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A Framework for Evaluating the Economic Viability of Autonomous Vehicles

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A Framework for Evaluating the Economic Viability of Autonomous Vehicles

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Transportation Science

by

Kotaro Yamada

Thesis Committee:
Professor Wilfred Recker, Chair
Professor R. Jayakrishnan
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2019

DEDICATION

To my colleagues and friends.

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ABSTRACT OF THE THESIS

A Framework for Evaluating the Economic Viability of Autonomous Vehicles

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Master of Science in Transportation Science

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This research aims to develop a framework investigating the viability of autonomous vehicles (AVs) in an urban area that enables multiple travel ways that potentially compete or coordinate with them. Based on the Household Activity Pattern Problem (HAPP) developed by Recker (1995), this research attempts to simulate travel-activity patterns with AVs by reformulating the original HAPP model. The revised framework succeeds in assessing the condition under which AVs can be advantageous over conventional vehicles (CVs) for a hypothetical household. It explicitly captures AVs' zero-occupancy trips and searching behavior for parking spots leading to the increase in vehicle travel miles. Finally, this research extends the formulation of HAPP to be capable of simulating multimodal transportation systems. In addition to conventional private vehicles and AVs, various private modes, rideshare (taxi), and public transit are incorporated into the framework. This extension distinguishes the framework from other activity-based models in depicting the coordination or competition between AVs and other modes. Thus, this framework shows that the availabilities of other transportation modes, as well as AVs' costs and households preferences, will affect households' decisions to embrace AVs. The results of this research imply that the proposed framework potentially serves as the demand-side component in an operational system for innovative transportation services such as Mobility as a Service.

Chapter 1

Introduction

Companies in various industry sectors have become increasingly interested in the realization of autonomous vehicles (AVs), which are heralded as dramatically transforming our daily lives and the automobile market. The AVs are alleged to influence many aspects of society. Some expected benefits, for example, are: improving safety on the road without risk of human errors or inappropriate driving manners, developing an intelligent transportation system that increases road traffic capacity and reduces fuel consumption by utilizing optimally programmed driving behaviors and a controlled operation, offering mobility to disabled or elderly people, and reducing perceived travel time costs by enabling driver to participate in an activity during a ride. On the other hand, there also are some anticipated drawbacks, such as: increased vehicle miles traveled (VMT) especially those induced by unoccupied AVs and the safety decline caused by the accidents involving conflict situations intractable for AVs. Fagnant and Kockelman (2015) [14] comprehensively summarize estimated impacts derived by AVs. Whether these influences are positive or negative, they seem significant enough to affect our daily travel-activity patterns. For example, as a result of reduction in travel time costs, one might want to participate in more activities and make more trips, while another might travel longer to enjoy activities during a trip.

If AV technologies are realized, households may consider replacing their conventional vehicles (CVs) with AVs, but their decision to do so depends on the comparison between the economic benefits of CVs and those of AVs. For a household considering purchase of an AV, it is essential to examine how much living cost the AV reduces compared to when they own a CV. For this examination, not only the prices and operational cost of the vehicles but also the household's travel-activity pattern matter. For example, for a household with two members who usually depart their home separately, having an AV may enable them to execute the same activity pattern without owning two CVs since the AV used by a member can automatically travel to pick up the other member who leaves home later. This kind of complex travel behavior cannot be illustrated by conventional trip-based models. In this sense, estimating the entire impacts of AVs on the society requires activity-based analysis that attempts to model household members' activities and trips as equally important parts of travel behavior.

The door was opened to the activity-based approach (ABA) by the intensive works in urban planning conducted by Chapin (1974) [10] and the activity path diagram representation shown by Hägerstrand (1970) [20] and his colleagues in the field of geographical science. Since then, ABA has become an area of science aimed toward better understanding of travel behavior and has evolved to use as transportation planning tools. The feature of this theory is that it explicitly describes activity systems underlying travel behaviors, the latter being regarded as derived from activity participations. This feature expectedly provides a solid basis for developing operational frameworks for transportation planning and other applications.

Practitioners, for the most part, have traditionally applied the four-step model which is inherently trip-based to forecast the change in travel demand after implementing a large construction project. This primarily has been because the four-step model is systematically well-defined enough to utilize in almost all the regions in the world based on conventional travel surveys. However, in some academic circles, the model has been criticized for a number of reasons including that it ignores important constraints restricting travel behavior and lacks capability of assessing the impacts of the policies that affect these constraints.

