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Development of a household travel resource allocation model

Kevin Yeung[1]
School of Planning and Department of Civil and Environmental Engineering, University of Waterloo, Canada.

Jeffrey M. Casello[2]
School of Planning and Department of Civil and Environmental Engineering, University of Waterloo, Canada.

Households allocate their travel resources – vehicles, time, budget, and supervision – to accomplish activities while minimizing overall time and cost subject to a set of constraints – the duration and sequence of activities, and the need to provide transportation to dependent travellers. In this research, we develop and test a heuristic based approach to schedule activities using a cost (disutility) minimization objective. The model is evaluated by comparing predicted schedules generated by the heuristics to actual travel patterns reported by participant households. While the dataset is small – only 14 households are included – the model successfully identifies tours for households of various compositions and demographics. The research is important in the local context as the study area – the Region of Waterloo, Canada – is a largely auto-dependent metropolitan area that is building a 19km, $818M (CDN) Light Rail Transit (LRT) system intended to increase public transport use and influence land use change. The Region is amongst the smallest municipalities in North America to implement this infrastructure.

Keywords: *activity scheduling, mode choice, household transport decisions, resource allocation, activity-based model, travel demand.*

1. Introduction

Households – a collection of individuals who live together in a dwelling – are the fundamental agents for change in urban regions. The behaviours of households – particularly location choice and travel decision-making – are understood to be part of a dynamic and interdependent system. Households choose locations that have both residential characteristics (e.g. building size, number of rooms, lot size, etc.) as well as transport characteristics (e.g. proximity to important destinations and availability of travel modes.)

The purpose of this research is to advance the understanding of household travel behaviour and decision making. On any given day, household members have activities that they would like to accomplish. These activities can be considered mandatory (e.g. work or school) or discretionary (e.g. groceries, social, recreational, or shopping). At recurring intervals – possibly weekly, daily or more frequently – household members attempt to generate tours that allow them to complete their activities. The formation of these tours is constrained by a number of available resources,

[1] A: 200 University Avenue West, Waterloo, ON, Canada, N2L 3G1 T: +1 519 888 4567 x37538 F: +1 519 725 2827 E: kevin.yeung@uwaterloo.ca
[2] A: 200 University Avenue West, Waterloo, ON, Canada, N2L 3G1 T: +1 519 888 4567 x37538 F: +1 519 725 2827 E: jcasello@uwaterloo.ca

such as vehicles, time or budget, within the household. As well, the independence of individuals – whether or not the person can travel on their own – is an important consideration in the resource allocation. Independent persons can travel to activities on their own. However, dependent individuals, such as children or seniors, require supervision from a chaperone in order to travel to activities. It may also be true that the presence (or absence) of various modes may influence the propensity for independent travel. For example, in cities with well-utilized transit systems, the social norm may be to allow children to travel independently at much younger ages than in cities where auto travel dominates.

These daily or weekly resource allocation decisions ultimately influence the demand for travel within the city's transportation network. Moreover, these also shape longer term household travel resource decisions. In cases where a household is not able to meet the demand with the given resources, several options may exist. 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. Understanding and modelling the household travel resource allocation decision is therefore fundamental to estimating future land use and transport scenarios.

In this paper, we build upon the literature focused on activity based models and household travel decision making by developing, applying and testing a heuristic model to represent the interactions of household members in their regular short-term transport decisions. Our model focuses on a typical daily schedule for a household given a set of constraints. Our research is conducted in the setting of an auto-dependent, Canadian region that is currently investing more than $800M (CAD) in a new Light Rail Transit system. The expectation amongst local planners is that the introduction of LRT will produce greater transportation options, lower household costs, and potentially greater independence of travel. Our model establishes a framework by which a before and after comparison can easily be completed. Moreover, our findings present a potentially contrasting environment to many European studies where social norms and the availability of public transport are notably different than in our context.

In the following sections, we review the context and development of recent activity-based models and outline the contributions of this work to the literature. We then outline the framework and logic of our model. Finally, we present the results of its application to a limited preliminary dataset, and discuss steps for further research.

2. Literature Review

The roots of activity-based models can be traced back to the seminal address by Hagerstrand (1970) who spoke broadly of the foundational considerations that should be included in any models of human activity. The first element for activity-based models identified by Hagerstrand is that activities in different locations necessitate travel. Naturally, some activities are considered more important than others. To reflect this hierarchy, some models incorporate a measure of the benefit (or utility) 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 key element of activity-based models is the consideration of temporal and spatial constraints that limit activities. 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. A key example is the potential requirement for at least two people to be in the same location at the same time to undertake certain activities. McNally (2000) extends the constraints to also include transport or interpersonal considerations.

These constraints are significant as they provide the framework for identifying decision-making rules in activity-based models. In particular, Hagerstrand specifically notes the lack of autonomy for children to travel, which requires a parent to partner with a child for travel to activities. This idea was supported further by Chapin (1974), who observed that children place a significant demand and constraint on others in the household. This suggests that travel is not an individual decision, but instead, must consider of the needs of the entire household.

Many of the activity-based travel models documented in the literature are developed with these principles. Some of the earlier activity-based travel models followed a utility maximization framework, where an individual selects an activity schedule with the highest utility after an exhaustive development of all possible alternatives. An example of this approach is STARCHILD (Recker, McNally, & Root, 1986b). One critique of this approach is that people are typically not capable of perceiving all potential alternatives, and that an exhaustive search is not completely representative of behaviour (Gärling, Kwan, & Golledge, 1994).

A second approach applied by activity-based models uses a step-wise method for scheduling activities. SCHEDULER is an example of such a model, which sequences the activities and selects activity locations with a heuristic that chooses the next closest activity for the schedule (Gärling, Säisä, Book, & Lindberg, 1986). If there are any schedule conflicts, the SCHEDULER may reorder the activities or select a lower priority activity to replace the conflict. SMASH builds upon this work and focuses on the decision to include, delete or substitute activities (Ettema, Borgers, & Timmermans, 1993). SMASH is based on the premise that 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. Both models contributed to the literature by focusing on the decision-making process. However, these two models are limited to individual decision making and neglect mode choice in their models.

