for each person in the household. All subsequent activities are scheduled in a step-wise approach in the order of priority. Throughout this step, the model will take one of three actions for each activity, as first illustrated in Figure 4-1:

1. Schedule the activity in an existing tour;
2. Schedule the activity in a new tour; or
3. Defer the activity.

To improve the clarity of the model description, this step will be first applied to the household with independent travellers (Household B), and then the concept will be then extended to the household with both independent and dependent travellers (Household A).

Application to Household with only Independent Travellers (Household B)

There are four activities that remain to be scheduled in Household B, as summarized in order in Table 4-18.

Table 4-18: Remaining Activities for Household B

Order	Person	Type	Location	Early Start Time	Late Start Time	Duration
1	1	Service	7013	10:00am	7:00pm	1 hr.
2	1	Social	7117	2:00pm	8:00pm	1 hr. 30 min.
3	2	Social	7141	4:00pm	10:00pm	1 hr. 30 min.
4	1	Recreation	7001	9:30pm	10:00pm	1 hr.
5	2	Recreation	7109	12:00pm	10:00pm	1 hr. 15 min.

Check Existing Tour

For each of the remaining activities, the model will first try to schedule the activity at the end of any existing tours. By scheduling within an existing tour, the model minimizes the additional time and costs incurred by a person travelling home prior to their next activity.

Consider the first activity for Household B. It is a service activity for Person 1 located TAZ 7013 that may be completed between 10:00am to 7:00pm. The model will check all existing tours for Person 1 to determine if it is feasible to schedule this activity at the end of an existing tour. Currently, there is only one existing tour for Person 1. The last activity on the tour is his work activity in TAZ 7105, which finishes at 5:00pm. The feasibility of scheduling this activity within the existing tour is dependent on the travel time to the next activity, which is dependent on the mode of the tour.

Confirm Mode Choice on Existing Tour

The mode of the tour depends on whether or not a vehicle was previously used for the tour. If the previous mode was Drive or Bike, then a vehicle was used and it must stay with the person for the duration of the tour. In this case, the mode must remain the same. If the previous mode was Share, Transit or Walk, the person may select from any of these three modes. For Person 1, he shared a ride for the first trip of the tour and must select Share, Transit or Walk as the mode of the following trip.

Check Feasibility for Shared Trip

The model determines if it is feasible to share a ride to the next activity by searching through all existing tours of drivers in the household. In this model, a driver is willing to wait 15 minutes prior to the completion of an activity, and a passenger is willing to wait up to 15 minutes after the completion of an activity for a ride share; otherwise, it is infeasible and the person will select from Transit or Walk. In this case, the driver (Person 2) is at work until 5:10pm, and based on a 10 minute travel time from TAZ 7135 to 7105, she would arrive to pick up Person 1 at 5:20pm, which is later than maximum waiting time for sharing. These time restrictions are assumed for this model and they may represent the notion that people do not desire to wait a long time prior to conducting other activities.

Mode Choice for Trip

Person 1 will select either Transit or Walk to travel to his next activity. The selection is based off of a mode choice exercise, where the utilities of the alternatives are calculated using Equation 4-5 for Transit, and Equation 4-7 for Walk. The utilities, probabilities and mode choice associated with this trip from TAZ 7105 to TAZ 7013 are outlined in Table 4-19.

Table 4-19: Example Mode Choice to Conduct Discretionary Trip on Existing Tour

Person	**Utility (Probability)**			**Mode Choice**
	Share	**Transit**	**Bike**	
1	N/A	-4.72 (79.2%)	-6.05 (20.8%)	Transit

Check Schedule Feasibility

A person schedule's an activity on an existing tour if he or she will be able to start the activity within its start time range, and if there is available time in the schedule for both the person and the resources he or she is using. If the activity would start later than the start time range, or would conflict with other existing activities or trips in the schedule, then the person will not schedule the activity in the existing tour.

Using this mode choice of transit, the model will determine if it is feasible to schedule the activity within the existing tour. The travel time between TAZ 7105 and TAZ 7013 by transit is 22 minutes. The earliest that this activity may start when connected to this tour is 5:22pm, which is within the start time range for this activity. Moreover, as there are currently no other scheduled activities later in the day, the entire duration of the activity may be scheduled without conflict. Therefore, the service activity for Person 1 will be scheduled in Tour 1, starting at 5:22pm and ending at 6:22pm. For Household B, three other remaining activities are also *scheduled in existing tours*, as detailed in Table 4-20.

Table 4-20: Scheduling of Subsequent Activities in Existing Tours for Household B

Person 1, Social Activity in TAZ 7117 (Duration: 1 hour, 30 minutes) Check Existing Tour: #1 (Last Activity Ends in TAZ 7013 at 6:22pm) - **Previous Mode**: Share; - **Check Shared Trip Feasibility**: Driver (Person 2) at would arrive too early at 5:18pm. - **Mode Choice**: Transit (-5.28, 82.1%) or Walk (-6.80, 17.9%); Select Transit; - **Travel Time to Activity**: 28 minutes - **Check Schedule Feasibility**: No conflicts in schedule after 6:22pm. **Arrive at Activity:** 6:50pm - **Feasible to Schedule in Tour #1**: Activity Starts at 6:50pm, Ends at 8:20pm
Person 2, Social Activity in TAZ 7141 (Duration: 1 hour, 30 minutes) Check Existing Tour: #1 (Last Activity Ends in TAZ 7135 at 5:10pm) - **Previous Mode**: Drive; **Travel Time to Activity**: 3 minutes - **Check Schedule Feasibility**: No conflicts in schedule after 5:10pm. **Arrive at Activity**: 5:13pm - **Feasible to Schedule in Tour #1**: Activity Starts at 5:13pm; Ends at 6:43pm
Person 2, Recreational Activity in TAZ 7109 (Duration: 1 hour, 15 minutes) Check Existing Tour: #1 (Last Activity Ends in TAZ 7141 at 6:43pm) - **Previous Mode**: Drive; **Travel Time to Activity**: 14 minutes - **Check Schedule Feasibility**: No conflicts in schedule after 6:43pm. **Arrive at Activity**: 6:57 pm - **Feasible to Schedule in Tour #1**: Activity starts at 6:57pm; Ends at 8:11pm

Sometimes an activity may be scheduled in an existing tour even though a person would arrive prior to the start time range. In this case, the person would wait until the early start time before initiating the activity. The amount of time that a person is willing to wait prior to the start of an activity is dependent on a comparison of travel times.

Consider the recreational activity for Person 1 located in TAZ 7001. The start time range for this activity is between 9:30pm and 10:00pm. When the existing tours are checked, Person 1 may share a ride with Person 2 from the previous social activity, which ended at 8:20pm. The travel time for this trip is 20 minutes, which would lead to an arrival time of 8:40pm. As the activity is not scheduled to start until 9:30pm, there is a wait time of 50 minutes prior to the start of the activity. The maximum amount of time a person is willing to wait is the difference in travel times between a direct trip from the previous activity (t_{ij}), and a trip from the previous activity that includes a stop at home ($t_{ih} + t_{hj}$), plus a 30 minute waiting period at home (t_{home}) as calculated in .

$$Max\ Waiting\ Time = t_{ih} + t_{hj} - t_{ij} + t_{home}$$

Equation 4-11: Maximum Waiting Time prior to Next Activity

If the waiting time prior to an activity is larger than the maximum waiting time, the activity should not be scheduled in the existing tour as there is too much time between activities, which could be spent at home or on other shorter activities. In this case, the total amount travel time to home and then to the next activity is 24 minutes, which is 4 minutes longer than the direct trip. With a 30 minute waiting period at home, the maximum waiting time is 34 minutes. Since the calculated waiting time is longer, it will not be scheduled in the existing tour.

Schedule in New Tour

If all existing tours were rendered infeasible, then the model would attempt to schedule the activity in a new tour from home. This is the case for the recreational activity for Person 1. In this step, the model identifies the preferred and alternate modes for the person to travel from home to this subsequent activity.

The model then searches the person's schedule within the activity start time range for a continuous amount of free time that includes the travel time to and from the activity, plus the duration of the activity. If this amount of continuous free time exists in the person's schedule, then the activity will be scheduled in a new tour. If a vehicle is required for this new tour, the vehicle must also be available for the same amount of time; otherwise, an alternate mode may be used. Table 4-21 summarizes this process for this activity.

If the model fails to schedule the activity in a new tour, then the activity is not scheduled within the current day. The model proceeds to schedule subsequent activities until there are no remaining activities.

Table 4-21: Scheduling Person 1 Recreational Activity into New Tour

<u>Person 1, Recreational Activity in TAZ 7001 (Duration: 1 hr)</u>
Check Existing Tour: #1 (Last Activity Ends in TAZ 7117 at 8:20pm)
- Waiting time prior to activity is greater than maximum waiting time. Not feasible in Tour #1.
Attempt to Schedule in New Tour: #2
- **Mode Choice**: Drive (-2.93, 94.9%), Transit (-6.28, 3.3%), Bike (-7.09, 1.5%) or Walk (-8.67, 0.3%); Select Drive; **Travel Time to Activity:** 19 minutes
- **Check Schedule Feasibility**: No conflicts in schedule. **Arrive at Activity**: 9:30pm.
- **Feasible to Schedule in Tour #2**: Activity Starts at 9:30pm, Ends at 10:30pm

Close Open Tours

When there are no more activities remaining to be scheduled, the model closes the tours by returning each person back home following the end of the last activity. Non-drive tours are closed first in order to determine potential shared trip opportunities. This step of the model is analogous to the scheduling of a subsequent activity into an existing tour; however, in this case, the location of the next activity is at home. Note that in this situation, there is an opportunity for Person 1 in his first tour to share a ride with Person 2 back home. Table 4-22 details the process of this step.

At the end of this step, the household travel resource allocation model is complete. The model has allocated the resources and scheduled the desired activities of the household. The final activity and tour schedule for all members of Household B is summarized in Figure 4-6.

Table 4-22: Closing Open Tours for Household B

Person 1

Closing Tour 1: (Last Activity Ends in TAZ 7109 at 8:20pm)

- **Previous Mode**: Transit
- **Check Feasibility for Shared Trip**: Driver (Person 2) arrives at 8:20pm, Sharing Feasible.
- **Mode Choice**: Share (-1.95, 49.3%) Transit (-3.60, 9.5%) or Walk (-2.13, 41.2%); Select Share.
- **Travel Time to Home:** 5 minutes; **Arrive at Home**: 8:25pm

Closing Tour 2: (Last Activity Ends in TAZ 7001 at 10:30pm)

- **Previous Mode**: Drive
- **Travel Time to Home:** 20 minutes; **Arrive at Home**: 10:50pm

Person 2

Closing Tour 1: (Last Activity Ends in TAZ 7106 at 8:25pm)

- Tour has already returned home.

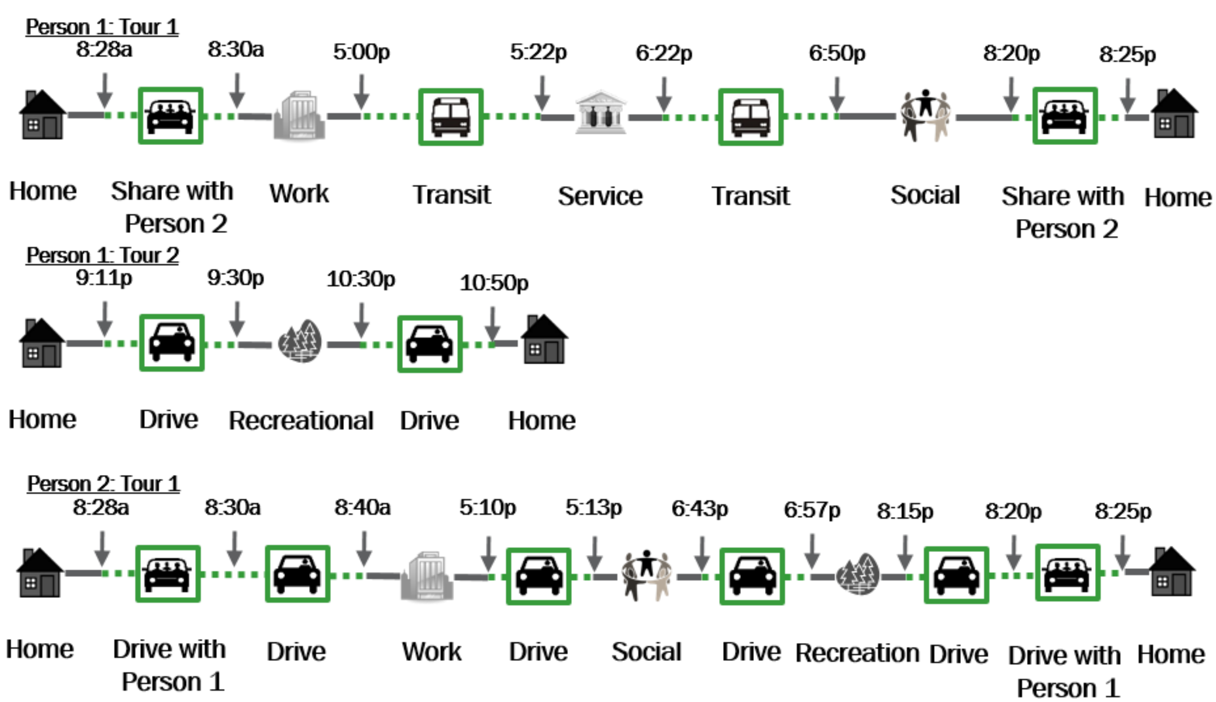


Figure 4-6: Summary of Tours and Scheduled Activities for Household B

Application to Household with Both Dependent and Independent Travellers (Household A)

In the previous section, this model step – Scheduling of Subsequent Activities – was described for its application to households with only independent travellers. The concepts are now extended to households with both dependent and independent travellers. The focus of this model description will be on Household A. There are four activities that remain to be scheduled in Household A, as summarized in order in Table 4-23.

Table 4-23: Remaining Activities for Household A

Order	Person	Type	Location	Early Start Time	Late Start Time	Duration
1	3	Service	7248	12:00pm	7:00pm	1 hr.
2	1	Service	7105	10:00am	7:00pm	15 min.
3	2	Grocery	7254	7:30am	10:00pm	30 min.
4	1	Recreation	7036	9:00pm	9:30pm	1 hr. 30 min.

The model schedules the remaining activities in the order of priority. Recall from Section 4.4.1 that since that the activities of dependent travellers have priority over the activities of independent travellers. Person 3 in Household A is a dependent traveller and desires to conduct a service activity. The scheduling of dependent travellers is slightly more complex as the schedules must be coordinated across two people. The following subsections describes the model approach to scheduling dependent activities.

Check Existing Dependent Tours

As with independent travellers, the model checks all existing tours for Person 3. There is one existing tour for this person. The last activity on the tour is her school activity in TAZ 7265, which finishes at 3:15pm.

As Person 3 is a dependent traveller, a chaperone is required to accompany her to any subsequent activities. In order for a chaperone to be assigned to the dependent, the chaperone must arrive within an amount of time prior to or after the end time of the previous activity, similar to how the model determines whether sharing is feasible. However, this amount of time is increased for dependents to 30 minutes before and 30 minutes after the end time of the previous activity. In this case, the chaperone must arrive between 2:45pm and 3:45pm for the pick up to be feasible.

The model iterates through all potential chaperones in the household. Analogous to the scheduling of subsequent independent activities, the model first checks the existing tours of all independent travellers. If there are no feasible existing tours for the chaperone, the model will attempt to schedule the trip in a new tour. The model also checks if there are any conflicts within the schedule of the chaperone, dependent and vehicle for when this activity may potentially take place. This results of this process is summarized in Table 4-24.

Table 4-24: Process of Assigning Chaperone for Subsequent Activity for Dependent Person 3

Check Person 1 as Chaperone Check Existing Tour: #1 (Last Activity Ends in TAZ 7020 at 4:15pm) - **Previous Mode**: Drive; **Travel Time to Dependent**: 12 minutes; **Pickup at**: 4:27pm - **Check Pickup Feasibility**: Chaperone arrives too late and pickup is infeasible. Attempt to Schedule in New Tour: - **Mode Choice**: Drive (-1.13, 84.8%); Transit (-6.00, 0.7%), Bike (-5.51, 1.1%) or Walk (-2.97, 13.5%); Select Drive. **Travel Time to Dependent**: 7 minutes; **Pickup at**: 3:15pm. - **Check Pickup Feasibility**: Pickup time conflicts with Tour #1. Not Feasible for Person 1 to Chaperone
Check Person 2 as Chaperone Check Existing Tour: #1 (Last Activity Ends in TAZ 7112 at 2:45pm) - **Previous Mode**: Drive; Travel Time to Dependent: 15 minutes; Pickup at 3:15pm - **Check Pickup Feasibility:** Chaperone arrives early and waits until 3:15pm; pickup is feasible. - **Travel Time to Activity:** 12 minutes; **Arrive at Activity:** 3:27pm - **Check Schedule Feasibility:** No conflicts with chaperone, dependent or vehicle schedules. Feasible for Person 2 to Chaperone in Existing Tour

Person 1 has commitments that preclude him from chaperoning Person 3 to her next activity. The model then proceeded to check Person 2 as a potential chaperone. From this step, Person 2 arrives 15 minutes prior to the activity end time for Person 3 and is therefore able to pick up Person 3 using an existing tour. Person 3 will travel to the subsequent activity with the mode used by the chaperone. In this case, Person 3 will share a ride with Person 2. Using this chaperone and mode, the model will determine if it is feasible to schedule the activity within the existing tour. The travel time between the pickup location in TAZ 7265 and the dependent's next activity in TAZ 7248 by car is 12 minutes. The earliest that this activity can start when connected to this tour is 3:27pm, which is within the start time range for this activity. Therefore, a new trip will be scheduled into Tour 1 of Person 2 in order to chaperone Person 3, and this activity for Person 3 will be scheduled, starting at 3:27pm and ending at 4:27pm.