In response to criticisms cast on the traditional demand forecasting system, researchers have developed a number of activity-based models (ABMs), which purportedly more accurately capture the nature of travel behavior and, therefore, are sensitive to a wider variety of policy applications. These models apply various behavioral theories but, as we discuss later, can be categorized into some groups based on their assumptions. Although all types of the ABMs deal with the complexity of travel-activity behavior and, moreover, some of those activity-based models have been implemented to evaluate multiple transportation policies, much still remains to be studied and developed about the approach due to the complicated nature of travel-activity behavior. Additionally, few ABM systems have been effectively utilized to assess the transportation systems with AVs.

Among the established ABMs, the household activity pattern problem (HAPP) framework due to Recker (1995) [35] mathematically describes the travel-activity pattern generation process. Since this problem is formulated as a variant of the well-known pickup-and-delivery mixed integer programming problem (PDP), it appears to have operational capability of rigorously considering multiple constraints that govern travel-activity behavior. The strength of this model is that it solves the travel-activity pattern problem as well as the vehicle routing problem. By taking advantage of this feature, this research is aimed at reformulating HAPP in order to represent possible travel-activity patterns with AVs.

The rest of this thesis consists of the following chapters. Chapter 2 reviews studies related to this research and shows its potential contributions. Chapter 3 describes the HAPP formulations and its revision to evaluate AV introduction. Chapter 4 illustrates numerical examples based on the revised formulation. This chapter also exemplifies the economic viability analysis of AV based on the proposed framework. Chapter 5 further develops the capability of the proposed framework of representing multimodal transportation systems and presents some examples based on this multimodal extension. Chapter 6 finally concludes this thesis while suggesting the direction of future research.

Chapter 2

Literature Review

2.1 Evaluation of AV

AVs are an emerging technology and relevant research related to their design and use has attracted growing attention in the recent years. In the field of transportation systems engineering, the relevant existing literature is, in large part, concerned with shared AV (SAV) systems in which an operator dispatches AVs to serve individual trips. For example, Fagnant and Kockelman (2014) [15] develop an agent-based simulation model to evaluate a hypothetical shared AV system that utilizes AV relocation strategies. Their work is regarded as an initial agent-based framework for SAV systems. Likewise, Hyland and Mahmassani (2018) [21] try to assess shared-use autonomous mobility service (SAMS) in which an operator dynamically assigns AVs to traveler requests by applying agent-based simulations. Masoud and Jayakrishnan (2017) [30], assuming shared ownership and ridership program of AVs, analyze the impacts of an AV sharing program for household clusters constructed relative to their travel behaviors. They apply a two-step mathematical programming problem to identify the minimum number of AVs required by each household cluster and then the maximum total number of on-demand car rentals. These studies assume that travel demand is given and not affected by an AV sharing system. However, this assumption is too restrictive to evaluate the full impacts of the system since, as previously mentioned, AVs are expected to change travel behavior.

Alternatively, private AV (PAV) ownership and its impacts on households' travel behavior have not been well-understood. Some have conducted stated preference surveys about PAV ownership. For example, Kröger et al. (2018) [28] estimate adaptation rate of AVs by households in Germany and in the US by using a trip-based mode choice model. However, they intentionally ignore zero-passenger trips which would be the most significant demand derived by introducing AVs. Zhang et al. (2018) [42] estimate the reduction in household vehicle ownership and excessive VMT resulting from PAVs. For the estimation, they solve a bi-level optimization problem that identifies the optimal number of PAVs for each household and their optimal routes for fixed trips distributed over the Atlanta, Georgia, area.

These preceding studies related to the potential adoption of PAVs are based on a conventional trip-based framework. A limited number of studies, such as Auld et al. (2017) [6], try to assess the impact of AVs based on ABMs. However, they do not consider AV-specific travel patterns but, rather, change the level of service data and model parameters only reflecting improved road capacity and the reduction in perceived travel time cost caused by AVs.

Little work has progressed toward the explicit illustration of a household's travel-activity pattern with AVs at this point in time. Nevertheless, because AVs are expected to affect our travel behavior and, moreover, induce extra trips and activities, such an illustration is crucial for a credible evaluation of AV adoption into a household's travel-activity routine. It is apparent that an activity-based analysis is needed to show the precise viability of PAVs.

Relative to the current literature, the work presented here may be regarded as one of the initial attempts to assess the viability of AVs by focusing on the possible household travel-activity patterns materialized by introducing AVs. As it has been pointed out that a comprehensive evaluation of the travel behavior needs to be supported by ABA, accordingly, the following subsections are devoted to an overview of the development of activity-based analysis and its particular affinity for forecasting the impacts of PAVs.