A third approach suggests that travel decisions are made at the household level. This approach incorporates the constraints that may be imposed by other individuals within the same household. Moreover, these models postulate that household travel is the result of disparate 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). In order to capture the complexity of these decisions, models within this approach are typically simulate the actions and characteristics of the household over time (Miller, 2005).

One example of this approach is Albatross (Arentze & Timmermans, 2000). One fundamental difference in this model is that the choice behaviour is not purely based on utility maximization. The algorithm for Albatross is capable of scheduling activities for up to two household members. 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 scheduled, the algorithm creates trips to link the different activities into a tour, and then selects a mode for each tour. One constraint in this model is that the mode must stay the same for the entire tour (Arentze & Timmermans, 2000). The presence of children can influence household decisions, but they are not specifically modelled in Albatross.

Another example of this approach is TASHA which is a simulation-based household travel model (Roorda et al., 2005). In this model, activities arise from the need to accomplish a project (Miller, 2005). As well, Miller (2005) suggests that activities may be completed jointly with more than one household member. Roorda et al. (2005) outline the first implementation of TASHA. The algorithm attempts to schedule each activity and its associated travel based on the priority of the activity. It is capable of adjusting the start and end times of activities 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 persons 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. 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. The model attempts to join together individuals on existing tours for ridesharing if it will increase 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-based models include CEMDAP (Bhat, Guo, Srinivasan, & Sivakumar, 2004), PCATS (Pendyala, Kitamura, & Akira Kikuchi, 2005) and ADAPTS (Auld & Mohammadian, 2009). Each of these models use a simulation-based approach with econometric models (e.g. discrete choice or hazard-based) to determine travel mode, activity locations and activity duration. These models employ a rule-based approach to resolve scheduling conflicts. These models provide alternative approaches to representing household travel decisions; however, each of these lack the explicit representation of children (or dependents) and their activities within the model.

There are also models in the literature that focus on the interactions of household members (both adults and children) as they collectively decide whether or not to participate within an activity. Kato and Matsumoto (2009) developed a utility model that allocates time resources for both obligatory and leisure activities taking place either in or out of the home for a weekday and a weekend. However, this model makes some simplifications as it assumes one household structure consisting of a husband, wife and one child. Moreover, it does not take into account the availability of travel resources in its activity decision.

Bhat et al. (2011) take another approach. The authors specify a Multiple Discrete Continuous Extreme Value model that estimates the activity participation of households up to five members in size (including adults and children). Accessibility measures, household demographics and individual characteristics are all modelled factors that contribute to activity participation. Again, this model does not directly take into account the availability of travel resources or mode choice, but instead these factors occur within a subsequent step of the broader "SimAGENT" framework within which this activity participation model sits.

In this same vein of work, Vuk et al. (2016) focuses specifically on the relationship between joint in-home activities and the overall household travel pattern. The authors demonstrated that joint family time that occurs at home – defined as Primary Family Priority Time (PFPT) – has a high importance for families in Copenhagen. This study identified a model structure that can be integrated with the activity-based model for Copenhagen (known as COMPAS). The results of this work shows how in-home activities are influential in the daily household activity pattern, and affect when and how long other activities (including work) occur.

2.1 Contributions of this Research

The heuristic model that is proposed in this paper builds upon the literature by adding to the collection of models that are able to represent the interactions of household members in transport decisions. The proposed model is similar in principle to the most recent household heuristic activity-based travel models, instead of the models that focus specifically on activity participation. Previous models tend to follow a sequential process to construct and select modes for tours. The proposed model differs from these existing models through the following contributions. This model improves upon Albatross, CEMDAP, FAMOS and ADAPTS by explicitly representing the travel demand and behaviour of dependents. In the proposed model, activities are scheduled in terms of priority, whereas in Albatross, the model alternates between household members to schedule activities. Unlike previous models for which the complexity of the decision making required more complex solution methods (such as genetic algorithms in TASHA), this model's rule-based approach offers greater simplicity and faster solution times. Thus, the model results can be input into a broader model that explores the relationships and changes within land use and transport systems. Finally, the empirical data which are used to validate the model developed here are generated from a unique context – an auto-dependent suburban region in North America.

3. Model Concept

In this model, we focus on the following household decision: how should travel resources be allocated such that its members are able to achieve their desired activities. We start with the following set of assumptions:

1. The household has an established list of activities for which the location and durations are known.
2. These activities are classified into two categories – mandatory activities (that must be satisfied) and discretionary activities (that if not satisfied, reflect lost utility for the household). Within the discretionary activities, a priority (hierarchy) exists.
3. The travel resources available to the household and regional travel costs are known.

Based on these assumptions, the model answers two basic questions for each activity:

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

These questions relate to two choice problems typical of activity-based models: mode choice and time-of-day choice, respectively. In this model, we assume that mode choice is modelled prior to the time-of-day decision identified through heuristics. We have made this ordering assumption as travel time is important in determining when it is feasible to complete the activity. Given that travel time is a function of the travel mode, and this is dependent on the availability of travel resources, such as a vehicle or supervision, we model this decision first. The time-of-day choice occurs after as the model seeks to schedule the activity and travel within an available period of time in the person's day. All of these choices are made in conjunction with other members of the household.

To answer the 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 will accompany the dependent on trips to activities?

The proposed model contains a set of rules to answer these questions. The model is based on the premise that household activities will be scheduled in order of priority. For each household, the model sorts all activities by their priorities, and then attempts to place activities into a person's schedule in order of priority. In this process, the model also determines who is responsible to chaperone dependents, and who has access to household vehicles. The model iterates through this process and attempts to schedule each activity for the household. Figure 1 provides an overview of the model concept and structure.