As this dependent activity is scheduled in an existing tour, the model does not attempt to schedule the activity in a new tour for Person 3.

Close Open Tours of Dependents

At this point, all of the activities for dependent travellers have been scheduled; however, the dependents still remain at their activities. It is important to return the dependents home prior to the scheduling of any other subsequent independent activities. There are only two open dependent tours as outlined in Table 4-25.

Table 4-25: Open Tours for Dependents in Household A

Person	Tour	Location	Last Activity End Time	Must be Picked Up by:
3	1	7248	4:27pm	4:42pm
4	1	7255	4:30pm	4:45pm

As with any subsequent dependent activity, a chaperone is required to accompany the dependent on the trip. The model will attempt to connect these trips to an existing tour for a chaperone. If none of these are feasible, then the model will attempt to start a new tour for the chaperone. The result of this process is detailed in Table 4-26 for Person 3 and in Table 4-27 for Person 4.

Table 4-26: Process to Close Tour 1 for Dependent Person 3

<u>Check Person 1 as Chaperone</u>
Check Existing Tour: #1
- Last Activity Ends in TAZ 7020 at 4:15pm.
- **Previous Mode**: Drive; **Travel Time to Dependent**: 15 minutes; **Pickup at:** 4:30pm.
- **Check Pickup Feasibility**: Person 1 arrives after dependent is available and pickup is feasible.
- **Travel Time to Home**: 14 minutes; **Arrive at Home**: 4:44pm.
- **Check Schedule Feasibility**: No conflicts with chaperone, dependent or vehicle schedules.
Feasible for Person 1 to Chaperone in Existing Tour.

Table 4-27: Process to Close Tour 1 for Dependent Person 4

<u>Check Person 1 as Chaperone</u> Check Existing Tour: #1 (Last Activity Ends in TAZ 7263 at 4:44pm) - **Previous Mode**: Drive; **Travel Time to Dependent**: 8 minutes; **Pickup at**: 4:52pm - **Check Pickup Feasibility**: Person 1 arrives too late and pickup is infeasible. Attempt to Schedule in New Tour: - **Preferred Mode**: Drive (-1.24, 93.7%); Transit (-6.84, 0.3%), Bike (-5.78, 1.0%) or Walk (-4.18, 4.9%); Select Drive. **Travel Time to Dependent**: 8 minutes; **Pickup at:** 4:30pm - **Check Pickup Feasibility**: Pickup trip conflicts with Tour 1. Not Feasible for Person 1 to Chaperone
<u>Check Person 2 as Chaperone</u> Check Existing Tour: #1 (Last Activity Ends in TAZ 7248 at 3:27pm) - **Previous Mode**: Drive; **Travel Time to Dependent:** 9 minutes; **Pickup at:** 3:36pm - **Check Pickup Feasibility:** Chaperone arrives too early and pickup is infeasible. Attempt to Schedule in New Tour: **Preferred Mode**: Drive (-1.24, 93.7%); Transit (-6.84, 0.3%), Bike (-5.78, 1.0%) or Walk (-4.18, 4.9%); Select Drive. **Travel Time to Dependent**: 10 minutes; **Pickup at:** 4:30pm - **Check Pickup Feasibility**: Chaperone arrives when dependent is available and pickup is feasible. - **Travel Time to Home**: 14 minutes; **Arrive at Home**: 4:44pm. - **Check Schedule Feasibility**: No conflicts with chaperone, dependent or vehicle schedules. Feasible for Person 2 to Chaperone in New Tour

Remaining Activities of Independent Travellers

Following the scheduling of activities and tours for the dependent travellers, the household is able to schedule the remaining activities for the independent travellers. Three discretionary activities remain to be scheduled. At this point, the model follows the same process as outlined for the household with only independent travellers. Table 4-28 provides the results of this process.

Table 4-28: Scheduling of Subsequent Activities in Existing Tours for Household B

<u>Person 1, Service Activity in TAZ 7105 (Duration: 15 minutes)</u> Check Existing Tour: #1 (Last Activity Ends in TAZ 7263 at 4:44pm) - Tour has already returned home. Not feasible to schedule in Tour #1. Attempt to Schedule in New Tour: #2 - **Mode Choice**: Drive (-1.91, 96.0%), Transit (-6.38, 1.1%), Bike (-6.25, 1.2%) or Walk (-5.96, 1.7%); Select Drive; **Travel Time to Activity:** 12 minutes - **Check Schedule Feasibility**: No conflicts in schedule after 4:44pm. **Arrive at Activity**: 4:56pm. - **Feasible to Schedule in Tour #2**: Activity Starts at 4:56pm, Ends at 5:11pm
<u>Person 2, Grocery Activity in TAZ 7254 (Duration: 30 minutes)</u> Check Existing Tour: #1 (Last Activity Ends in TAZ 7248 at 3:27pm) - **Previous Mode**: Drive; **Travel Time to Activity**: 8 minutes; **Arrive at Activity**: 3:35pm - **Check Schedule Feasibility**: Activity will conflict with Tour 2. - Not feasible to schedule in Tour #1 Check Existing Tour: #2 (Last Activity Ends in TAZ 7263 at 4:40pm) - Tour has already returned home. Not feasible to schedule in Tour #2. Attempt to Schedule in New Tour: #3 - **Mode Choice:** Drive (-1.62, 91.8%); Transit (-7.03, 0.4%); Bike (-5.79, 1.4%); Walk (-4.28, 6.4%); Select Drive; **Travel Time to Activity:** 11 minutes - **Check Schedule Feasibility:** No conflicts in schedule after 4:40pm. **Arrive at Activity**: 4:51pm - **Feasible to schedule in Tour #3**: Activity Starts at 4:51pm, Ends at 5:21pm.

<u>Person 1, Recreational Activity in TAZ 7036 (Duration: 1 hour, 30 minutes)</u> Check Existing Tours: #1 (Last Activity Ends in TAZ 7263 at 4:44pm) - Tour has already returned home. Not feasible to schedule in Tour #1. Check Existing Tours: #2 (Last Activity Ends in TAZ 7105 at 5:11pm) - **Previous Mode**: Drive; **Travel Time to Activity**: 12 minutes; **Arrive at Activity**: 5:23pm - **Wait Time at Activity:** 4 hours and 7 minutes. **Max Wait Time:** 46 minutes - Activity starts much later than arrival time. Not feasible to schedule in Tour #2 Attempt to Schedule in New Tour: #3 - **Mode Choice**: Drive (-2.78, 97.3%), Transit (-7.68, 0.7%), Bike (-6.91, 1.6%) or Walk (-8.30, 0.4%); Select Drive; **Travel Time to Activity:** 15 minutes - **Check Schedule Feasibility**: No conflicts in schedule. **Arrive at Activity**: 9:00pm. - **Feasible to Schedule in Tour #3**: Activity Starts at 9:00pm, Ends at 10:30pm

Close Open Independent Tours

After all activities have been scheduled, the model closes the tours by returning each person back home following the end of the last activity. Table 4-29 provides the results of this step.

Table 4-29: Closing Open Tours for Independent in Household A

<u>Person 1</u> Closing Tour 1: (Last Activity Ends in TAZ 7263 at 4:44pm) - Tour has already returned home. Closing Tour 2: (Last Activity Ends in TAZ 7105 at 5:11pm) - **Previous Mode**: Drive; **Travel Time to Home:** 13 minutes; **Arrive at Home**: 5:24pm Closing Tour 3: (Last Activity Ends in TAZ 7036 at 10:30pm) - **Previous Mode**: Drive; **Travel Time to Home:** 15 minutes; **Arrive at Home**: 10:45pm
<u>Person 2</u> Closing Tour 1: (Last Activity Ends in TAZ 7248 at 3:27pm) - **Previous Mode**: Drive; **Travel Time to Home:** 14 minutes; **Arrive at Home**: 3:41pm Closing Tour 2: (Last Activity Ends in TAZ 7263 at 4:40pm) - Tour has already returned home. Closing Tour 3: (Last Activity Ends in TAZ 7254 at 5:21pm) - **Previous Mode**: Drive; **Travel Time to Home:** 11 minutes; **Arrive at Home**: 5:32pm

At the end of this step, the household travel resource allocation model is complete for Household A. The model has allocated the resources and scheduled the desired activities of the household. The final activity and tour schedule for all members of Household A is summarized in Figure 4-7.

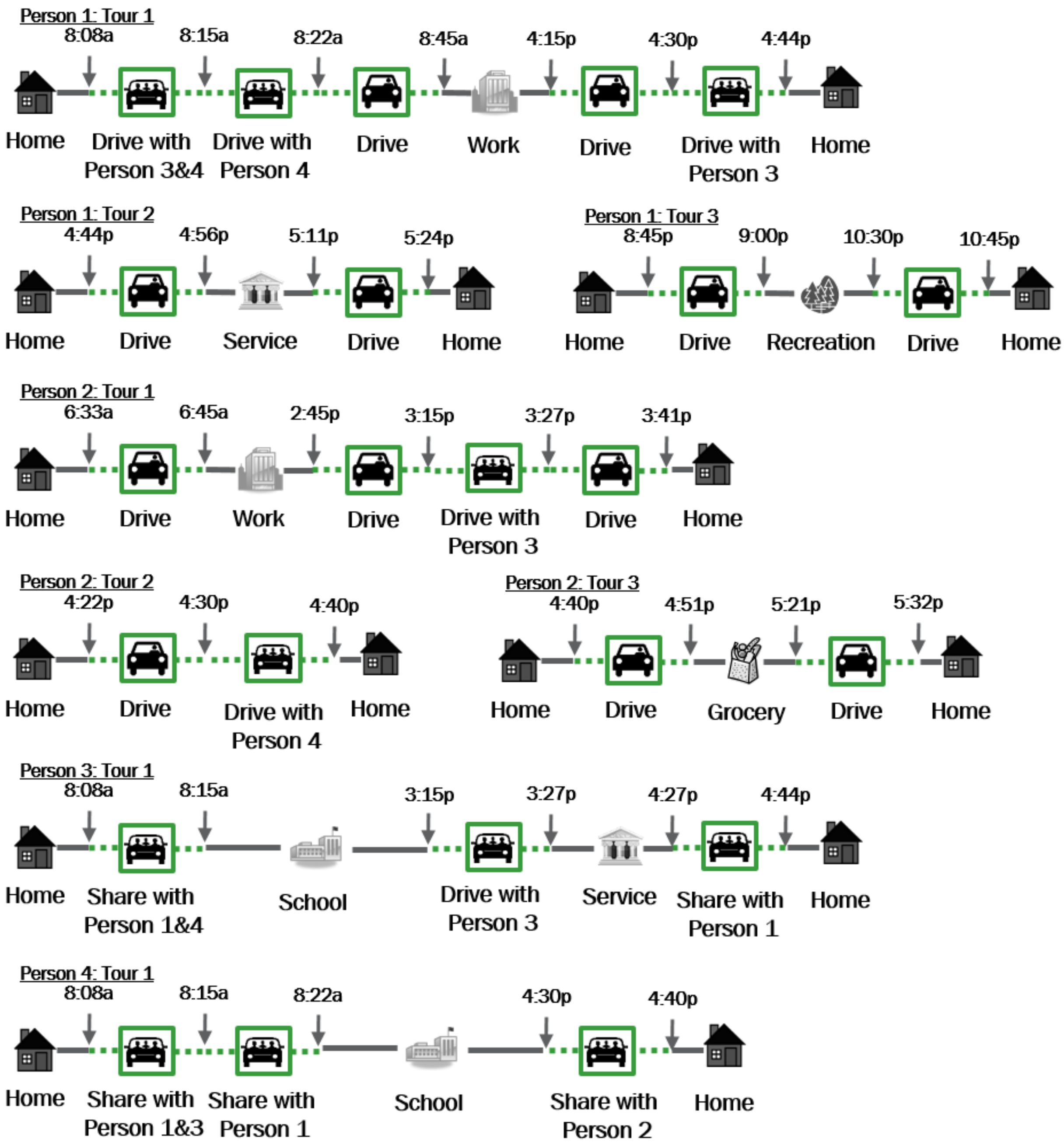


Figure 4-7: Summary of Tours and Scheduled Activities for Household A

4.5 Model Outputs

The resulting output following the completion of the model is a list of the scheduled activities and tours for each person in the household. These results answer the original two basic questions set forth in the beginning of this chapter:

1. When will the activity be accomplished?
2. How will the person travel to the activity?

The list of scheduled activities for each person indicates when the activity starts and ends, as well as the location for the activity, as indicated in Figure 4-8. The list of scheduled tours indicates the departure time, arrival time, and mode for each trip, as indicated in Figure 4-9. Note that the model also automatically calculates the duration of activities and travel, as well as the cost that is associated with each mode of travel, based on the methods outlined in Section 4.3.2. Full model outputs for the example households have been provided in Appendix D.

```
Activities for Person #1
Activity #:     1       2       3
Priority:       1       2       5
Location:       7020    7105    7036
Starts:         8:58    17:11   18:03
Ends:           16:27   17:25   19:32
Total Time:     9:15
```

Figure 4-8: Example Output of Scheduled Activities (Household B, Person 1)

Person #1, Tour #1					
Trip#:	1	2	3	4	5
Mode:	D	D	D	D	D
O-TAZ:	7263	7265	7255	7020	7248
D-TAZ:	7265	7255	7020	7248	7263
Departs:	8:08	8:15	8:41	16:28	16:43
Arrives:	8:14	8:21	8:57	16:42	16:57
Duration:	0:07	0:07	0:17	0:15	0:15
Tour Time:	1:01				
Tour Cost:	2.59				

Figure 4-9: Example Output of Scheduled Tours (Household B, Person 1)

With an understanding of travel time and travel cost, these outputs can be extended to determine an overall metric that represents the amount of resources that are dedicated to household travel. Since some households may elect to save money by using active modes of transportation, but this inexpensive alternative may have longer travel times, it is important to use a metric that accounts for this trade-off between travel time and travel cost. Both travel time and cost can be combined using the value of time calculated in Section 4.3.3 to determine the generalized cost of travel for the household, as outlined in Equation 4-12.

$$Generalized\ Cost = (Value\ of\ Time) * \sum Tour\ Travel\ Times + \sum Tour\ Travel\ Costs$$

Equation 4-12: Generalized Cost of Transport

As discussed in Section 4.3.3, the value of time may be interpreted as the amount of money one is willing to spend to save one hour of travel time.

Assuming that the value of time is the same as what was derived in Equation 4-8 - $5.25 per hour – the following generalized costs are estimated and summarized in Table 4-30 for Household A and Table 4-31 for Household B.

Table 4-30: Generalized Cost of Transport for Household A

Person	Tour	Travel Time	Travel Cost	Generalized Cost
1	1	61 minutes	$2.59	$7.92
1	2	25 minutes	$1.43	$3.62
1	3	47 minutes	$0.00	$4.11
2	1	53 minutes	$2.07	$6.71
2	2	18 minutes	$0.67	$2.24
2	3	22 minutes	$1.10	$3.02
3	1	34 minutes	$0.00	$2.98
4	1	24 minutes	$0.00	$2.10
Total Household A Generalized Cost of Transport:				$32.70

Table 4-31: Generalized Cost of Transport for Household B

Person	Tour	Travel Time	Travel Cost	Generalized Cost
1	1	57 minutes	$3.95	$8.94
2	1	39 minutes	$1.60	$5.01
Total Household B Generalized Cost of Transport:				$13.95

Based on the proposed model and resulting household schedules, the generalized cost of transport for Household A is $32.70 and for Household B is $13.95. This cost is for a household that is able to schedule all of their desired activities. In the case where an activity is not scheduled, or if an external resource is required to accomplish a trip, an additional generalized cost should be assigned to the household. No attempt is made here to establish what this additional cost is for unaccomplished activities; however, the cost should be proportional to the priority of the activity. If a high priority activity is unable to be scheduled, then a significant cost should be placed to the household.