2.2 Activity-Based Approach

As, illustrated above, ABA is an alternative approach to overcome some of the well-known limitations of the four-step model. Unlike conventional trip-based model systems, ABA exploits the fact that travel demand is derived from activity participations and focuses on representing the interdependency between trips and activities rather than on individual trips. Because ABA is capable of representing a detailed travel-activity pattern and, thus, has greater sensitivity to planning and policies than the classical four-step demand forecasting system, it has been gaining application in practice. Yet, this approach is not a unified discipline; rather, due to the complexity of the nature of travel-activity patterns, diverse model systems have been proposed.

According to McNally and Rindt's (2007) [31] distinction, these activity-based models are classified into four groups: simulation-based models, utility maximization-based econometric models, computational process models (CPMs), and mathematical programming models. This subsection describes the characteristics and the examples of model systems developed to date in each model category.

2.2.1 Simulation-based models

Models in this category are the most prevalent type of ABMs and a direct implementation of Hägerstrand's path paradigm. The models in this category are also called constraint-based models (Rasouli and Tinmmermans, 2014) [33] because they essentially aim to illustrate the activity-pattern generation process under spatial-temporal constraints. PESASP (Lenntorp, 1976) [29] and CARLA (Jones, 1983) [22] pioneer the simulation-based approach, and STARCHILD (Recker et. al, 1986) [37] [38] can be regarded as an extension of the two predecessors. STARCHILD consists of several activity-based submodels, one of which applies utility maximization assumption for choice behavior. McNally and Rindt (2007) [31] indicate, however, that STARCHILD was not targeted for a planning use because it utilizes generally unavailable data at that time. This fact limits STARCHILD to remain in this class even though it could have sensitivity to policies. Although simulation-based models primarily aim to check the feasibility of a given activity agenda in a certain temporal-spatial space (Rasouli and Tinmmermans, 2014) [33], they provide significant implications for the development of the following operational ABMs.

2.2.2 Econometric Models

This second type of ABMs assumes that decision makers maximize their utility when executing their travel-activity patterns. Conventionally, the models in this group are typically based on discrete choice econometrics. Additionally, econometric models have been implemented in many practical situations because of their high sensitivity to changes in environment and policies.

Adler and Ben-Akiva (1979) [2] present an early primitive example of this category. They attempt to simulate non-work travel behavior using multinomial logit model. Then, Bowman and Ben-Akiva (2001) [9] extend its capabilities by using a nested-logit model to represent a simultaneous decision-making process realizing an activity pattern. Each nest of the model expresses a choice of activity pattern, time-of-day of the primal or secondary activities, and travel mode to them. Importantly, the model has shown transferability in several regions.

For example, while it is validated on the data surveyed in Boston, its prototype is applied in Portland (Bowman, 1998) [8].

PCATS (Kitamura and Fujii, 1997) [26] simulates sequential activity executions within a day by a Monte-Carlo simulation of several econometric models such as the nested-logit model while explicitly considering time-space constraints for each activity execution. It is later combined with DEBNetS, a mesoscopic traffic flow simulator, to evaluate the effect of demand management policies (Kitamura et al., 2005) [27] and also incorporated into Florida Activity Mobility Simulator (FAMOS) as a submodel (Pendyala, et al, 2005) [32].

Another example is the comprehensive econometric micro-simulator for daily activity-travel patterns (CEMDAP) (Bhat, 2004) [7]. which simulates the multi-level structure of activity pattern choice by applying multiple econometric models, each of which represents a different choice behavior. This model is later included as a submodel in SimAGENT (Goulias et al, 2012) [19], a comprehensive simulator of travel activities across a large-scale region.

According to Rasouli and Tinmmermans (2014) [33], econometric models, with some exceptions, tend to ignore the spatial-temporal constraints on a resultant travel-activity pattern. This means that they would simulate unrealistic patterns without consideration on those constraints. Thus, this limitation of econometric models calls for the development of Computational Process Models (CPMs), which enable taking into account other decisive factors in addition to utility.

2.2.3 Computational Process Models

In contrast to econometric models, CPMs focus on decision rules reflecting heuristics or constraints determining behavioral outcomes. Because these models attempt to "construct" activity patterns based on rules rather than to choose one from alternatives, these models are also called scheduling models or rule-based models.