The output of the model is a set of tours – a collection of consecutive trips that starts and ends at the household's place of residence (Adler & Ben-Akiva, 1979) – for each person. Multiple activities may be conducted on a tour. With these tours, the model identifies for one typical 24-

hour period when activities take place, when travel takes place and how trips are accomplished. The model also calculates the total travel time and cost for the tour.

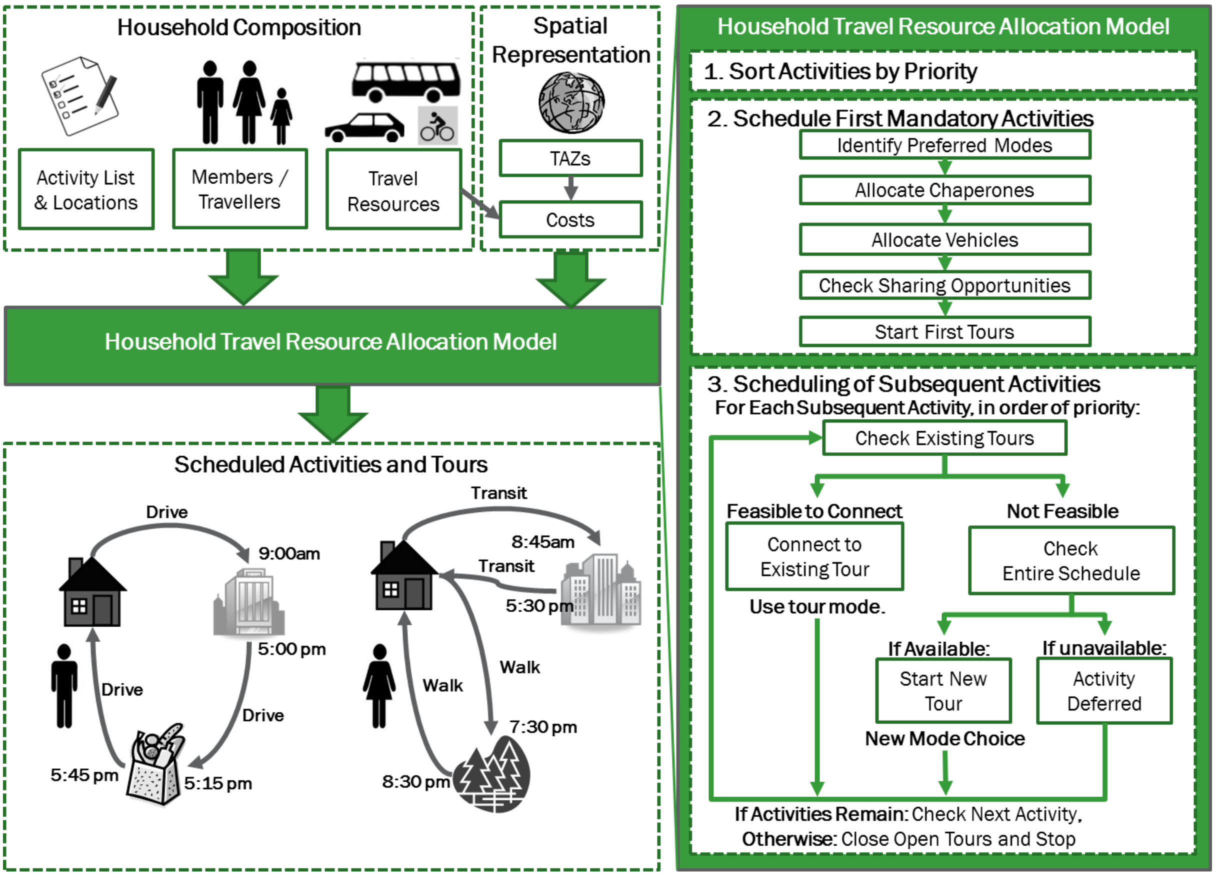

Figure 1. Model overview

3.1 Inputs – Household Composition

In this model, a household is defined as a collection of individual persons that live together within the same housing unit. Each household is associated with a physical location where each person must start and finish all tours.

Members

Household members are described by socioeconomic characteristics including age, gender, employment status, or student status. Furthermore, the persons can be described with transport characteristics, such as whether or not the person has a driver's license or a transit pass, and also whether or not the person has travel independence.

The travel independence status of the person is especially important in this model. A person who is *independent* is fully capable of travelling to activities by themselves using any of the travel resources that are available. A person who is *dependent* is not able to travel without supervision. A dependent traveller requires a chaperone to accompany them to activities.

Activities

Each person within the household has a set of activities that they may accomplish during the course of the day. Some of these activities may be considered *mandatory* – those that must be accomplished at regular intervals (i.e. every weekday). Examples of mandatory activities include work or school. Other activities may be considered *discretionary* – those that occur with less frequency, have less importance, and as a result are accommodated when resources allow. Discretionary activities used in the model include grocery shopping, other (non-essential) shopping, service activities (including medical appointments, visiting banks or other services), social activities, and recreational activities (including exercising, or playing sports).

Each activity has a pre-determined location and duration. The activities also have time windows during which they can occur, defined by an earliest and latest start time.

Travel Resources
Each household has a set of resources that enable travel to activities. In this model, a person may drive, share a ride, use transit, bike or walk to their activities. The set of modes available to the household depends on the characteristics of the travellers in the household. Households that do not own a vehicle, or have no licensed drivers, cannot travel by automobile. Dependent travellers require independent travellers to complete any travel activity. The model assumes that all independent travellers can serve as chaperones. Any travel must be completed within the constraints of time and out of pocket expenses.