The generalized cost of transport may then be compared to a household transportation budget, which would account for both travel time and travel cost. Again, no attempt is made here to establish the value of the household transport budget. As mentioned earlier, Mokhtarian & Chen (2004) summarized over 24 empirical studies of time and cost budgets and found that time budgets are not constant but are context-specific, depending on the characteristics of the household, its members, and their activities. In particular, the characteristics that are of interest include income, car ownership, gender, employment, activity type, and activity duration. Arentze, Ettema, & Timmermans (2010) also attempted to incorporate time and money budgets into an activity-based travel model, but they noted challenges as households may not have the same travel budget on a day-to-day basis; instead, there may be fluctuations depending on the amount of fluctuations that need to be accomplished on that day.

By comparing the generalized cost of transport expended by a household to a household travel budget, this model of short-term transport decisions may trigger a longer term household decision. Specifically, if the generalized cost exceeds the household travel budget, the household may need to consider alternatives to reduce the generalized cost. These alternatives may include: increasing the resources available to the household (e.g. purchase of a new household vehicle or transit pass), or moving the household to a location that is closer to activities. These decisions, and in particular, the household relocation decision, is the focus of the broader integrated land use - transport model for Kitchener - Waterloo.

4.6 Chapter Summary

This chapter detailed the concept and development of a household-based activity-travel model for Kitchener - Waterloo. This model concept is based off a review of the existing literature on activity-based travel models, and a household travel survey intended to inform this model development. This model consists of a traffic analysis zone-based representation of the study area, which is fundamental to the calculation of travel costs and travel times between each origin - destination pair for each mode in Kitchener - Waterloo.

Households in this model are collections of people who live in the same dwelling, and can consist of independents who can travel on their own without supervision, as well as dependents who can travel with the supervision of a chaperone. Each of these people have a set of mandatory and discretionary activities, which they desire to achieve on a given day. Each household has a set of limited resources that are available to them for travel to activities, which include household vehicles and independents who able to chaperone dependents. Furthermore, each person may choose drive, share, transit, bike or walk to each activity, depending on what resources are available.

The objective of this model, therefore, is to create a feasible activity and travel schedule that allocates the travel resources in a way that the household members are able to achieve their activities. Several main principles may be drawn from the description of the model:

1. Activities are scheduled in order of priority. Moreover, dependent activities take precedence over independent activities. The priority that is used in this model is based off of the results from the household travel survey.
2. Schedule feasibility is important in the development of the activity-travel schedule. Activities must begin within the specified start time range, which is representative of time constraints such as the opening hours of activities. Furthermore, there must be no scheduling conflicts; therefore, the availability of vehicle and chaperone resources limit the possibilities of when activities can be scheduled.
3. Utility maximization is fundamental to the mode choice decision and to the allocation of resources. A random utility-based multinomial logit model was specified using 2011 Transportation Tomorrow Survey data. From this model, utility functions for auto, transit, bike and walk modes are used in the broader activity-based model. These functions are applied whenever there is a mode choice decision.
4. Interactions between household members are represented when the first mandatory activities are scheduled in the model. Dependents and vehicles are first assigned to chaperones to maximize

household utility. Then remaining vehicles are assigned to independent travellers to maximize household utility. A person may share a ride to his or her first mandatory activity if it is feasible and if it maximizes household utility.

5. Subsequent activities are scheduled in the order of priority and in a step-wise approach. The model first attempts to schedule each activity because it minimizes the amount of travel time and cost incurred by the household. If it is not feasible, then the model will start a new tour in order to schedule the activity. If the scheduling of the activity is still not possible in a new tour, the activity is deferred. The model continues until all activities in the household have been attempted to be scheduled.

Based on these principles, this model develops an acceptable and feasible (but not necessarily optimal) household schedule. It establishes when activities occur and how each person will travel to their activity. A generalized cost of transport may be calculated from the scheduled activities and tours, and then compared with a household travel budget to connect with the broader integrated land use - transport model of household decisions in Kitchener - Waterloo.

The model proposed in this chapter was developed in its entirety by the researcher and implemented in Java, which is an object-oriented programming language. The only assistance provided for the model development was for the estimation of travel times and costs for the study area. The model structure is depicted again in Figure 4-10 with a summary of the detailed steps discussed in this chapter.

The testing of this model is detailed further in Chapter 5, and the limitations and further work recommended for this model is discussed in Chapter 6.

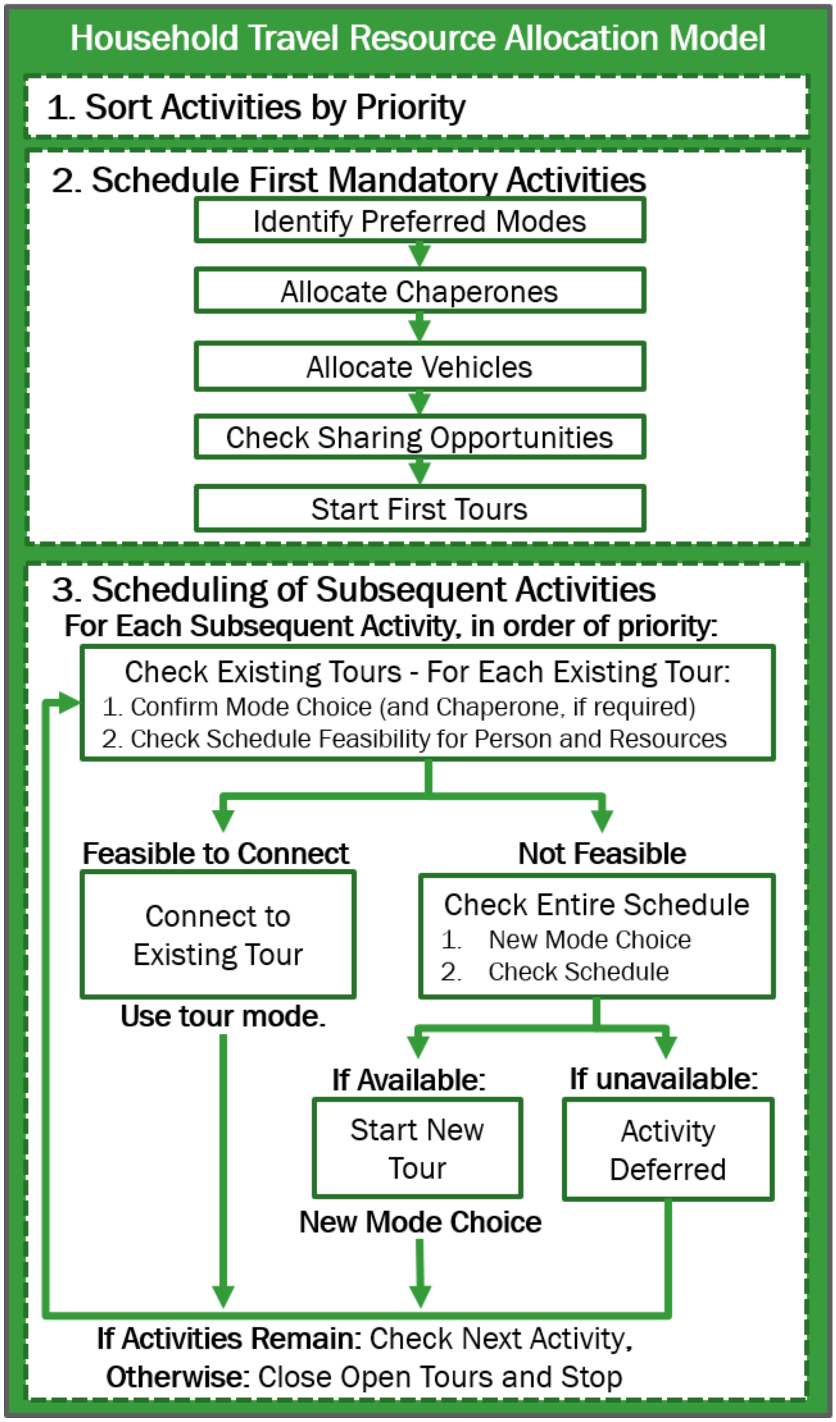


Figure 4-10: Household Travel Resource Allocation Model

5.0 MODEL TESTING

5.1 Overview

Following the conceptual development and implementation of a household activity travel model, the final objective of this study is to test the model to ensure its applicability to the Kitchener - Waterloo study area. These model tests how well the model logic and data reflects an actual travel schedule. The model is tested using a single day of activity and travel provided from the households that participated in the exploratory household travel survey. Moreover, these tests also demonstrate how long the model takes to arrive at a solution for a household. This chapter discusses the method and the results of the tests conducted on this proposed model.

5.2 Representativeness of Household Behaviour

The following section discusses the tests of the model using a limited data set to demonstrate the model's capability to represent household travel behaviour. The following subsections discuss the data, method, results and interpretations of the tests.

5.2.1 Test Data Source

The exploratory household travel survey discussed in Chapter 3 is the source of the data that is used for model testing. Recall that this household travel survey consisted of 14 households and of these households 9 of them have been used to test the model. These households were used as they were located in Kitchener - Waterloo, and travel time data was available for the origin and destination pairs identified for trips. In this group of 9 households, 2 have identified that at least one of their members is dependent or semi-dependent. The rest of the households consist of independent travellers. As the activity and schedule data are from the same households that provided their activity priorities and motivations (which are used in the development of the model), these tests may be considered as a 'within calibration sample verification'.

In preparation for the test, the data from the household survey is converted into three comma separated value or 'CSV' files that act as inputs into the computer model. The first CSV file consists of the postal code and the number of vehicles in the household. The second CSV file outlines the characteristics of each person including: age, gender, employment, student status, and traveller independence, as well as whether or not each person has a driver's license or a transit pass. The final CSV file consists of the activities for all of the household members. The file includes the postal code location, activity type, start time and duration for each activity. While chaperoning and home activities are reported in the exploratory survey, these have been removed from the input activity list in order to test if the model is able to endogenously generate these two activity types. The household model accepts these files in order to perform the household travel allocation.

5.2.2 Test Methods

Nine households were used as tests for the model. Given the household resources, persons and activities, the model creates a schedule based on the rules and principles outlined in Chapter 4.

Two tests were conducted for each household: a fixed test and a flexible test. The fixed test assumed that the start time for each activity is similar to the one reported by the household. The feasible start times for each activity in the fixed test ranged from 15 minutes prior to 15 minutes after the reported start time. The Flexible test relaxes this start time restriction for any discretionary activity, which enables the model to determine when to schedule the activity. The assumed ranges of start times are listed in Table 5-1.

Table 5-1: Assumed Ranges of Start Times for Flexible Test

Activity Type	Early Start Time	Late Start Time
Work / School	15 minutes prior to reported time	15 minutes after reported time
Service	10:00am	7:00pm
Grocery	7:30am	10:00pm
Other Shopping	9:30am	9:00pm
Social	10:00am	10:00pm
Recreation	10:00am	10:00pm

The outputs of these two tests are compared with the actual schedule reported by the households in the exploratory household survey. These outputs provide an indication of the performance of the model. In particular the outputs are analyzed to answer the following questions:

- Does the model schedule all reported activities for the household?
- Does the model correctly estimate the number of tours for each person in the household?
- Does the model correctly predict the mode choice of travellers for the first tour?
- In households that have dependents, does the model correctly assign the pairs of chaperones and dependents?

A comment should be made on the question regarding the estimation of mode choice and the emphasis on the first tour. As the model can rearrange activities in the schedule and mode choice is a function of the travel time and cost between the origin and destination, it is difficult for the model to exactly replicate mode choice in the actual schedule. However, the mode choice decision in the model that remains relatively similar to reality is the mode choice and resource allocation decision for the first tour that serves the mandatory activities of the household. This mode choice decision eventually affects the rest of the mode choice and scheduling decisions for the household. By comparing the predicted and actual mode choice for the first tours for each person, the results should provide insight on the performance of the resource allocation and mode choice logic of the model.

Specific results are presented and discussed for one household test case. Following this discussion is a summary of the key themes that emerged from the 9 household test cases.

5.2.3 Test Case 1: Household 1

Household 1 consists of 5 people who live in a suburban neighbourhood in northwest Waterloo (TAZ# 7247). This household owns one vehicle. Table 5-2 summarizes the characteristics of the people in this household.

Table 5-2: Person Characteristics of Household 1

Person	Age	Gender	Employed?	Student?	Independent?	Driver?	Has Transit Pass?
1	50	F	Yes, full time	No	Yes	Yes	No
2	49	M	No	No	Yes	Yes	No
3	17	M	Yes, part time	Yes	No	No	Yes
4	15	M	No	Yes	No	No	Yes
5	12	F	No	Yes	In some cases	No	No

It is important to note that in the survey, Household 1 noted that Person 5 is dependent in some cases, but is able to travel to school on their own on foot or bike only. Based on this definition from the respondent, and as Person 5 was able to travel to their mandatory activity on their own, Person 5 was classified as independent for the purposes of the model. In this way, Household 1 is does not require resources to chaperone dependents to activities. The activities that are associated with Household 1 are listed in Table 5-4. Figure 5-1 depicts these locations on a map of the study area.

Table 5-3: Activities for Household 1

Person	Act. #	Type	Location	Start Time	End Time	Duration
1	1	Work (1)	7042	7:30am	5:15pm	9 hr. 45 min
1	2	Work (2)	7087	7:10pm	8:50pm	1 hr. 40 min.
1	3	Recreation	7028	9:35pm	10:35pm	1 hr.
2	1	Grocery (1)	7254	9:10am	9:50am	40 min.
2	2	Grocery (2)	7109	10:00am	10:30am	30 min.
2	3	Grocery (3)	7053	10:40am	11:00am	20 min.
3	1	School	7050	8:10am	4:30pm	7 hr. 25 min.
3	2	Work	7253	7:00pm	9:00pm	2 hr.
4	1	School	7050	8:00am	2:50pm	6 hr. 50 min.
4	2	Recreation	7107	3:00pm	4:30pm	1 hr. 30 min.
4	3	Social	7248	7:05pm	8:30pm	1 hr. 25 min.
5	1	School	7248	9:15am	4:30pm	7 hr. 15 min.
5	2	Social	7248	3:05pm	4:00pm	55 min.
5	3	Recreation	7244	7:10pm	7:50pm	40 min.

A graphical representation of the actual schedule is depicted in Figure 5-2. Two tests were conducted on this household case: one where the start times were fixed within 30 minutes of the actual start time and another where the start times were flexible depending on the activity type. The results of the fixed test are represented in Figure 5-3, and the results of the flexible test are represented in Figure 5-4. Comparing these results to the actual schedule can reveal the ability of the model to represent household travel behaviour.