3.2 Inputs – Spatial Representation
Each trip in the model has an associated travel time and cost to travel from the origin to the destination. This model relies on a Traffic Analysis Zone (TAZ) system to represent locations within the study area. A TAZ system is often used in transportation planning as the spatial resolution that provides a balance between high accuracy and fast processing speed. The study area (Kitchener-Waterloo, Canada) has been divided into 270 TAZs, which correspond to the zones in the local travel survey (Data Management Group, 2011).

Calculating Travel Times
Trips by all modes are assumed to begin at the centroid of the origin zone and end at the centroid of the destination zone. The travel times for these trips are calculated using open data for transport network and transit schedule information (OpenTripPlanner, 2013) for the shortest path between centroids. Matrices of travel times are calculated between all zones for each mode; the model's algorithm accesses these travel times as necessary during runtime.

Calculating Travel Costs
Travel costs included in the model reflect what a person would pay "out-of-pocket" for each trip for a given mode. For drive and share modes, the travel costs include only fuel and maintenance. We have not included average parking or toll costs as these were unavailable for our study area. Other fixed costs of automobile travel related to vehicle ownership, insurance or depreciation 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. For travel by transit, the out-of-pocket expense is limited to fares. We assume that those with transit passes pay a per trip fee that is much lower than those who pay the cash fare. There are no out-of-pocket costs for walking or cycling.

Calculating Utility and Mode Preferences
The model uses a multinomial logit formulation, shown below in equation (1), to determine the probability (P) that a person would select a particular travel mode (m), based on the utility (V) of the alternatives (Ben-Akiva & Lerman, 1985). This enables the model to identify what are the preferred travel modes for an individual.

$$P_m = \frac{e^{V_m}}{\sum e^{V_z}} \qquad (1)$$

The utility (V) for each mode (m) is assumed to be a function of travel cost (c), and travel time (t) from the origin (i) to the destination (j). Single (as opposed to mode-specific) β_{time} and β_{cost} coefficients have been assumed for this model, which implies that any change in travel time or cost, is valued the same across all modes. The model does include a mode specific constant (β_{mode}), which represents the elements of utility that are measurable but not explained by time or cost. Equation (2) represents the utility function used in this model:

$$V_{ij}^{m} = \beta_{cost} C_{ij} + \beta_{time} t_{ij} + \beta_{mode} \quad (2)$$

The coefficients for the utility functions are typically estimated using the maximum likelihood approach by McFadden (1974). For this model, a data set of 14,014 trips for calibration and 6,867 trips for validation were collated from the 2011 Transportation Tomorrow Survey, which samples 5% of households in the study area (Data Management Group, 2011). The data were processed with the 'mlogit' package in the statistical software R, which follows a maximum likelihood approach (Croissant, 2013). Table 1 presents the results.

Table 1. Mode Choice Model Estimation Results

Parameter	Estimate	Standard Error	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; ρ^2 = 0.1046

Given these results, every additional minute of travel time leads to a decrease in utility of 0.0935. Every additional dollar of travel cost leads to a decrease in utility of 1.0698. 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. Moreover, the value of time implied from these results is $5.25 per hour. This value might be considered low for commuting trips. It is important to note that the value of time should vary based on trip purpose, with the highest for business trips, and lowest for discretionary trips (Small, 2012). A lower value of time in this study should not be surprising as it was estimated using all trip purposes in the study area.

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. Each of these mode-specific constants are negative, which suggests that there are real or perceived costs related to safety, energy, reliability, weather, or convenience that reduce the attractiveness of these modes. These results are indicative that the car is the preferred mode within the study area, which is typical of the North American context.

This model was tested against a set of data to ensure that the specified model provides reasonable estimates of mode choice. The validation set consisted of the 33% of the trip data that were not used in the estimation of the model. Utilities and probabilities were calculated to predict the mode choice of the validation data. As the mode choice selection is a random process, the validation test was repeated 100 times and then these results were averaged across the number of repetitions. The specified mode choice model was able to predict mode choice split within +/- 0.2% of the actual mode choice split. Therefore, this model can be used with confidence to estimate mode choice behaviour for the study area.

3.3 Model Algorithm Overview

Given the previously discussed inputs, the model produces 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. Scheduling decisions are made with consideration of the actions and activities of all household members.

The household travel resource allocation model follows three main stages: 1. Sort Activities by Priority; 2. Schedule the First Mandatory Activities; and 3. Schedule Subsequent Activities. Each of these is described in more detail in subsequent sections. Pseudo-code for the model algorithm has also been provided as an appendix to this paper.

3.4 Model Stage 1 – Sort Activities by Priority

In the first stage of the 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 activity-based travel models (Arentze & Timmermans, 2000; Gärling, Kwan, & Golledge, 1994; 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 to fulfil a lower priority activity.

This model prioritizes the activities in this order: 1. Work or School Activities; 2. Chaperone Activities; 3. Service Activities; 4. Grocery Activities; 5. Social Activities; 6. Recreational Activities; then 7. Other Shopping Activities. The order follows the results of a survey developed for this study. In this survey, respondents identified that mandatory activities, such as work and school activities, take schedule precedence over discretionary activities, such as shopping, recreational or social activities. Furthermore, respondents also noted that 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. We define schedule flexibility in equation (3) as the difference between the early and late start times for an activity.

$$Flexibility = Late\ Start\ Time - Early\ Start\ Time \quad (3)$$

If any two activities have the same priority, the activity that has less flexibility 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.

3.5 Model Stage 2 – Schedule First Mandatory Activities

In the second stage, the model initiates tours by scheduling the activity that has the highest priority for each member of the household. This stage first identifies the preferred mode choices for each member of the household, and then assigns chaperones and vehicles to minimize the household costs and to ensure schedule feasibility based on the mode preferences. Once the mode choice has been confirmed, the model then identifies when the first trip and activities will take place. Each step in the process is described below.