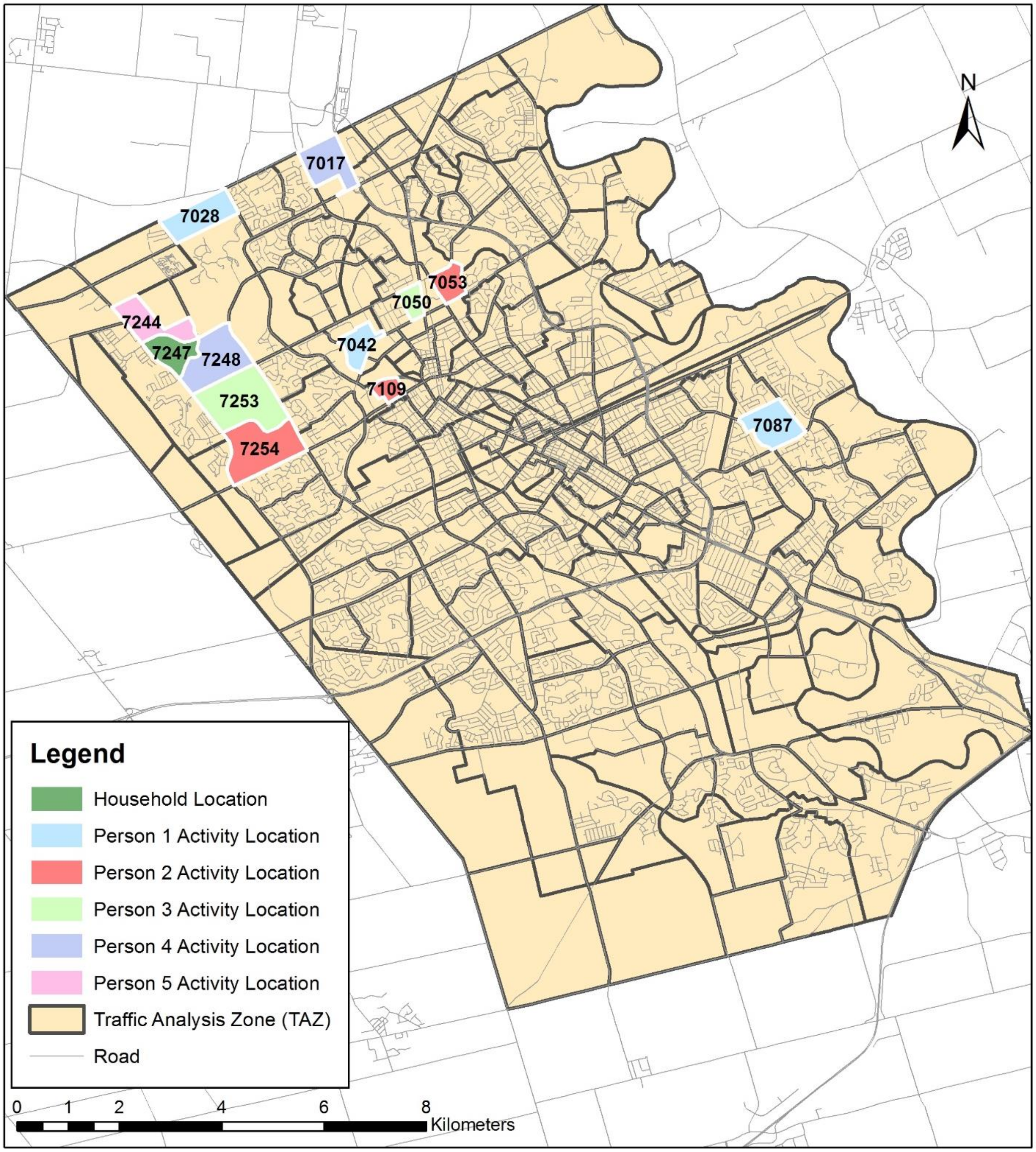


Figure 5-1: Map of Household 1 and Activity Locations

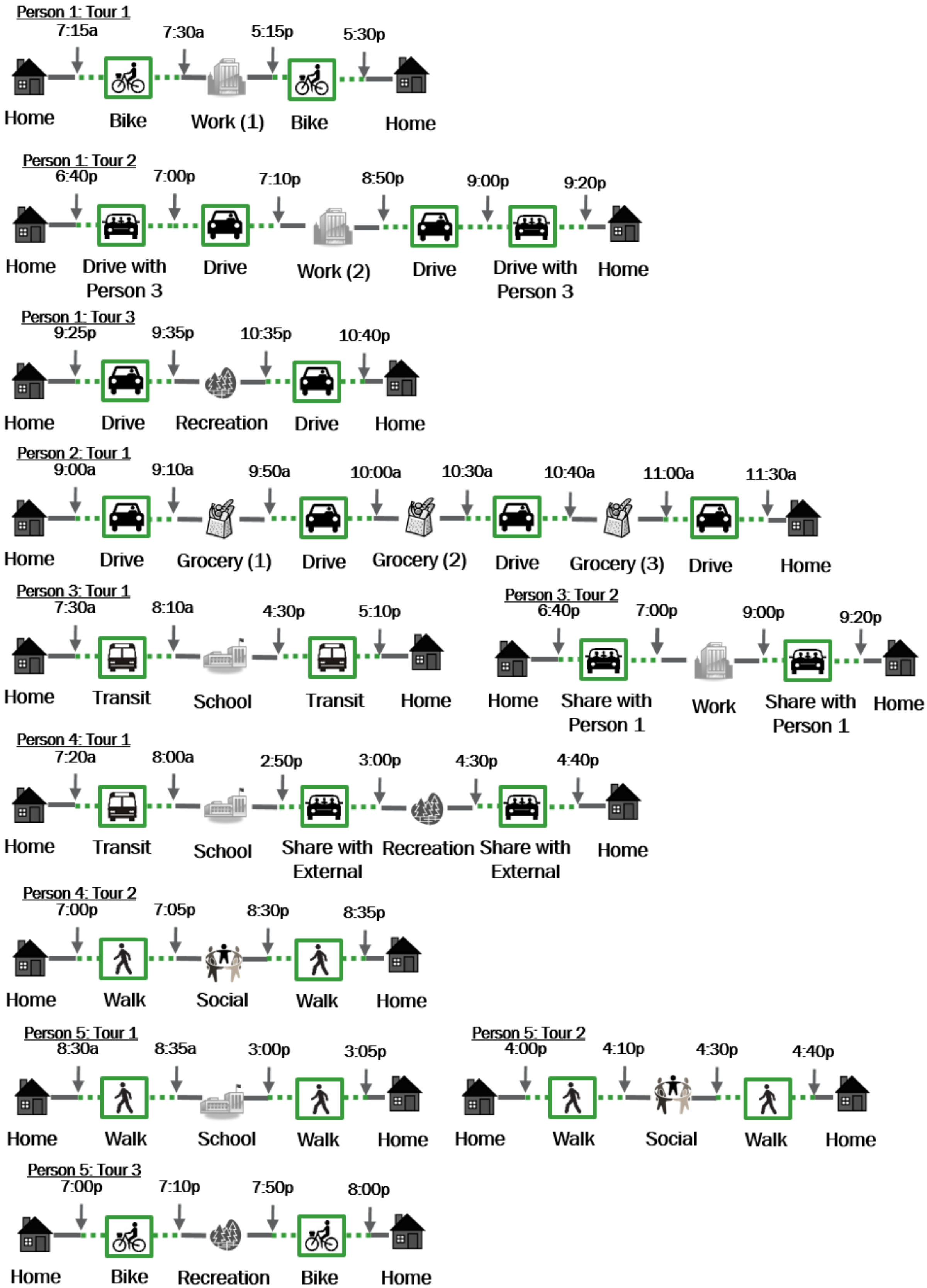


Figure 5-2: Actual Schedule for Household 1

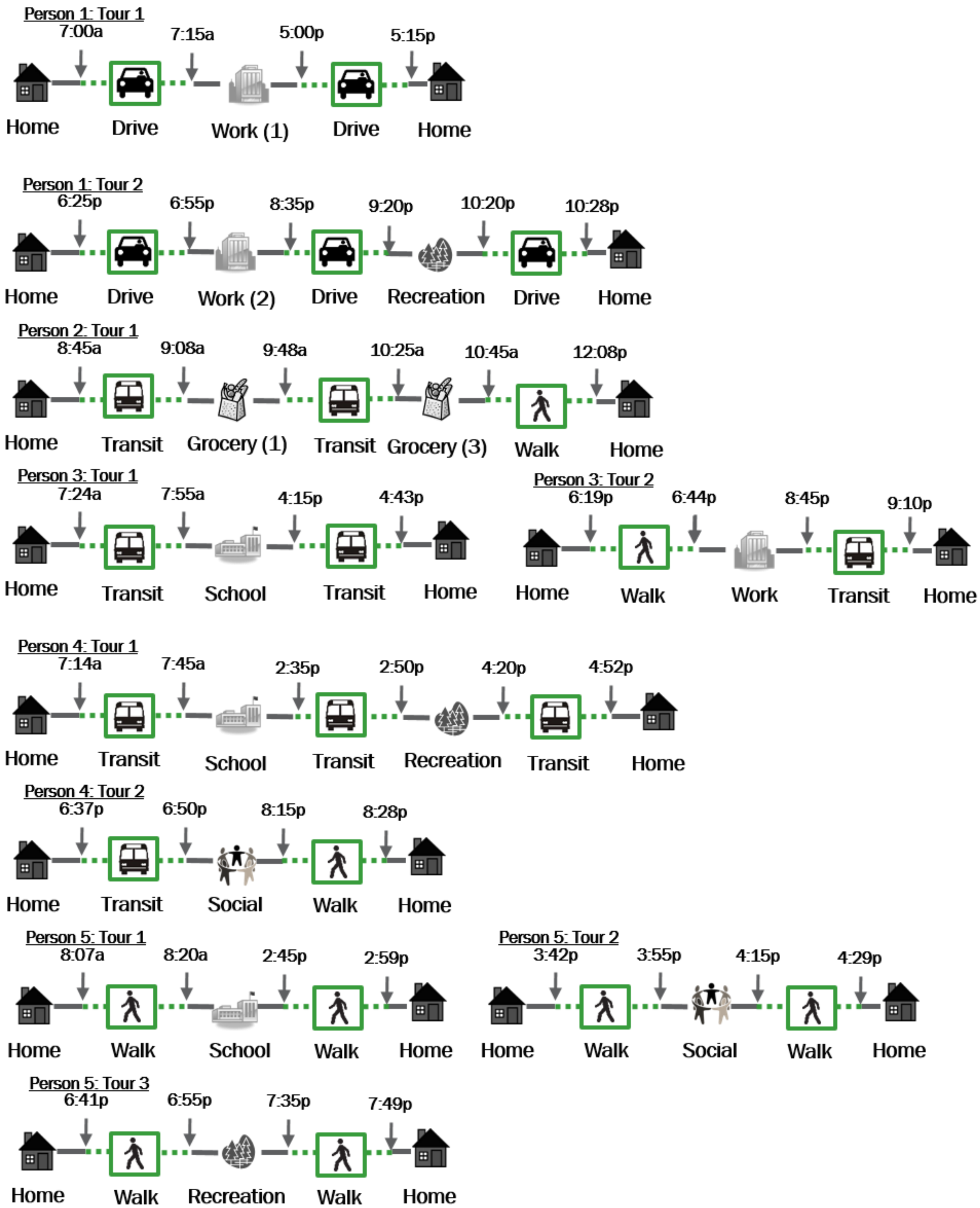


Figure 5-3: Result of Fixed Test on Household 1

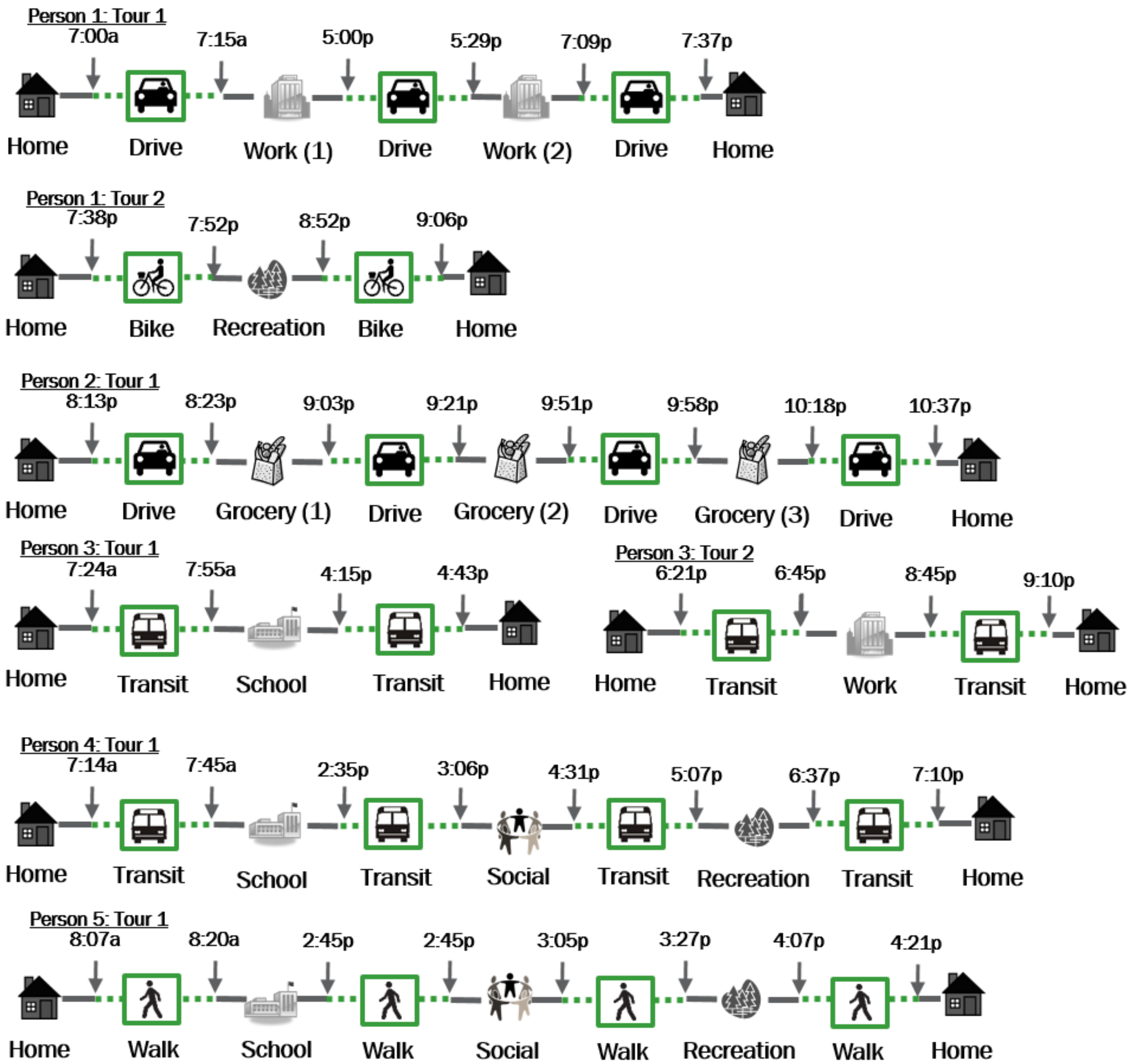


Figure 5-4: Result of Flexible Test on Household 1

Under the fixed test, the model is able to able to schedule all activities for 4 of the 5 persons in the household. In this test, Person 2 was unable to accomplish one of their activities. Under the flexible test, the model is able to schedule all activities. With respect to the number of tours that are created for each person, the number of tours matches the actual number of tours for 4 out of the 5 persons under the fixed test under the fixed test, and for 2 out of the 5 persons for the flexible test. In the flexible test, many of the activities have been scheduled on a single tour to minimize travel time and cost to the person.

The resulting schedules can be directly attributed to the resource allocation and mode choice conducted for the first tours of this household. In this test, both Person 1 and Person 2 preferred to drive to their first activity; however, only one vehicle is available in the household. The vehicle was assigned to Person 1, which meant that Person 2 needed to use an alternative mode of transport to travel to activities. Under a flexible activity start time, all persons are able to conduct all of their activities and the mode choice of Person 2 matched the actual mode choice; however, a closer inspection of the activity start times revealed that Person 2 conducted activities only when Person 1 returned home with the vehicle. In reality, Person 1 cycled on the first tour enabling Person 2 to conduct activities with the household vehicle earlier in the day.

An inspection of the utilities associated with this first trip for Person 1 suggests that the utility function and mode choice model specified in this household model would likely not be able to capture this preference for cycling over driving. For this particular trip, Person 1 would experience a utility of -2.28 for Drive, -5.81 for Transit, -6.25 for Bike and -5.96 for Walk. The probability that a person would drive in this situation is 93.2% whereas the probability that a person would bike is 1.8%. Based on these probabilities, Person 1 and this household are likely outliers compared to other households in Kitchener - Waterloo and other factors appear to influence this initial mode choice decision.

5.2.4 Test Case 2: Household 9

This second test case is known as Household 9 in the survey data set. Household 9 consists of 4 people who live east of downtown Kitchener (TAZ# 7151). This household has 2 vehicles. The characteristics of the people in this household are summarized in Table 13. The activities for Household 9 are listed in Table 5-3 and mapped in Figure 5-5. A graphical representation of the actual schedule is depicted in .

Table 5-4: Person Characteristics of Household 9

Person	Age	Gender	Employed?	Student?	Independent?	Driver?	Has Transit Pass?
1	35	F	Yes, full time	No	Yes	Yes	No
2	39	M	Yes, full time	No	Yes	Yes	No
3	5	F	No	Yes	No	No	No
4	3	M	No	Yes	No	No	No

Table 5-5: Activities for Household 9

Person	Act. #	Type	Location	Start Time	End Time	Duration
1	1	Work	7042	8:30am	12:00pm	3 hr. 30 min
1	2	Grocery	7248	12:10pm	12:35pm	25 min.
1	3	Work	7042	1:00pm	4:30pm	3 hr. 30 min.
1	4	Recreation	7021	6:45pm	8:00pm	1 hr. 15 min.
2	1	Work	9888*	9:40am	4:00pm	6 hr. 20 min.
3	1	School	7151**	8:55am	4:20pm	7 hr. 25 min.
3	2	Service	7104	4:30pm	5:45pm	1 hr. 15 min.
4	1	School	7189	9:15am	4:30pm	7 hr. 15 min.

* **Note**: Zone 9888 represents a zone external to Kitchener - Waterloo. Since there was only one external zone, the model assumed that all trips to/from this external zone is on average 25 minutes, which is reflective of the amount of actual driving travel time.
** **Note**: Zone 7151 is the same zone as the location of the household.