Step 1 – Identify Preferred Modes

The model identifies the preferred and alternate transport modes that each independent person would use to travel to their first activity. At this step, there is no consideration of household resource constraints. The options that each independent traveller can initially choose from are Drive, Transit, Bike and Walk. To select the preferred mode, the utilities of these options are calculated using equation (2) based on the travel time and cost from the household to the activity location. The probabilities of selecting each mode are then estimated through equation (1). Using the calculated probabilities, the model implements a random process to select the preferred mode. To determine the alternate mode, the probabilities are recalculated and the same random process is repeated without the preferred mode in the choice set.

Step 2 – Allocate Chaperones

In households that have dependent travellers, the model determines which independent traveller has the responsibility of accompanying the dependent on the trip to the dependent's first 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.

This process can be best demonstrated using an example. Suppose a household has two independents (Person 1 and 2) and two dependents (Person 3 and 4). Each person has a mandatory activity with the following start time ranges in Table 2.

Table 2. Start Times of Mandatory Activities

Person	Early Start Time	Late Start Time
1	8:45am	9:15am
2	6:45am	7:15am
3	8:15am	8:45am
4	8:30am	9:00am

The model allows for an independent to chaperone up to two dependents to their first mandatory activities. This leads to four possible chaperone allocations, shown in Table 3.

Table 3. Potential Chaperone-Dependent Combinations

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 their activity within their own acceptable start time range, after dropping off the dependent(s) at their activity within their acceptable start time range(s).

In the first combination, Person 1 chaperones Person 3. To determine feasibility, the model must consider the travel time between the two activity locations, which depends on the preferred mode of the chaperone. The model selects the preferred mode based on the total travel time and cost from the household to the dependent's activity, and then to the chaperone's activity. In this case, suppose the preferred mode is to drive and the travel time between the dependent and the chaperone's activity 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 chaperone would arrive at his activity, 22 minutes later, prior to the early start time. Therefore, this pairing is considered feasible.

However, in the case where Person 2 chaperones Person 4, the dependent's activity start time range begins after the start time range of the chaperone's activity. Person 2 would not be able to start her activity on time. Therefore, this pairing is considered infeasible. In fact, since Person 2 has 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 model will therefore return a household utility of negative infinity for these combinations.

The only combination that is 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 late start time activity should be dropped off first. In this case, Person 1 will drop off Person 3, then Person 4, prior to the start of his mandatory activity. We use this strict time feasibility heuristic in order to be consistent with the principles in Model Stage 1. By dropping off the person with the earlier activity first, the model preserves as much flexibility as it can for future activities within the daily schedule. Moreover, empirical data from the survey conducted for this study suggests that the households within the study area make their scheduling decisions based on a maintaining schedule flexibility prior to minimizing cost.

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. 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 summarizes this check.

Table 4. Feasibility of Person 1 Chaperoning Persons 3 and 4

Person	Travel Time to Activity	Arrival Time	Early Start Time	Late Start Time	Feasible?
3	7 minutes from home	8:15 am	8:15 am	8:45 am	Yes
4	7 minutes from Person 3	8:22 am	8:30 am	9:00 am	Yes
1	17 minutes from Person 4	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 model then calculates the combined utility for the entire household by calculating the utility for each individual person using the parameters in Table 1 input into equation (2), and then summing them across the household. This calculation is summarized in Table 5. Note that we have assumed that there is no marginal travel cost for anyone using the Share mode, as this is already counted within the travel cost of the chaperone (i.e. Person 1).

Table 5. Calculation of Household Utility in Chaperone Allocation Process

Person	Mode	Total Travel Time	Travel Cost to Activity	Utility
1	Drive with 3 and 4	31 minutes	$1.41	-4.41
2	Drive	12 minutes	$0.60	-1.76
3	Share with 1 and 4	7 minutes	$0.00	-0.65
4	Share with 1 and 3	14 minutes	$0.00	-1.31

The household utility for this combination is the sum of the individual utilities, which in this case is -8.58. Given that all other combinations have a utility of negative infinity, the model allocates Person 1 to accompany both dependents to their activities using his preferred mode, which is to drive.

Step 3: Allocate Vehicles

In this step, the model determines the allocation of vehicles and assigns the mode for the first tour of each independent traveller. Note that chaperones will be allocated vehicles first prior to other independent travellers. All remaining vehicles will be assigned to independents whose preferred mode is drive, as long as there are enough vehicles. If there are more independents who prefer to drive to their first activity than the number of available vehicles, the model assigns the vehicles to maximize the overall utility to the household.

Suppose there is a household with two independent travellers, each with the preferred and alternate modes with their associated individual utility identified in Table 6.

Table 6. Utility Summary of Vehicle Allocation Process

Person	Preferred Mode (Utility)	Alternate Mode (Utility)
A	Drive (-0.27)	Walk (-1.38)
B	Drive (-1.48)	Transit (-4.44)

Both persons prefer to drive; however there is only one vehicle in the household. Therefore, the model will compare the combined household utility of the two scenarios. If the vehicle is assigned to Person A while the alternate mode is assigned to Person B, the combined utility is the sum of the preferred mode utility for Person A (-0.27) and the alternate mode utility for Person B (-4.44), which is -4.71. In contrast if the vehicle was assigned to Person B the combined utility is the preferred mode utility for Person B (-1.48) and the alternate mode utility for Person A (-1.38), which sums to -2.86. The latter allocation has the higher household utility; therefore, the vehicle is assigned to Person B, while Person A may use the alternate mode, which is to walk to his first activity.

Step 4 – 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 is using a mode other than Drive to their first activity, they may share a ride with a driver that is available and is not already chaperoning other people.

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 an independent if the trip meets the schedule feasibility requirement and if the combined utility with the shared trip is greater than the combined utility of the independent trips. The utility associated with sharing 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. In the case of the previous example, Person A would share with Person B, if the combined utility for sharing was greater than -2.86, and if the ridesharing still allowed for the driver (Person B) to arrive at her activity on-time.