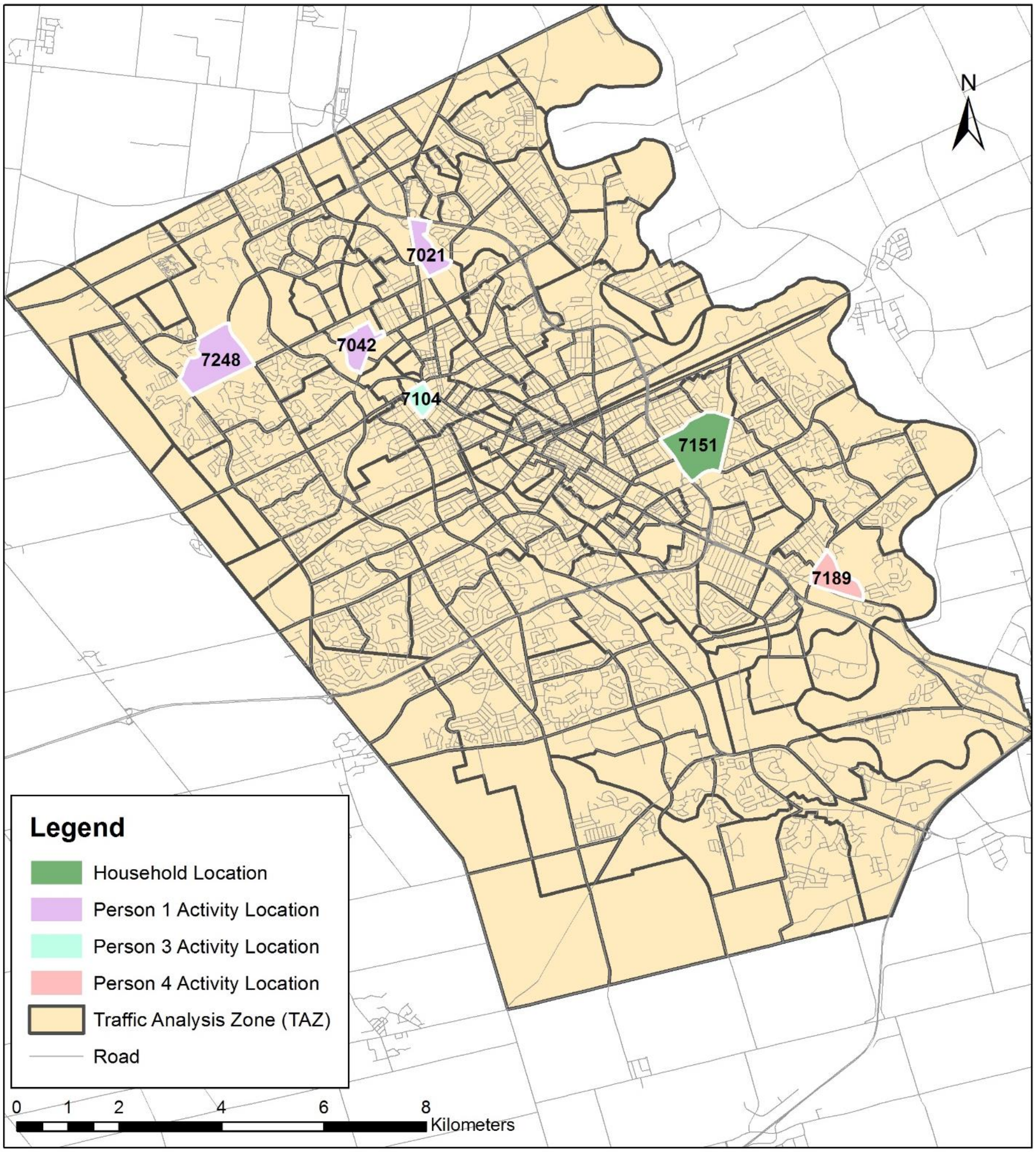


Figure 5-5: Map of Household 9 and Activity Locations

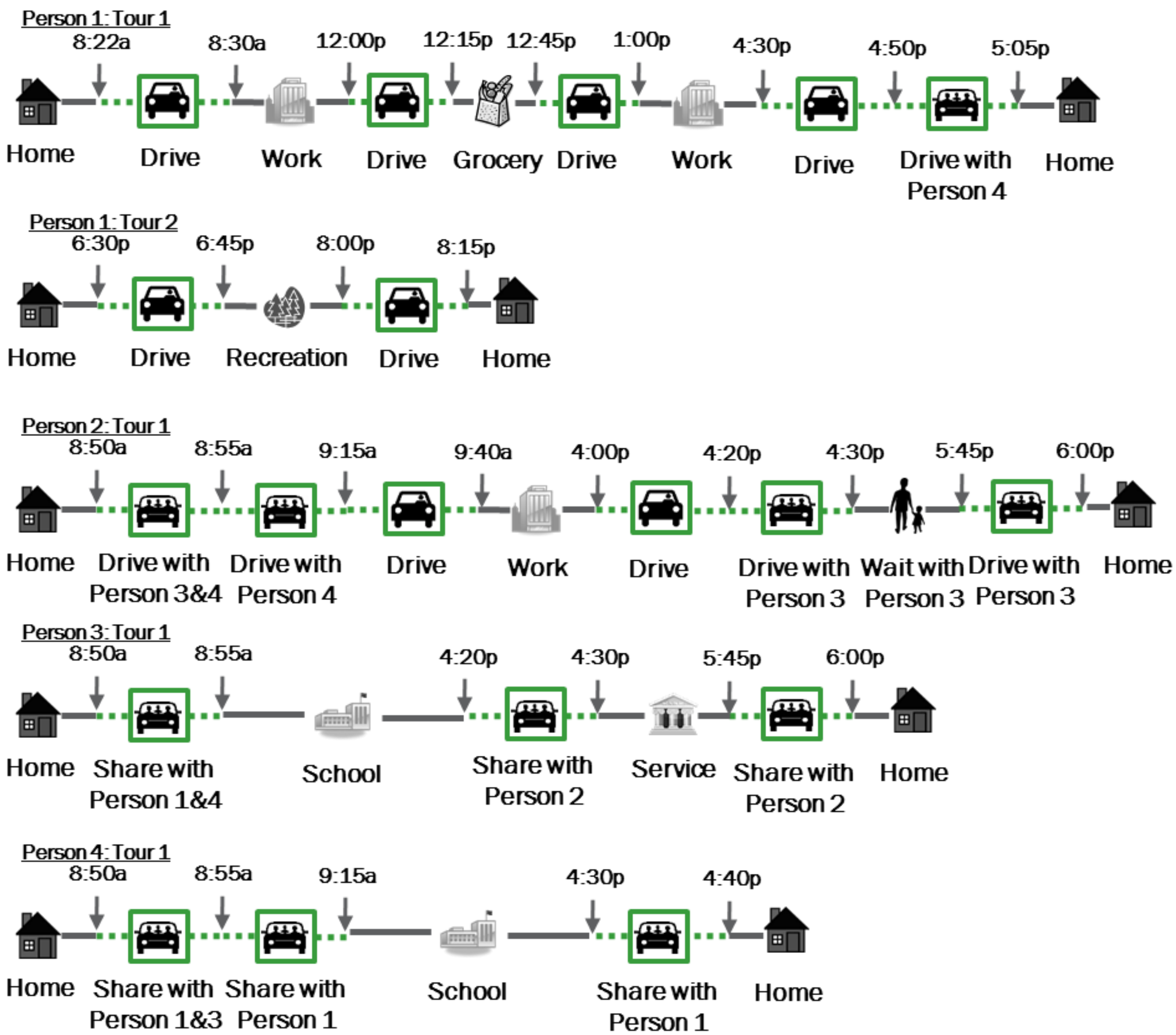


Figure 5-6: Actual Schedule for Household 9

Two tests were conducted on this household case: one where the start times were fixed within 30 minutes of the actual start time and another where the start times were flexible depending on the activity type. The results of the fixed test are represented in Figure 5-7, and the results of the flexible test are represented in Figure 5-8. Comparing these results to the actual schedule can reveal the ability of the model to represent household travel behaviour.

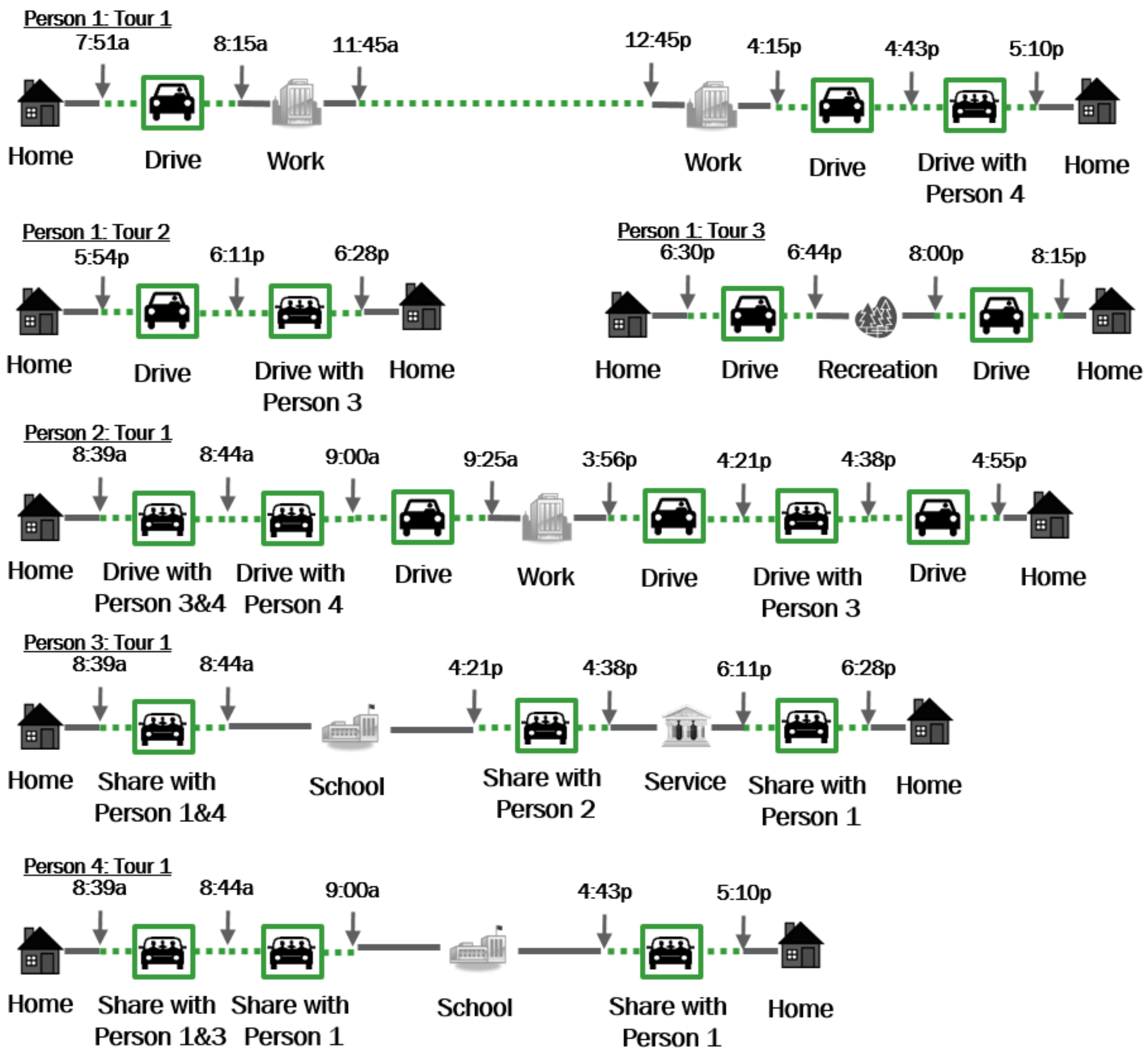


Figure 5-7: Results of Fixed Test on Household 9

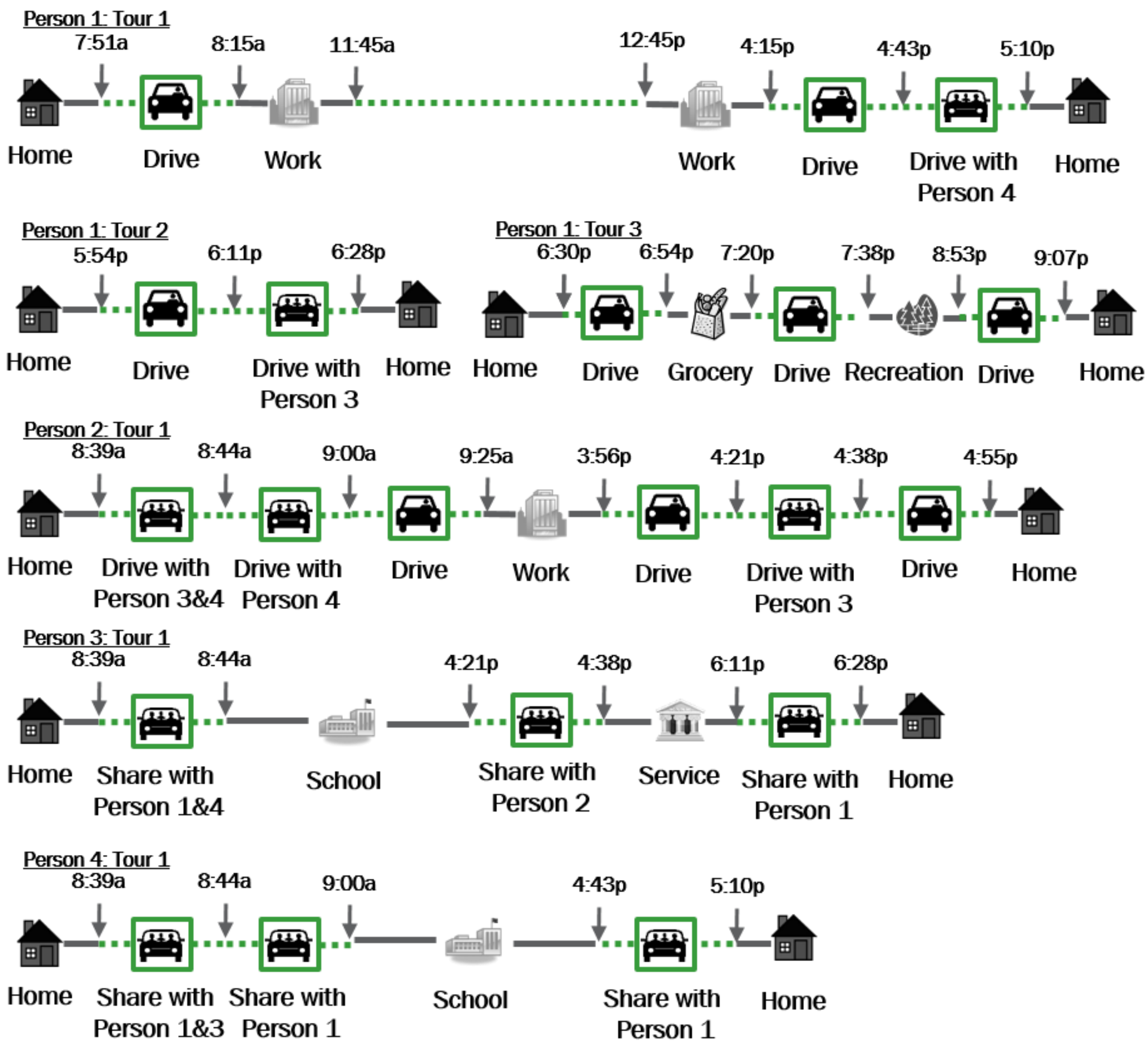


Figure 5-8: Result of Flexible Test on Household 9

The model performed very well for this household with dependents. The model was able to schedule almost all of the activities for each person of the household with one exception. The one activity that was not scheduled in the fixed test was a grocery shopping trip that occurred over the Person 1's lunch break. As this discretionary activity has a lower priority, it would have been scheduled after both work activities have been placed in the schedule. The current version of the model is unable to insert activities between existing activities in the schedule. Once the time constraint is removed in the flexible test, all activities were scheduled.

The model correctly estimated the mode choice for the first tour for all persons in this household. Moreover, this household consists of two dependents. The model was able to correctly allocate chaperones for the dependents' first tour and subsequent activities, with the exception of one activity. In this activity, the model suggested that the dependent was dropped off by one chaperone and then picked up by another chaperone, whereas in reality the same chaperone conducted both trips and stayed with the dependent for the duration of the activity. The behaviour of this household indicates that the person was willing to wait longer than the maximum wait time defined in the model. This decision is evident in the extra tour that was created for Person 1 in order to serve this trip.

5.2.5 Test Result Summary

Several key themes emerge from these tests. These themes are discussed in response to the original questions posed for model testing. The results are summarized for all households in the following subsections. The specific household test results are included and discussed in Appendix B.