Step 5 – Start First Tours
In this step, the first tours for each person of the household are initialized using the chaperones, vehicles and modes assigned through this stage. At this point, each person that had a mandatory activity will have one initialized tour with an activity in their schedule. The model protects an amount of time following the end of the activity equal to the travel time to return home using the previous mode of the tour. Subsequent activities may be scheduled at the end of these tours, but cannot be scheduled when activities or travel take place.

3.6 Model Stage 3 – Schedule Subsequent Activities
All subsequent activities are scheduled in a step-wise approach in the order of priority. Note that the activities of dependents are scheduled prior to any of the activities of independents. Throughout this stage, the model will take one of three actions for each activity: 1. Schedule activity in an existing tour; 2. Schedule activity in a new tour; or 3. Defer activity.

Option 1: Schedule Activity in an Existing Tour
The model first considers the feasibility of scheduling the activity at the end of any existing tours. In this way, the model attempts to trip-chain activities together and minimize the overall cost and time for travel. In this option, the mode choice for this trip is dependent on the previous mode of

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. Therefore, the mode must remain the same.

If the previous mode was Share, Transit or Walk, then the person may select from any of these three modes. In this case, the model searches through all existing tours of drivers to see if they are available to pick up a passenger. The model rules assume that a driver is willing to wait up to 15 minutes prior to the desired pick-up time, and a passenger is willing to wait up to 15 minutes after the desired pick-up time for a ride share. If it is feasible, Share will be included in the choice set for mode selection. Otherwise, the person will choose from Transit or Walk.

Once the mode choice has been determined, the model checks the feasibility of scheduling this activity and trip. The activity will be scheduled on an existing tour if the traveller 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 (e.g. vehicles or chaperones). If the activity starts later than the start time range, or conflicts with other existing activities or trips in the schedule, then the person does not schedule the activity in the existing tour.

Sometimes an activity may be scheduled in an existing tour even though a person would arrive before the early start time causing the person to wait before commencing the activity. A person would only schedule an activity in this way if the waiting time prior to the activity is less than the maximum waiting time defined in equation (4):

$$Max\ Wait\ Time = t_{ih} + t_{hj} + t_{home} - t_{ij} \tag{4}$$

where t_{ih} is the travel time from the previous activity to home, t_{hj} is the travel time from home to the next activity, and t_{home} is the time spent at home, which is assumed to be 30 minutes in this model, and t_{ij} is the direct travel time between the previous and next activities.

If the waiting time prior to an activity is greater than the maximum waiting time, the activity will 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.

Option 2: Schedule Activity in a New Tour

If the addition of an activity to all existing tours was infeasible, then the model attempts to schedule the activity in a new tour from home. This option is analogous to the second stage of the model when the first activities are scheduled. 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 and in the schedules of any required resources (e.g. vehicle or chaperone), then the activity will be scheduled in a new tour. In the case, a vehicle is unavailable, an alternate mode may be used. These feasibility constraints must be met in order for the activity to be scheduled in a new tour.

Option 3: Defer 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 iterates through this stage until there are no remaining activities.

3.7 Model Outputs

When there are no more activities remaining, 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. At this point, the household travel resource allocation model is complete. It has allocated the resources and scheduled the desired activities of the household.

The resulting model output is a list of the scheduled activities and tours for each person in the household. The list of scheduled activities for each person indicates when the activity starts and ends, as well as the location (i.e. zone) for the activity. The list of scheduled tours indicates the departure time, arrival time, and mode for each trip. The model also calculates the duration of activities and travel, as well as the cost that is associated with each mode of travel.

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. Both travel time and cost can be combined using the value of time to determine the generalized cost of travel for the household, as outlined in the following equation (5).

$$Generalized\ Cost = (Value\ of\ Time) * \sum Tour\ Times + \sum Tour\ Costs \tag{5}$$

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.

4. Preliminary Results

We have tested the proposed model with households and data from the Region of Waterloo, in Canada. The Region is rapidly growing – the current population of 550,000 is expected to reach 731,000 in the next 15 years – and is investing in infrastructure with a 19km, $818M CDN Light Rail Transit system under construction. The preliminary data collection effort involved detailed activity records for a small number of households – 14 in the first study. The data were gathered by one-on-one interviews with participants; respondents were selected from within the authors' university community with purposeful sampling to reflect different household compositions, locations, and sensitivity to travel costs. Given the detailed and personal nature of the survey data, we have treated this information as confidential and have stored all data in a secure computer. During analysis and results presentation, locations of activities are aggregated to the traffic analysis zone level to remove any possibility of personally identifying any respondents. Furthermore, while household members can be described using demographic characteristics such as age and gender, these have no bearing on the actual result of the model and could be removed from modelling to address privacy concerns.

The purposes of the data collection were to generate an actual activity and travel schedule, against which the model's predictions could be compared. We provide two examples in this section to demonstrate the effectiveness of the model logic.

In the first example household, there are four people: two independents with driver's licenses (Persons 1 and 2), and two dependents (Persons 3 and 4). There are two vehicles in the household. Table 7 summarises the household activities with their actual start and end times. This can be compared to the modelled schedule in Figure 2, which shows the predicted tours for the household based on the logic discussed in this paper.

This example illustrates that the model performs well in estimating a complex household schedule with both independent and dependent persons. In particular, the model was able to correctly assign the chaperone responsibilities for all but one dependent trip. In this case, Person 2 should have remained with Person 3 on his Service activity and then chaperoned him home. Moreover, the model was able to schedule all activities within a reasonable margin of the actual schedule for all but one activity. In this case, the model scheduled Person 1's Grocery activity in the evening, instead of over the lunch hour.