Activity Scheduling

The first key question explored for each of the household tests was: "does the model schedule all reported activities in the household?" The model was able to schedule all activities for 16 out of the 21 persons in the fixed test or a 76% success rate. The remaining 5 persons had at least one activity that was not scheduled at a time similar to the one reported in the household survey. In a further exploration of these fixed test results, the model was not able to fully schedule activities for two of the five persons because the travel time of the estimated travel mode was longer than the amount of time allotted in the actual schedule. This result is an effect of the mode choice decision conducted by the model. Changes to the mode choice model may improve the ability for the model to schedule these activities. The model was not able to fully schedule activities for the other three persons because their scheduling decision is not supported in the current version of the developed model. The model is not able to add activities at the start or within an existing tour, whereas in reality, people are able to make these scheduling decisions. The inclusion of this capability in subsequent model versions should enable the model to schedule these activities. In the flexible test, which relaxes this scheduling restriction, the model was able to schedule all activities for all 21 persons.

Trip Chaining and Tours

The second key question for the household tests was: "does the model correctly estimate the number of tours for each person in the household?" In the fixed test, the model was able to estimate the same number of tours as reality for 14 out of 21 persons. This discrepancy between the estimates and reality may be attributed to the amount of time a person remains at home between tours. Recall that the model will schedule an activity in an existing tour if the waiting time does not exceed a duration that includes the difference of the time to travel home then to the next activity and the time to travel directly to the next activity, plus a minimum amount of time resting at home. The current assumed time at home is 15 minutes. In the case where the model underestimates tours, the person in reality may be returning home for a shorter amount of time than the 15 minutes specified in the model. Reducing this assumed minimum time at home between tours may improve the performance of the model.

In the flexible test, the model performed expectedly worse, estimating the same number of tours as reality for 8 out of 21 persons. In most cases, the model underestimated the number of tours and in some cases combined all activities onto one tour. The poor performance of the model in the flexible test demonstrates that some level of time constraint should be applied to the activities. This constraint may be the inclusion of home activities at particular times of the day, such as a common meal time at home. While in this version of the model, persons would return home, the model did not directly schedule particular activities to be conducted at home. Inclusion of home activities may improve the model's ability to create the correct number of tours.

Mode Choice

The third key question for model testing was: "Does the model correctly predict the mode choice of travellers for the first tour?" This question explores the performance of the initial resource allocation logic and the mode choice model. The fixed test and flexible test had similar results. The fixed test was able to estimate the first tour mode correctly for 13 of 21 persons, while the flexible test was able to estimate the first tour mode correctly for 14 of 21 persons. The model performed better for households that were adequately resourced in terms of vehicles. This result is not surprising as the individuals in these households do not need to coordinate across their schedules in order to accomplish their activities. An inspection of the results that were incorrect revealed that other costs may influence mode choice. In particular, parking costs were not considered, which would have an influence on the probability of driving. This is evident in the results for persons in Households 6 and 7, where Drive was estimated by the model as the preferred mode, whereas Transit was actually selected by the person in the household. Furthermore, the results revealed that the model is limited in its ability to capture particular preferences that go beyond the common attributes of travel time and travel cost. This is evident in the result for an individual in Household 1. For this individual, the model estimated that he would drive to his activity while in reality, this person chose to Bike to the activity. An inspection of the probabilities for this mode choice revealed that it is highly unlikely (1.8% chance) for a person to Bike based on the calibrated model. This suggests that this person has a particular preference or confidence for bicycling that is not captured in the current model. Consideration of these costs and preferences may improve these models. However, a larger data set that have measurements for these various attributes are required in order to estimate an improved mode choice model.

Allocation of Chaperones

The fourth key question of the model testing asked: In households that have dependents, does the model correctly assign the pairs of chaperones and dependents? Only one household case had persons that were dependent for all activities and trips. In this one case, the model was able to correctly allocate the chaperones to the dependents for the first activity and almost all of the subsequent activities. There was only one instance in which the model allocated the chaperone incorrectly. Further discussion of this situation was provided in Household 9. For this household, the model suggested that the dependent was dropped off by one chaperone and then picked up by another chaperone, whereas in reality the same chaperone conducted both trips and stayed with the dependent for the duration of the activity. The behaviour of this household indicates that the person was willing to wait longer than the maximum wait time defined in the model. While this result provides initial confidence for the developed logic, further tests should be conducted to demonstrate the capability of the model.

Additional Observations

In addition to the four key questions for model testing, there are additional observations that can be derived from the model results. In particular, the model is limited in the ability to schedule joint activities in which two or more individuals in the household spend time and travel together. Some of the household survey results indicated that some household members conduct the same activity in the same location and time. The fixed test with time constraints on the activities would be able to capture these joint activities. However, in the flexible test without time constraints, the model would simply schedule these activities at the earliest time that minimizes the travel time and cost. Consideration of joint activities would add another constraint that would improve the representativeness of travel behaviour.

5.3 Model Run Times

An important aspect of model performance is the amount of time it takes for the model to determine a solution. This characteristic is especially important once the model is applied not only to one household but to others that have a broader representation of Kitchener - Waterloo.

5.3.1 Test Method

Two times were measured using a timer embedded into the model code. These times included the amount of time to set up the model with the travel time and travel cost tables for Kitchener - Waterloo, and the amount of time to read the input household data and produce a solution using the algorithm outlined in Chapter 4. These tests were performed on a personal computer with an Intel Core i5-4200 processor with 8.00 GB of RAM running Windows 8.1. The times were recorded for each of the tests conducted on the household, which led to a total of 18 tests conducted to measure the model run time.

5.3.2 Test Results

Table 5-6 presents the average model run times of the tests.

Table 5-6: Average Model Run Times per Test

Time and Cost Table Setup	Household Allocation	Total Test Time
4885 milliseconds	36 milliseconds	4921 milliseconds

It is clear from the results that the setup of the time and cost tables takes a significant amount of processing time for each test. During this time, the model is reading from a file and storing into memory the travel time and cost for each origin - destination pair (approximately 270^2 pairs) in the study area. This process was conducted each time a household was tested in the model. Significant model run time savings can be attained if the time and cost tables for the study area are set up once and multiple households are processed at a time.

The actual allocation process outlined in Chapter 4 takes much less time to run. On average, it took the model 36 milliseconds to reach a solution for a household. This time depends on the complexity of the household as it determines how many schedules that must be searched through before arriving at a solution. From these tests, the fastest processing time was 23 milliseconds for Household 6, which consisted of one individual and three activities. The slowest processing time was 86 milliseconds for Household 1, which consisted of a household with 4 independents and 1 semi-dependent individual.

These results can be extended to demonstrate the amount of time it would take to reach a solution for a larger sample of households in the study area. As an example, the 2011 Transportation Tomorrow Survey has data for 10,412 households in the Region of Waterloo (Data Management Group, 2011). Using the average of household allocation run times, the model would be able to process this collection of households in approximately 7 minutes. Even in the case where each household takes the upper bound of time to process, the model would be able to process this collection of households in approximately 15 minutes.

5.4 Chapter Summary

In this chapter, the model that was developed in this research was tested to demonstrate its ability to represent travel behaviour. The model was tested using 9 households from the exploratory household survey discussed in Chapter 3. The tests explored whether the model was accurate in the scheduling of activities, creation of tours, and selection of first tour travel modes. Two tests were undertaken for each household: a fixed test that used the times reported for each activity in the household survey, and a flexible test that used a range of assumed start times. The results were presented for each household, and then key themes and insights were interpreted from the results. The model performed reasonably well for the tests; however, the model performed better in the scheduling of activities and the creation of tours when there is some level of time constraint on the discretionary activities. Moreover, the model worked well in the selection of the mode for the first tour in households that have the same number of drivers and vehicles. In cases where the mode choice was not selected correctly, the inclusion of parking costs, and personal mode preferences may improve the model's capability.

Additionally, these same household tests were used to determine the length of time required for the model to reach a solution. The model tests had a run time that averaged 36 milliseconds and ranged from 23 milliseconds to 86 milliseconds for the household allocation. This range depended on the complexity of the household. An extension of these results revealed that the application of this model to a larger data set, such as the 2011 TTS data for the Region of Waterloo (approximately 10,400 households) may take up to 15 minutes.

The following Chapter 6 provides a summary of what has been accomplished in this research and identifies the limitations and steps for future research.

6.0 CONCLUSIONS

6.1 Summary of Research

Jara-Díaz (2000) said: "Understanding travel demand is nearly like understanding life itself." While it is widely acknowledged that travel demand is the result of the desire to conduct activities in different locations, travel demand is complex and is a result of a confluence of factors. In particular, when and how people travel are influenced by a set of resources and constraints. Moreover, where people travel and conduct activities are based on the land use of the city and the locations of residences, employment, shopping and recreational opportunities. The resulting travel behaviour is difficult to estimate but it is important to understand, as travel demand decisions affect the system performance of transport networks, which influences the mobility of households, and the accessibility of activities in a city. As cities grow, a better understanding of travel demand will help planners and engineers make more informed decisions for land use plans and infrastructure investments. Through this research, a small step is made towards this understanding.

At the outset of this research, the primary objective established was to create a model that is representative of household transport decisions, and in particular, the travel resource allocation decision. To guide the scope and to inform the development of the model, an exploratory household survey of 14 households was conducted to answer the following questions:

1. *How do households allocate resources – vehicles, time, and supervision – to conduct travel for independents who are able to travel on their own and for dependents who require supervision or chaperoning from an independent?*

   In the survey, respondents provided a one-day schedule of activities and travel, representative of the busiest household travel day, for each member of their household. This schedule included the type, location, start and end time of activities, as well as the travel mode for each of the trips to and from activities. This schedule is used to answer some of the following questions, but it primarily used to test the proposed household travel model.

2. *How do households prioritize their various activities? In what order are activities are scheduled?*

   From the survey, households generally prioritize their activities in this order: Work or school activities, grocery shopping activities, service activities, social activities, recreational activities and then other shopping activities. It is important to note that chaperone activities, where a person accompanies another on a trip to an activity, are ranked the lowest for households without dependents, and ranked second highest for households with dependents.

3. *What factors do households consider when making travel decisions?*

   When households are making travel decisions, they seek to maximize schedule convenience and flexibility and to maximize the benefit from achieving activities. These motivations are consistent regardless of whether or not there are dependents within the household. Minimizing travel cost, minimizing environmental impact and achieving fitness and exercise are relatively important for households without dependents, and significantly less important for households with dependents.

4. *How much flexibility do households have in their household schedule?*

   Based on the one day schedules provided by households, the amount of free time in the household was calculated. Respondents were also asked about the amount time the household would have to add an additional activity. In households with a dependent traveller, those responsible for chaperoning have on average 13.5 hours of free time at home, while dependents and non-chaperones had approximately 14 hours of free time. 40% of these households indicated that there is no additional flexibility to add additional activities, while the balance of the households with dependents indicated that they are able to add an activity between 30 and 60 minutes in duration. In households without a dependent traveller, the persons have close to 11 hours of free time. These households indicate that they would be able to add an activity between 60 and 120 minutes in duration.

5. *What role do external resources, such as extended family or neighbours, have in satisfying household travel demands?*

   Households do use external resources to satisfy travel demands; however, the frequency of this reliance is low. The majority of respondents indicated that they rely on external resources at least once a year, while 14% of respondents indicated that the frequency was at least once a week. In the cases where the use of external resources is frequent, it is for the purposes of rideshares or carpools to common activity locations.

6. *How do households respond when presented with an unexpected activity?*

   When presented with an unexpected activity, households tend to avoid placing the activity within the same busiest travel day for the household, with the exception of high priority activities for dependents. For high priority independent activities, and all low priority activities, the respondents would attempt to schedule this activity on another weekday or on the weekend when there is more flexibility.

The answers to these questions guide the scope and development of the household travel resource allocation model. In particular, the survey reinforces the literature that suggest that household schedule activities in the order of priority. The activity priority included in the model is based on the results from the above question 2. Moreover, once an activity is scheduled, the model does not need to consider the rescheduling of activities since most unexpected activities are scheduled in another day with more flexibility. Finally, the model scope does not consider the use of external resources as the respondents in the survey indicated that this occurs infrequently.

The model proposed in this research strives to allocate household travel resources to travellers so that they are able to achieve their desired activities in a given day. The model uses the following information as input: household location, household vehicles, traveller characteristics, and traveller activities. The model then undertakes the following process to allocate the travel resources:

1. Prioritize Activities into Mandatory and Discretionary Activities;
2. Schedule First Mandatory Activities by assigning chaperones and vehicles to maximize household utility; then
3. Schedule Subsequent Activities in a step-wise approach and in the order of priority until all activities are scheduled. These activities may be scheduled on an existing tour, or in a new tour.

Once the model is complete, the model produces a feasible schedule of activities and tours that may be undertaken for the household. This model establishes when activities will occur and how people will travel to their activity. This model was also tested using activities and characteristics provided by households in the survey. In particular, these secondary questions were explored:

1. *How well does the proposed model developed in this study replicate actual household activity and travel schedules?*

   The model was evaluated on its ability to schedule all reported activities, create the reported number of tours, and select the first tour travel modes. The model was tested using nine households from the original survey data set. The households were tested using the activity start time provided in the survey, as well as a set of flexible start times based on activity type. The tests revealed that the model performed better in activity scheduling and the creation of tours when there is some level of time constraint on the discretionary activities. The first tour modes were selected correctly for the households that have the same number of drivers and vehicles. Incorrect first tour mode choices resulted from the exclusion of parking costs and personal mode preferences in the model.
2. *What is the time required for the model to discover a solution?*

   The processing time per household for this model ranged from 23 milliseconds to 86 milliseconds depending on the complexity of the household. By projecting these results to a larger data set, such as the Region of Waterloo (with 10,400 households), the model may take up to 15 minutes to process.

Through this research, a model has been developed to represent the short-term decision of travel resource allocation. This model follows an activity-based approach and estimates travel behaviour based on the interaction and decisions of multiple household members, including those who must travel with a chaperone. The model serves as the foundation for a broader integrated land use - transport model that represents longer term transport decisions and residential location choices in Kitchener - Waterloo.

6.2 Limitations

As with all research, there are some limitations. The following have been identified as limitations with respect to the household travel survey:

- The survey participants were all recruited from the University of Waterloo, and may not be entirely representative of all households in Kitchener - Waterloo. However, the results of the survey enable the development of the proposed model concept.
- Participants were asked for the schedules of the busiest travel day for the household to minimize the length of the survey. While this busiest day should represent the 'worst case scenario' for the household, this definition is subjective. Moreover, the activity schedule for one day does not completely reveal how households defer activities, or how activities are scheduled throughout the week. A survey that asks for the activities for an entire week would provide a more comprehensive perspective of the household schedule.

The following have been identified as limitations with respect to the model concept and testing:

- The model uses TAZs to calculate the travel time and cost between activity locations. As with most travel models, the trip is assumed to start and end in the centroid of the zone. This assumption affects the accuracy of the travel times and costs calculated for this model. Moreover, in some cases, the OpenTripPlanner was unable to find a route between certain zones in Kitchener - Waterloo (because the distance between the centroid of the zone and the nearest road was too long). This prevented some households from being tested in this study.

- Some households also had activities that took place outside of Kitchener - Waterloo. As the model is restricted to the study area, these activities cannot be currently scheduled.
- One mode choice model was calibrated using TTS data. However, this assumes that all mode choice decisions are the same regardless of the household preferences or activity type. Calibration of additional mode choice models may improve the behavioural representativeness of the model.
- Activities do not necessarily need to be completed in locations outside of the home. Certain activities may be completed at home, and with current technology, they may also be completed online. While people may spend time at home, this is an outcome of the allocation process. Home activities were not explicitly modelled in this research.
- An activity duration is treated as a single block of time that must be scheduled in its entirety. This model does not allow for an activity to be split into two separate blocks. This prevents the model from representing activities that are conducted between two activities (e.g. a grocery shopping trip conducted over the lunch period).
- Once activities are scheduled into the model, no adjustments may be made to the activity. However, in reality, minor adjustments may be made in order to fit a subsequent lower priority activity into the schedule. Furthermore, activities are scheduled at the earliest feasible time, whereas some activities may be scheduled later to minimize waiting time on a tour.
- The model was tested with the same data used for model development. Out-of-sample tests will help to strengthen the validity of the model. Moreover, a sample that is spatially stratified by the various locations in Kitchener-Waterloo would further the applicability of the model.

6.3 Future Research

In addition to future work that would address the above limitations, there are opportunities to extend this model. In particular, this model focused on the timing and mode choice of tours, given a set of activities and their locations. Research that incorporates the location choice of activities, such as in Albatross (Arentze & Timmermans, 2000), would significantly advance this model. Furthermore, this model should be connected to a route choice algorithm to determine the actual travel times and costs (with congestion effects) for household tours. These travel times are what households would actually experience. Depending on their satisfaction with the travel experience, a household may make adjustments to their route, departure time, or mode. If the cumulative dissatisfaction with travel exceeds a particular threshold, the household may elect to change travel resources by adding an additional vehicle, or by changing their residential location to improve travel times. This threshold may be a household travel budget of both travel time and cost that is a function of the structure or characteristics of the household. Extensive research is required to establish these feedbacks and choices, but these build off of the travel resource allocation model that has been developed in this study.