Table 7. Activity List for Example Household with Dependents

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

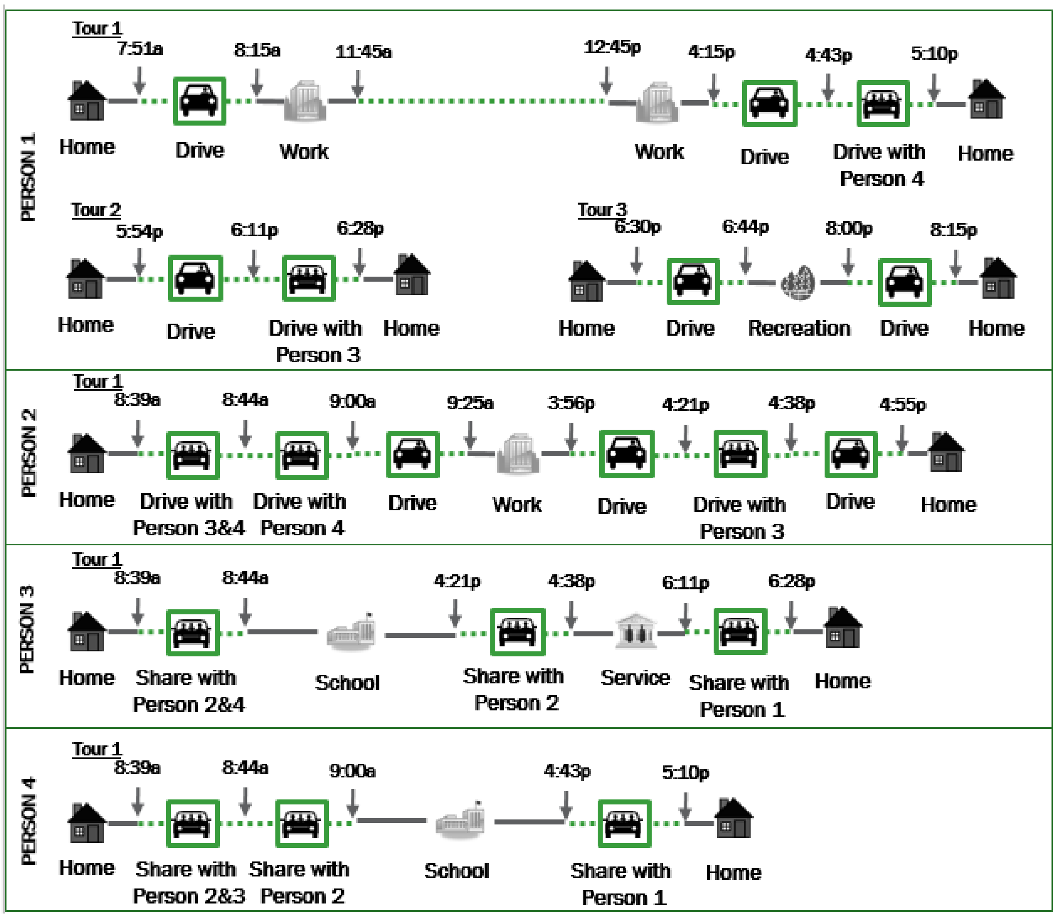

Figure 2. Modelled Schedule of Activities and Trips for Household with Dependents

In the second example, we demonstrate the model's ability to allocate vehicle resources. This household has five independent people (two of whom have driver's licenses) and one vehicle. For this example, we will focus on the activities of the two drivers (Persons 1 and 2), summarised in Table 8. This can be compared to the modelled schedule in Figure 3.

Table 8. Activity List for Example Household with Multiple Drivers

Person	Act. #	Type	Start Time	End Time	Duration
1	1	Work (1)	7:30am	5:15pm	9 hr. 45 min
1	2	Work (2)	7:10pm	8:50pm	1 hr. 40 min.
1	3	Recreation	9:35pm	10:35pm	1 hr.
2	1	Grocery (1)	9:10am	9:50am	40 min.
2	2	Grocery (2)	10:00am	10:30am	30 min.
2	3	Grocery (3)	10:40am	11:00am	20 min.

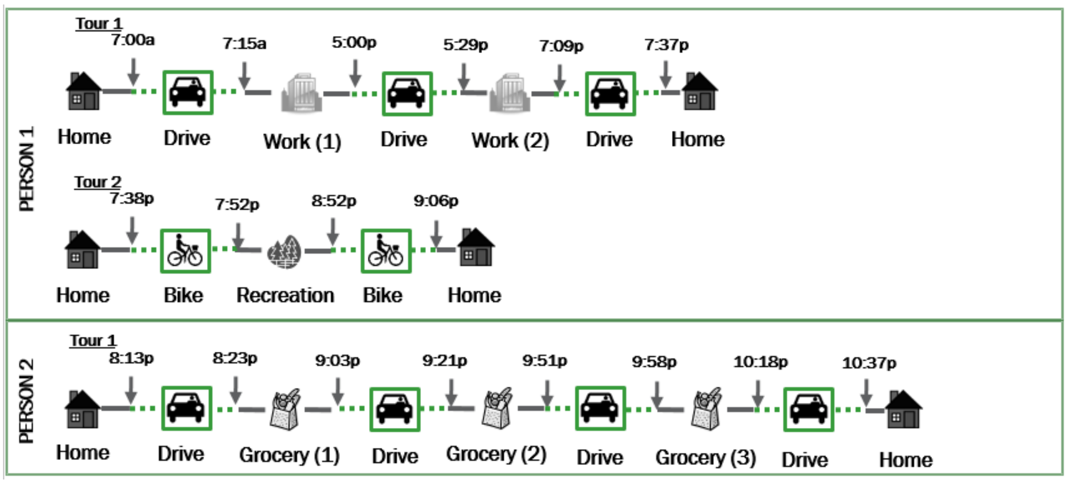

Figure 3. Modelled Schedule of Activities and Trips of Drivers

The model assigned the vehicle to Person 1 who had the higher priority activity. In reality, he cycled to work, which allowed Person 2 to drive to the grocery activities in the morning, instead of the modelled evening trips. This outcome illustrates that the model process is working correctly, however, it did not capture the particular mode preferences of Person 1.