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APPENDIX A: Household Travel Survey Questions

Household Allocation Model – Household Survey

Kevin Yeung

Section 1: Introduction

1. What is the postal code for your household's place of residence?

2. How many vehicles do you own or lease in your household?

3. How much money does your household spend on transportation (each week / month / year)?

Section 2: Household Travel Profile

In the following section, I would like to create a profile of your household's travel over the course of your household's busiest workday.

For each person in the household:

1. What is this person's age?

2. What is this person's gender?

3. Is this person employed? Full Time | Part Time | Not Employed

4. Is this person a student? Yes | No

5. Is this person able to travel to activities independently? Yes | No | In some circumstances
    a. If in some circumstances; (please explain):
    ____

6. Does this person have a driver's license? Yes | No

7. Does this person have a transit pass? Yes | No

8. List out all of the activities that require travel for **your household's busiest** weekday. For each activity, indicate the activity type, location, trip start time, activity start time, activity end time, as well as the mode of transport used to travel to this activity.

Act. #	Type	Location	Trip Start Time	Activity Start Time	Activity End Time	Mode
1	CH- Chaperone SG- Grocery SH- Shopping WS- Work/School SR- Service SO- Social RC- Recreation HO- Home	Postal Code	HH:mm	HH:mm	HH:mm	D - Drive S# - Share with: # T - Transit C - Cycle W - Walk X - External

Household Allocation Model – Household Survey
Kevin Yeung

Section 3: Household Scheduling Questions

1. Please rank the following types of activities in terms of its priority in your household travel schedule, where 1 is the highest priority activity type that is very important to accomplish, and 7 is the lowest priority activity type that may be deferred to another day.
   ____ Chaperone Activities (e.g. accompanying others to their own activities)

   ____ Grocery Shopping Activities

   ____ Other Shopping Activities (e.g. shopping for housewares, clothing or other personal items)

   ____ School / Work Activities

   ____ Service Activities (e.g. attending medical appointments, visiting banks or other services)

   ____ Social Activities (e.g. meeting with friends or family, attending events, or helping others)

   ____ Recreational Activities (e.g. exercising, playing team sports, or visiting parks)
2. How much flexibility does your household schedule have on your busiest travel day? We have…
   a. … Enough flexibility to add an activity of at least 2 hours in duration.
   b. … Enough flexibility to add an activity of at most 2 hours in duration.
   c. … Enough flexibility to add an activity of at most 1 hour in duration.
   d. … Enough flexibility to add an activity of at most 30 minutes in duration.
   e. … Have no flexibility in my schedule.

3. If you had an unexpected high priority activity needed to be accomplished, when would you schedule this activity?
   a. During the busiest day by adjusting my previously scheduled activities
   b. During another weekday that has more flexibility
   c. During the weekend
   d. I would not schedule this activity.

4. If you had an unexpected low priority activity needed to be accomplished, when would you schedule this activity?
   a. During the busiest day by adjusting my previously scheduled activities
   b. During another weekday that has more flexibility
   c. During the weekend
   d. I would not schedule this activity.

5. If a dependent in your household had an unexpected high priority activity needed to be accomplished, when would your household schedule this activity?
   a. During the busiest day by adjusting previously scheduled activities
   b. During another weekday that has more flexibility
   c. During the weekend
   d. I would not schedule this activity.

6. If a dependent in your household had an unexpected low priority activity needed to be accomplished, when would your household schedule this activity?
    a. During the busiest day by adjusting previously scheduled activities
    b. During another weekday that has more flexibility
    c. During the weekend
    d. I would not schedule this activity.

7. How often do you rely on external resources – family, neighbours, others – to meet your household's transportation needs?
    a. Never
    b. At least once a year
    c. At least once a month
    d. At least once a week
    e. At least once a day

8. Based on your available transportation resources, are you able to achieve all of your desired activities? If not, which types of activities would you like to accomplish?

9. If you have dependents, please rate the following factors based on their importance in influencing your household's decision on who chaperones the dependent. Use a scale from 1 (very important) to 5 (not very important).

    ____ Travel distance to chaperone the dependent

    ____ Schedule availability

    ____ Nature of the activity

    ____ Travel cost to chaperone the dependent

    ____ Other, please specify

10. Please rate each of the following objectives based on their level of importance in influencing your household travel decisions. Use a scale from 1 (very important) to 5 (not very important).

    ____ Minimizing Household Travel Cost

    ____ Maximizing the Benefit Derived from Achieving Household Activities

    ____ Minimizing Environmental Impact

    ____ Maximizing Convenience or Schedule Flexibility

    ____ Achieving Fitness and Exercise

    ____ Other; please specify: ____

APPENDIX B: Household Survey and Model Test Results

Household 1

Household 1 consists of 5 people who live in a suburban neighbourhood in northwest Waterloo. This household owns one vehicle. Table B-1 summarizes the characteristics of the people in this household.

Table B-1: Person Characteristics of Household 1

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	3
2	No	No	Yes	Yes	No	3
3	Yes, part time	Yes	Yes	No	No	2
4	No	Yes	Yes	No	Yes	3
5	No	Yes	In some cases	No	Yes	3

As this household has one vehicle and two drivers, this household may be classified as under resourced in terms of vehicles. This respondent indicated that Person 5 is dependent in some cases, but is able to travel to school on their own on foot or bike only. Based on this definition from the respondent, and as Person 5 was able to travel to their mandatory activity on their own, Person 5 was classified as independent for the purposes of the model. In this way, Household 1 does not require resources to chaperone dependents to activities. The results of the model tests for Household 1 are summarized in Table B-2.

Table B-2: Household 1 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	3	3	3	2	2	3	Drive	Drive	Bike
2	2	3	3	1	1	1	Walk	Drive	Drive
3	2	2	2	2	2	2	Share	Share	Transit
4	3	3	3	2	1	2	Transit	Transit	Transit
5	3	3	3	3	1	3	Walk	Walk	Walk

Discussion

Under the fixed test, the model is able to able to schedule all activities for 4 of the 5 persons in the household. In this test, Person 2 was unable to accomplish one of their activities. Under the flexible test, the model is able to schedule all activities. With respect to the number of tours that are created for each person, the number of tours matches the actual number of tours for 4 out of the 5 persons under the fixed test under the fixed test, and for 2 out of the 5 persons for the flexible test.

The resulting schedules can be directly attributed to the resource allocation and mode choice conducted for the first tours of this household. In this test, both Person 1 and Person 2 preferred to drive to their first activity; however, only one vehicle is available in the household. The vehicle was assigned to Person 1, which meant that Person 2 needed to use an alternative mode of transport to travel to activities. Under a flexible activity start time, all persons are able to conduct all of their activities and the mode choice of Person 2 matched the actual mode choice; however, a closer inspection of the activity start times revealed that Person 2 conducted activities only when Person 1 returned home with the vehicle. In reality, Person 1 cycled on the first tour enabling Person 2 to conduct activities with the household vehicle earlier in the day.

An inspection of the utilities associated with this first trip for Person 1 suggests that the utility function and mode choice model specified in this household model would likely not be able to capture this preference for cycling over driving. For this particular trip, Person 1 would experience a utility of -2.28 for Drive, -5.81 for Transit, -6.25 for Bike and -5.96 for Walk. The probability that a person would drive in this situation is 93.2% whereas the probability that a person would bike is 1.8%. Based on these probabilities, Person 1 and this household are likely outliers compared to other households in Kitchener - Waterloo and other factors appear to influence this initial mode choice decision.

The one remaining difference in the mode choice for the first tour is for Person 3, who shares a ride with Person 1 to their first activity instead of taking transit. In this case, this result is possible as the schedule of these two individuals align and this choice to share likely improves the utility attained by the household.

Household 2

Household 2 consists of 3 people who live in a suburban neighbourhood in western Kitchener. This household owns two vehicles. Table B-3 summarizes the characteristics of the people in this household.

Table B-3: Person Characteristics of Household 2

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	2
2	Yes, full time	No	Yes	Yes	No	2
3	No	Yes	In some cases	No	No	2

As this household has two vehicles and two drivers, this household may be classified as equally resourced in terms of vehicles. This respondent indicated that Person 3 is dependent in some cases, but is able to travel to the local store by bike only. Based on this definition from the respondent, Person 3 was classified as dependent for the purposes of the model. However, Household 2 was not tested in the model as the Person 1 had several activities that were located outside of the study area.

Household 3

Household 3 consists of 2 people who live in a neighbourhood in central Kitchener west of downtown. This household owns one vehicles. Table B-4 summarizes the characteristics of the people in this household.

Table B-4: Person Characteristics of Household 3

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	No	Yes	Yes	Yes	Yes	7
2	No	Yes	Yes	Yes	Yes	7

As this household has one vehicle and two drivers, this household may be classified as under resourced in terms of vehicles. This model was not able to test this household as the input table of travel times and costs were not available for this particular household location.

Household 4

Household 4 consists of 2 people and is located in a neighbourhood east of the University of Waterloo. This household has no access to a vehicle. Table B-5 provides a summary of the characteristics of the persons in the household.

Table B-5: Person Characteristics of Household 4

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	No	Yes	Yes	No	Yes	4
2	Yes, full time	No	Yes	No	No	3

As this household has no drivers, and no vehicles, it may be classified as being equally resourced in terms of vehicles. As there are no dependents in this household, chaperone resources are not required. The results of the model tests for Household 1 are summarized in Table B-6.

Table B-6: Household 4 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	4	4	4	1	1	2	Transit	Transit	Transit
2	3	3	3	2	1	3	Walk	Walk	Walk

Discussion

The model performed relatively well in the estimates of this household. The model was able to schedule all activities for all persons in both fixed and flexible schedule tests. The model was also able to correctly predict the modes of the first tour for all persons in the household. The estimation of tours was incorrect in both tests for both persons. The model is underestimating the number of tours that each person takes in order to accomplish their activities. A possible cause for this result is that the locations for each of these activities are nearby to each other within walking or transit distance. Without knowledge of time constraints for an activity, or knowledge of the need to be at home for an activity, the model will strive to complete all of the activities in fewer tours to minimize the additional travel time in the schedule.

Household 5

Household 5 consists of two people who live in central Kitchener, west of the downtown core. It does not have access to a vehicle. Table B-7 outlines the characteristics of each person in the household.

Table B-7: Person Characteristics of Household 5

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, part time	Yes	Yes	Yes	Yes	2
2	Yes, full time	No	Yes	No	No	3

As this household has no vehicle but one driver, this household may be classified as under resourced in terms of vehicles. There are no dependents in this household so chaperone resources are not required. The results of the model tests on this household are summarized in Table B-8.

Table B-8: Household 5 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	2	2	2	2	1	2	Transit	Transit	Walk
2	3	3	3	2	1	2	Bike	Transit	External

Discussion

The model is able to schedule the activities for all persons under both fixed and flexible tests. The model is able to create the actual number of tours in the fixed test but underestimates the number of tours when time constraints for activities are removed. The model did not estimate the first tour mode correctly for both persons in the household. Person 2 relied on an external resource, which is not considered in the model, so no further comment is necessary for this result. An inspection of the utilities and mode choice model yields these mode choice probabilities: 74.3% for transit, 4% for bike, and 21.7% for walk. The model in this case selected the most probable alternative, while particular preferences of Person 1 may influence the decision to walk.

Household 6

Household 6 consists of 1 person who lives in a suburban neighbourhood in west Kitchener. This person owns a vehicle. The characteristics of this person are outlined in Table B-9.

Table B-9: Person Characteristics of Household 6

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	No	Yes	Yes	Yes	Yes	3

As this household has one vehicle and one driver, this household may be classified as equally resourced in terms of vehicles. There are no dependents in this household so chaperone resources are not required. The results of the model tests on this household are summarized in Table B-10.

Table B-10: Household 6 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	2	3	3	1	2	2	Drive	Drive	Transit

Discussion

The model had difficulty scheduling one of the activities in the fixed test, and as a result also underestimated the number of tours. However, in the flexible test, the number of activities and tours matched what happened in reality. The important difference to discuss in this case is the mode choice for the first tour. The model estimated that the person would drive to their first activity; however, in reality, the individual took transit. An inspection of the utilities and mode choice probabilities for this first trip is outlined in the following Table B-11.

Table B-11: Mode Choice Utilities and Probabilities for Household 6, Person 1

Mode	**Utility**	**Probability**
Drive	-1.96	85.6%
Transit	-3.98	11.3%
Bike	-6.25	1.2%
Walk	-5.77	1.9%

As expected, the model selected the most probable mode for this origin-destination pair, while Person 1 selected the second most probably mode. The reason behind this decision may be attributed to the costs associated at parking at this destination. Recall that the utility for each mode is a function of the travel time and travel cost, and that travel cost only includes the per kilometre cost of fuel and maintenance, but does not include parking. It is important to note that for this individual, the first tour is to the University of Waterloo, and there is an associated cost to park on campus. Assuming that the person pays the daily $5 fee for parking, the utility associated with the Drive mode would decrease to -4.21 and the probabilities would be updated to: 39% drive, 48% transit, 5% bike and 8% walk. Based on this result, the model is making the appropriate choices given the existing data, but additional data would be useful in improving the representativeness of the results.

Household 7

Household 7 consists of two people who live near Uptown Waterloo. It has access to one vehicle. Table B-12 outlines the characteristics of each person in the household.

Table B-12: Person Characteristics of Household 7

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	2
2	Yes, full time	No	Yes	Yes	Yes	2

As this household has no vehicle but one driver, this household may be classified as under resourced in terms of vehicles. There are no dependents in this household so chaperone resources are not required. The results of the model tests on this household are summarized in Table B-13.

Table B-13: Household 7 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	2	2	2	1	1	1	Walk	Walk	Transit
2	2	2	2	2	1	2	Drive	Drive	Transit

Discussion

The model was able to schedule all activities for each person of the household for both fixed and flexible tests. The model was able to correctly predict the number of tours in the fixed test but underestimated the number of tours in the flexible test. The model was unable to select the actual mode for both persons in both tests. An inspection of the model outputs suggested that Drive was the preferred mode for both Person 1 and 2. This result can be attributed to the exclusion of parking costs at both first activity locations. The model worked as expected and conducted a pairwise comparison of the preferred and alternate travel modes.

It determined that the assignment of the vehicle to Person 2 would maximize the household utility. Inclusion of these parking costs in the utility function may improve the mode choice model.

Household 8

Household 8 consists of 3 people who live in a rural neighbourhood west of Kitchener. This household owns two vehicles. Table B-14 summarizes the characteristics of the people in this household.

Table B-14: Person Characteristics of Household 8

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, part time	No	Yes	Yes	No	3
2	Yes, full time	No	Yes	Yes	No	2
3	Yes, part time	Yes	Yes	Yes	No	3

As this household has three vehicle and three drivers, this household may be classified as adequately resourced in terms of vehicles. However, Household 2 was not tested in the model as the household location is located outside of the study area.

Household 9

Household 9 consists of 4 people who live east of downtown Kitchener. This household has 2 vehicles. The characteristics of the people in this household are summarized in Table B-15. As this household has 2 vehicles and two drivers, this household may be classified as equally resourced in terms of vehicles. Moreover, there are equal numbers of independents and dependents in this household, so this household can be classified as adequately resourced in terms of chaperones. Table B-16 provides the results of the model tests for this household.

Table B-15: Person Characteristics of Household 9

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	4
2	Yes, full time	No	Yes	Yes	No	1
3	No	Yes	No	No	No	2
4	No	No	No	No	No	1

Table B-16: Household 9 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	3	4	4	3	3	2	Drive	Drive	Drive
2	1	1	1	1	1	1	Drive	Drive	Drive
3	2	2	2	1	1	1	Share	Share	Share
4	1	1	1	1	1	1	Share	Share	Share

Discussion

The model performed very well for this household with dependents. The model was able to schedule almost all of the activities for each person of the household with one exception. The one activity that was not scheduled in the fixed test was a grocery shopping trip that occurred over the Person 1's lunch break. As this discretionary activity has a lower priority, it would have been scheduled after both work activities have been placed in the schedule. The current version of the model is unable to insert activities between existing activities in the schedule. Once the time constraint is removed in the flexible test, all activities were scheduled.

The model correctly estimated the mode choice for the first tour for all persons in this household. Moreover, this household consists of two dependents. The model was able to correctly allocate chaperones for the dependents' first tour and subsequent activities, with the exception of one activity. In this activity, the model suggested that the dependent was dropped off by one chaperone and then picked up by another chaperone, whereas in reality the same chaperone conducted both trips and stayed with the dependent for the duration of the activity. The behaviour of this household indicates that the person was willing to wait longer than the maximum wait time defined in the model. This decision is evident in the extra tour that was created for Person 1 in order to serve this trip.