Based on the preliminary test of nine households, we demonstrate that the model performs reasonably well in the scheduling of activities and creation of tours for households if there is some level of time constraint associated with the activities. Further work to the model to include the scheduling of home activities as an additional constraint, or the ability to schedule activities at the start or between two activities in an existing tour, are expected to improve the model's ability in representing household schedules.

As well, the results show that the model is able to predict the mode choice for most tours, but some mode preferences and costs were not entirely captured. In particular, parking costs were not considered, which would influence the probability of driving. Furthermore, particular mode preferences, such as preference for active transport, or reliability is not captured in the current model. Consideration of these costs and preferences may improve these models. However, a larger data set with these attributes are required to estimate an improved mode choice model.

5. Conclusions

This paper presents a model that employs a heuristic rule set that represents the short-term, interdependent decisions of household members, considering explicitly those who are dependent and must travel with a chaperone. The model considers the mode choice, vehicle, chaperone, and ride sharing decisions, all with the objective of maximizing household utility. The model schedules activities in order of priority using tours, with a preference for adding activities to existing tours, rather than creating new. In some cases, not all activities can be scheduled and, as a result, some activities may be deferred.

The model output is a feasible but not necessarily optimal household schedule of travel and activities. The model also produces a total generalized cost – the amount spent in time and expenses – to complete the tour. Because the model's formulation is straightforward, its solution is very fast. While we have not been able to compare the relative performance of our algorithm in detail with existing agent-based modelling software, we believe that our work has achieved gains in simplicity that outweigh the computational cost of achieving more robust results. As such, the modelling presented here may be valuable to more complex transportation – land use models. For example, if the total cost incurred by a household (as measured by the model) exceeds that household's desired travel budget, longer-term household decisions – increasing the resources available to the household (e.g. purchase of a new household vehicle), or moving the household to a location that is closer to activities – may be triggered. These decisions, and in particular, the household relocation decision, is the focus of an integrated land use - transport model for Kitchener - Waterloo. The principles and logic presented in this paper may also be applied in other urban regions.

In addition to further testing and refinement of the model, there are opportunities to extend this work. In particular, 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 transport assignment model to determine the actual travel times and costs (with congestion effects) for household tours. 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 change travel resources by adding an additional vehicle, or by changing their residential location to improve travel times. Further work is required to establish these feedbacks and choices, but these build off of the model developed in this study. As well, while not explicitly considered within this study, the influence of an electric vehicle on household travel behaviour could be modelled in this framework. In this case, the cost to drive may be potentially reduced (if electricity costs lower than gas), however, an additional heuristic that limits the amount of time it can travel between charge points should be introduced. It can be incorporated within the existing framework as the vehicle is defined with its own schedule.

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Appendix A – Model Pseudo Code

Main Routine

1. Calculate Travel Times and Costs for All Origin-Destination Pairs and Modes
   a. Input shortest path data from Region's Travel Model
   b. Read input time and cost tables for each mode and origin-destination pair
2. Create Household with People, Vehicles and Activities
   a. Initialize Household object and assign TAZ for household location
   b. Initialize Persons object for each household member with data from input file
   c. Sort members into a list of independent travellers and dependent travellers
   d. Initialize Activity object for each desired activity with data from input file
3. Sort Activities by Priority
   a. 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 from highest to lowest priority.
4. Determine Preferred Modes for First Mandatory Activity for Independents
   a. Determines Mode from Origin to Destination with discrete choice model
   b. Given preferred mode, determine an alternate mode with discrete choice model

If Household has Dependents:

5. Assign Chaperones to Dependents

   For each potential chaperone – dependent pairing:

   a. Get mode choice, check feasibility and calculate utility to chaperone dependents
   b. Get mode choice and calculate utility for non-chaperones
   c. Assigns remaining vehicles to maximize household utility
   d. Calculate Total Household Utility of Chaperone Assignment
6. Initialize first tours:
   a. Use chaperone assignment that has the maximum household utility
   b. Create tour for dependent and chaperone:
   c. Create tour for independents without chaperones

If Household does not have dependents:

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

Once mandatory activities scheduled, and first tours initialized:

7. Schedule Subsequent Activities in order of priority, based on the lists of sorted activities in Step 3. Uses either AllocateNextDependentActivity or AllocateNextIndependentActivity subroutines.
    a. Schedule any other mandatory activities of dependents
    b. Schedule any other mandatory activities of independents
    c. Schedule any discretionary activities of dependents
    d. Return all dependent tours to home by assigning chaperones to dependents
    e. Schedule any discretionary activities of independents
    f. Once all activities checked: return all independent tours to household location with previous mode on tour
8. Output results. Calculate household travel costs and present results.

Major Subroutine: AllocateNextDependentActivity
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)
        i. If existing tour feasible, activity may be scheduled using previous mode
        ii. If no existing tour feasible, check feasibility of starting new tour with new mode choice for chaperone
        iii. If starting new tour is not feasible, check next potential chaperone
2. If activity is not scheduled in an existing tour, attempt to start new tour for activity
    a. Check feasibility to start new tour for each independent (same as 1a)
3. If activity is not schedule in a new tour, activity is deferred
4. Check next activity until all activities checked.

Major Subroutine: 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, recalculate utility and mode choice
    c. Determine feasibility of scheduling activity with previous mode:
    d. If feasible, schedule in existing tour
2. If activity is not scheduled in an existing tour, attempt to start new tour for activity
    a. Calculate Utilities and Determine Preferred Mode Choice
    b. Determine feasibility of scheduling activity from home using preferred mode
    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