Household 10

Household 10 consists of 5 people who live in a Woodstock, a municipality west of Kitchener-Waterloo. This household owns two vehicles. Table B-17 summarizes the characteristics of the people in this household.

Table B-17: Person Characteristics of Household 10

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	5
2	Yes, part time	No	Yes	Yes	No	1
3	No	Yes	In some cases	No	Yes	2
4	No	Yes	In some cases	No	No	2
5	No	Yes	In some cases	No	No	2

As this household has two vehicle and two drivers, this household may be classified as adequately resourced in terms of vehicles. This respondent indicated that Persons 3 through 5 are dependent in some cases. The circumstances in which Persons 3 and 4 are independent are for school and some recreational trips. Person 5 is may travel independently only for recreational trips. Based on this definition from the respondent, Persons 3 and 4 would be identified as independent in the model, whereas Person 5 would be dependent. However, since the household is located outside of the study area, the household was not tested.

Household 11

Household 11 consists of 4 people who live in a rural community west of Kitchener. This household owns three vehicles. Table B-18 summarizes the characteristics of the people in this household.

Table B-18: Person Characteristics of Household 11

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	2
2	Yes, full time	No	Yes	Yes	No	1
3	No	Yes	No	No	No	3
4	No	Yes	No	No	No	3

As this household has three vehicle and two drivers, this household may be classified as adequately resourced in terms of vehicles. This respondent indicated that Persons 3 and 4 are dependent; however, these dependents are able to walk home from their school location. Since the household is located outside of the study area, the household was not tested.

Household 12

Household 12 consists of 2 people who live in a neighbourhood in south Kitchener. This household has 2 vehicles. The characteristics of the people in this household are outlined in Table B-19.

Table B-19: Person Characteristics of Household 12

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	2
2	Yes, full time	No	Yes	Yes	No	2

As this household has two vehicles and two drivers, this household may be classified as adequately resourced in terms of vehicles. There are no dependents in this household so chaperone resources are not required. The results of the model tests on this household are summarized in Table B-20.

Table B-20: Household 12 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	3	4	4	2	1	2	Drive	Drive	Drive
2	2	2	2	2	1	2	Drive	Drive	Drive

Discussion

The result of this test demonstrates that the model performs fairly well with respect to households that are adequately resourced for vehicles. This result is not surprising as there is minimal interaction or coordination required between persons in these types of households in order to allocate resources. One activity was not scheduled in the fixed test for Person 1. This activity was a lower priority discretionary activity that occurred prior to the person's work activity. The current version of the model is unable to append an activity at the start of a tour. Once the time restriction was removed in the flexible test, all activities were scheduled; however, all activities would be scheduled into one tour. The model performed well in the mode choice for the first tours of the household.

Household 13

Household 13 consists of 1 person who lives in a suburban neighbourhood in west Waterloo. This person owns a vehicle. The characteristics of this person are outlined in Table B-21.

Table B-21: Person Characteristics of Household 13

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	3

As this household has one vehicle and one driver, this household may be classified as adequately resourced in terms of vehicles. There are no dependents in this household so chaperone resources are not required. The results of the model tests on this household are summarized in Table B-22.

Table B-22: Household 13 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	3	3	3	3	1	3	Drive	Drive	Drive

Discussion

Similar to the previous household, the model was performed well in the scheduling of activities, as well as the creation of tours for the fixed test. As with the other households, without some form of temporal constraint, the model will combine all the activities into one tour. The model correctly predicted the first tour mode for this household.

Household 14

Household 14 consists of 2 people who live in a suburban neighbourhood in southwest Kitchener. This household has 2 vehicles. The characteristics of each person in the household are included in Table B-23. As this household has two vehicles and two drivers, this household may be classified as adequately resourced in terms of vehicles. There are no dependents in this household so chaperone resources are not required. The results of the model tests on this household are summarized in Table B-24.

Table B-23: Person Characteristics of Household 14

Person	Employed?	Student?	Independent?	Driver?	Has Transit Pass?	# of Activities
1	Yes, full time	No	Yes	Yes	No	2
2	Yes, full time	No	Yes	Yes	No	2

Table B-24: Household 14 Model Test Results

Person	Activities			Tours			First Tour Mode		
	Fixed	Flexible	Actual	Fixed	Flexible	Actual	Fixed	Flexible	Actual
1	3	4	4	3	2	2	Drive	Drive	Drive
2	3	3	3	2	1	3	Drive	Drive	Drive

Discussion

The results of this test are very similar to the results of Household 12. In the fixed test, one of the activities for Person 1 was not scheduled because this discretionary activity took place in between two mandatory activities. The scheduling of the discretionary activity took place after the activity and travel schedule had been set for the mandatory activities. As there is no mechanism in the current version of the model to modify existing tours, the activity was not scheduled. In this case, there was enough time between the two mandatory activities for the individual to return home prior to the start of the next activity, which led to an overestimation of tours for Person 1 in the fixed test.

APPENDIX C: Model Pseudo-Code and Major Sub-routines

Household Travel Resource Allocation Model: Pseudo – Code and Major Subroutines

<u>Main Routine</u>

1. **Calculate Travel Times and Costs for All Origin-Destination Pairs and Modes**
   - Input shortest path data from Region's Travel Model
     - HHTravelAllocator.getDriveDistances
   - Read input time and cost tables for each mode and origin-destination pair
     - HHTravelAllocator.generateCostTimeTables
2. **Create Household with People, Vehicles and Activities**
   - Initialize Household object and assign TAZ for household location
     - HHTravelAllocator.createHousehold
   - Initialize Persons object for each household member with data from input CSV file
     - HHTravelAllocator.populateHousehold
   - Sort members into a list of independent travellers and dependent travellers
     - HHTravelAllocator.sortPeopleByDependence
   - Initialize Activity object for each desired activity with data from input CSV file
     - HHTravelAllocator.getActivities
3. **Sort Activities by Priority**
   - Identifies first mandatory (work/school) trips. Sorts remaining activities based on whether it is conducted by an independent or a dependent, and based on whether it is a mandatory or discretionary trip. Orders the activities within these lists from highest to lowest priority.
     - HHTravelAllocator.sortActivities
4. **Determine Preferred Modes for First Mandatory Activity for Independents**
   - Determines Mode from Origin to Destination with discrete choice model
     - HHTravelAllocator.get1StopModeChoice
   - Given preferred mode, determine an alternate mode with discrete choice model
     - HHTravelAllocator.getAlternateof3Modes

If Household has Dependents: (HHTravelAllocator.allocateDependentHousehold)

5. **Assign Chaperones to Dependents**
   For each potential chaperone – dependent pairing:
   - Get mode choice, check feasibility and calculate utility to chaperone dependent
     - HHTravelAllocator.getSingleChaperoneAllocationMap (to chaperone 1 dependent)
     - HHTravelAllocator.getDoubleChaperoneAllocationMap (to chaperone 2 dependents)
   - Get mode choice and calculate utility for non-chaperones (other independent first activities) Assigns remaining vehicles to maximize household utility;
     - HHTravelAllocator.getIndependentAllocationMaps
   - Calculate Total Household Utility of Chaperone Assignment
6. **Initialize first tours**:
   - Use chaperone assignment that has the maximum household utility
   - Create tour for dependent and chaperone:
     - HHTravelAllocator.initializeDependentTour1 (for chaperone with 1 dependent)
     - HHTravelAllocator.initializeDependentTour2 (for chaperone with 2 dependents)
   - Create tour for independents without chaperones
     - HHTravelAllocator.initializeIndependentTour

If Household does not have dependents: (HHTravelAllocator.allocateIndependentHousehold)

5. **Assign Vehicles to Independents**
   - Get mode choice and calculate utility for independents; If number of vehicle is less than number of drivers, assign vehicles to maximize household utility;
     - o HHTravelAllocator.getIndependentAllocationMaps
6. **Initialize first tours**
   - Create tour for independents based on vehicle assignment and preferred mode choice
     - o HHTravelAllocator.initializeIndependentTour

7. **Schedule Subsequent Activities in order of priority**, based on the lists of sorted activities in Step 3.
   - Schedule any other mandatory activities of dependents
     - o HHTravelAllocator.AllocateNextDependentActivity
   - Schedule any other mandatory activities of independents
     - o HHTravelAllocator.AllocateNextIndependentActivity
   - Schedule any discretionary activities of dependents
     - o HHTravelAllocator.AllocateNextDependentActivity
   - Return all dependent tours to household location by assigning chaperones to dependents
     - o HHTravelAllocator.CloseDependentTours
   - Schedule any discretionary activities of independents
     - o HHTravelAllocator.AllocateNextIndependentActivity
   - Once all activities checked: return all independent tours to household location with previous mode on tour
     - o HHTravelAllocator.CloseIndependentTours

<u>Major Subroutine: HHTravelAllocator.AllocateNextDependentActivity</u>

For each dependent activity in list:

1. Attempt to schedule activity in an existing open tour of dependent
   a. Check feasibility of each existing tour of independents (potential chaperones) HHTravelAllocator.checkDependentTourConnection
      i. If existing tour feasible, activity may be scheduled using previous mode
         - HHTravelAllocator.checkSharedVehicleSchedule (for drive/share mode)
         - HHTravelAllocator.checkSharedPersonSchedule (for all other modes)
      ii. If no existing tour feasible, check feasibility of starting new tour with new mode choice for chaperone
         - HHTravelAllocator.checkSharedVehicleSchedule (for drive/share mode)
         - HHTravelAllocator.checkSharedPersonSchedule (for all other modes)
      iii. If starting new tour is not feasible, check next independent (potential chaperone)
2. If activity is not scheduled in an existing tour, attempt to start new tour to schedule activity
   a. Check feasibility to start new tour for each independent (potential chaperones) HHTravelAllocator.checkDependentTourConnection (uses same logic as above)
3. If activity is not schedule in a new tour, activity is deferred
4. Check next activity until all activities checked.

Major Subroutine: HHTravelAllocator.AllocateNextIndependentActivity

For each independent activity in list:

1. Attempt to schedule activity in an existing open tour of independent using previous mode
   a. If previous mode was Drive or Bike, continue to use Drive or Bike
   b. If previous mode was Share, Transit or Walk, calculate new utility and mode choice:
      - HHTravelAllocator.getFeasibleShareMap
      - HHTravelAllocator.calculateUtility (for share, transit and walk)
      - HHTravelAllocator.getDiscreteChoice (for share, transit and walk)
   c. Determine feasibility of scheduling activity with previous mode:
      - HHTravelAllocator.checkDriverSchedule (for drive mode)
      - HHTravelAllocator.checkSharedVehicleSchedule (for share mode)
      - HHTravelAllocator.checkPersonSchedule (for all other modes)
   d. If feasible, schedule in existing tour
2. If activity is not scheduled in an existing tour, attempt to start new tour to schedule activity
   a. Calculate Utilities and Determine Preferred Mode Choice
      - HHTravelAllocator.calculateUtility (for each mode)
      - HHTravelAllocator.getDiscreteChoice (from all modes)
   b. Determine feasibility of scheduling activity from home using preferred mode
      - HHTravelAllocator.checkDriverSchedule (for drive mode)
      - HHTravelAllocator.checkSharedVehicleSchedule (for share mode)
      - HHTravelAllocator.checkPersonSchedule (for all other modes)
   c. If feasible, schedule in new tour.
3. If activity is not schedule in a new tour, activity is deferred
4. Check next activity until all activities checked.

APPENDIX D: Example Model Outputs

Household A

Person #1, Tour #1

Trip#:	1	2	3	4	5
Mode:	D	D	D	D	D
O-TAZ:	7263	7265	7255	7020	7248
D-TAZ:	7265	7255	7020	7248	7263
Departs:	8:08	8:15	8:41	16:28	16:43
Arrives:	8:14	8:21	8:57	16:42	16:57
Duration:	0:07	0:07	0:17	0:15	0:15
Tour Time:	1:01				
Tour Cost:	2.59				

Person #1, Tour #2

Trip#:	1	2
Mode:	D	D
O-TAZ:	7263	7105
D-TAZ:	7105	7263
Departs:	16:59	17:26
Arrives:	17:10	17:38
Duration:	0:12	0:13
Tour Time:	0:25	
Tour Cost:	1.43	

Person #1, Tour #3

Trip#:	1	2
Mode:	B	B
O-TAZ:	7263	7036
D-TAZ:	7036	7263
Departs:	17:40	19:33
Arrives:	18:02	19:56
Duration:	0:23	0:24
Tour Time:	0:47	
Tour Cost:	0.00	

Total Number of Tours: 3
Total Person Travel Time: 133

Person #2, Tour #1

Trip#:	1	2	3	4
Mode:	D	D	D	D
O-TAZ:	7263	7112	7265	7248
D-TAZ:	7112	7265	7248	7263
Departs:	6:33	15:15	15:30	15:42
Arrives:	6:44	15:29	15:41	15:55
Duration:	0:12	0:15	0:12	0:14
Tour Time:	0:53			
Tour Cost:	2.07			

Person #2, Tour #2

Trip#:	1	2
Mode:	D	D
O-TAZ:	7263	7255
D-TAZ:	7255	7263
Departs:	16:30	16:38
Arrives:	16:37	16:47
Duration:	0:08	0:10
Tour Time:	0:18	
Tour Cost:	0.67	

Person #2, Tour #3

Trip#:	1	2
Mode:	D	D
O-TAZ:	7263	7254
D-TAZ:	7254	7263
Departs:	17:40	18:21
Arrives:	17:50	18:31
Duration:	0:11	0:11
Tour Time:	0:22	
Tour Cost:	1.10	

Total Number of Tours: 3
Total Person Travel Time: 93

Person #3, Tour #1

Trip#:	1	2	3
Mode:	S	S	S
O-TAZ:	7263	7265	7248
D-TAZ:	7265	7248	7263
Departs:	8:08	15:30	16:43
Arrives:	8:14	15:41	16:57
Duration:	0:07	0:12	0:15
Tour Time:	0:34		
Tour Cost:	0.00		

Total Number of Tours: 1
Total Person Travel Time: 34

Person #4, Tour #1

Trip#:	1	2	3
Mode:	S	S	S
O-TAZ:	7263	7265	7255
D-TAZ:	7265	7255	7263
Departs:	8:08	8:15	16:38
Arrives:	8:14	8:21	16:47
Duration:	0:07	0:07	0:10
Tour Time:	0:24		
Tour Cost:	0.00		

Total Number of Tours: 1

Total Person Travel Time: 24

Activities for Person #1

Activity #:	1	2	3
Priority:	1	2	5
Location:	7020	7105	7036
Starts:	8:58	17:11	18:03
Ends:	16:27	17:25	19:32
Total Time:	9:15		

Activities for Person #2

Activity #:	1	2
Priority:	1	3
Location:	7112	7254
Starts:	6:45	17:51
Ends:	14:44	18:20
Total Time:	8:30	

Activities for Person #3

Activity #:	1	2
Priority:	1	2
Location:	7265	7248
Starts:	8:15	15:42
Ends:	15:14	16:41
Total Time:	8:00	

Activities for Person #4

Activity #:	1
Priority:	1
Location:	7255
Starts:	8:30
Ends:	16:29
Total Time:	8:00

Time to Generate Tables: 4525 ms.
Time to Finish Allocation: 47 ms.
Model Elapsed Time: 4572 ms.

Household B

Person #1, Tour #1

Trip#:	1	2	3	4
Mode:	S	T	T	S
O-TAZ:	7106	7105	7013	7117
D-TAZ:	7105	7013	7117	7106
Departs:	8:28	17:00	18:22	20:25
Arrives:	8:29	17:21	18:49	20:29
Duration:	0:02	0:22	0:28	0:05
Tour Time:	0:57			
Tour Cost:	3.95			

Total Number of Tours: 1
Total Person Travel Time: 57

Person #2, Tour #1

Trip#:	1	2	3	4	5	6
Mode:	D	D	D	D	D	D
O-TAZ:	7106	7105	7135	7141	7109	7117
D-TAZ:	7105	7135	7141	7109	7117	7106
Departs:	8:28	8:30	17:10	18:43	20:20	20:25
Arrives:	8:29	8:39	17:12	18:56	20:24	20:29
Duration:	0:02	0:10	0:03	0:14	0:05	0:05
Tour Time:	0:39					
Tour Cost:	1.60					

Total Number of Tours: 1
Total Person Travel Time: 39

Activities for Person #1

Activity #:	1	2	3
Priority:	1	2	4
Location:	7105	7013	7117
Starts:	8:30	17:22	18:50
Ends:	16:59	18:21	20:19
Total Time:	11:00		

Activities for Person #2

Activity #:	1	2	3
Priority:	1	5	4
Location:	7135	7109	7141
Starts:	8:40	18:57	17:13
Ends:	17:09	20:11	18:42
Total Time:	11:15		

Time to Generate Tables: 4779 ms.
Time to Finish Allocation: 26 ms.
Model Elapsed Time: 4805 ms.