SCHEDULER (Gärling, 1989) [18] is the first reported ABM that aims to simulate the activity scheduling process; however, it only proposes a conceptual framework and no practically applicable system. AMOS (Kitamura, 1998) [26] models travel behavior as a response to changes in circumstances. It assumes the travel-activity pattern change as a scheduling process in which the initial activity pattern is modified in the following steps. SMASH (Ettema et al, 2007) [13] in this category utilizes a utility-maximization framework as well as heuristics. In the sense of application of heuristics, some of the econometric models also can be regarded as CPMs depending on their process system.

Others, such as ALBATROSS (a learning-based transportation-oriented simulation system) (Artentz and Timmermans, 2004) [4] and TASHA (Roorda et al., 2008)[39], can be said to be data-oriented models in that they take advantage of the characteristics of observed activity diary data. The outstanding feature of ALBATROSS is that, for each decision step of scheduling, it applies choice heuristics represented by decision-trees derived from observed data of an activity diary survey. Seminal work has been presented expanding the model capability, such as destination choice, activity allocation, and uncertainty analysis (Rasouli and Tinmmermans, 2014) [33]. TASHA generates an activity pattern by sampling and scheduling activity agendas from their attributes' probability distribution estimated on observed data. It then plans an activity pattern in the following scheduling process based on some heuristics.

Despite that CPMs specifically describe decision processes, their limitation is that they need to rely on *ad hoc* or *a priori* rules which, in most instances, are unobservable to researchers and hard to validate. To relax this limitation, Agent-based Dynamic Activity Planning and Travel Scheduling (ADAPTS) (Auld, 2012) [5] attempts to model the activity planning and scheduling process as a dynamic, rather than as a fixed, system. Since it assumes a decision is made at each time step of the simulation, it does not only construct an activity schedule but also allows for rescheduling behavior.

2.2.4 Mathematical Programming Models

The mathematical programing model also could be categorized into the first group in the literature because it also assumes utility maximization behavior in travelers' decision making. However, differing from the econometric models, it does not require enumerating choice alternative sets. The advantage of mathematical programing is its descriptive ability in temporal-spatial constraints, as well as in the decision process of a travel-activity pattern. Instead of using heuristics, mathematical formulations rigorously describe those constraints.

The representative model for this category is the Household Activity Pattern Problem (HAPP) proposed by Recker (1995) [35]. Since HAPP simultaneously solves both the household travel pattern and vehicle routing problem, the model has outstanding potential for the desired evaluation framework for AVs which can travel independently from their drivers. Accordingly, this thesis proposes such a framework to assess the viability of AVs in households based on HAPP; correspondingly, the following section will discuss this HAPP development in detail.

2.3 Development of HAPP

Although HAPP is formulated as a mathematical programming model as stated above, it is specifically regarded as a network-based model, similar to the shortest-path problem. It is designed to have capability of considering spatial-temporal constraints and representing regarding both continuous (i.e. time) and discrete (i.e. transportation mode and location) choices. The solution of HAPP simultaneously gives optimal solutions to the travel-activity pattern scheduling and vehicle routing problems based on utility maximization principles.

In other words, it directly illustrates activity-paths of a household and vehicle trajectories in time-space. Recker (1995) [35] proposed the method by building on the pick-up and delivery problem with time window constraints (PDPTW) specified by Solomon and Desrosiers (1988) [40]. Later, Recker (2001) [36] showed the relationship between HAPP and conventional trip-based models and proposed a parameter estimation process for HAPP analogous to other travel behavioral theories such as discrete choice models. Several studies have been conducted to extend HAPP's capability. For example, stochastic HAPP (SHAPP) whose solution considers the probabilities that an activity is not be realized and the rescheduling process that can occur after the execution of a pattern was proposed by Gan and Recker (2008) [16] and (2013) [17]. Kang and Recker (2013) [24] extend the HAPP framework to incorporate an activity location choice behavior model called location selection problem (LSP-HAPP) that allows agents in the problem to choose a location from alternatives in a same activity category.

Since HAPP is defined as a mixed integer linear problem (MILP), it has an objective function that represents the (dis)utility of a travel-activity pattern for a household. The objective function can include several terms which expresses multiple aspects of the pattern. The weights of these terms are essential to determine the solution (i.e. an optimal travel-activity pattern)—presumed to be one that replicates the observed pattern. As for the estimation technique for the weight of each term in an objective function, Recker et al. (2008) [34] present an estimation framework applying multi-dimensional alignment method (MDSAM) and genetic algorithm (GA). Chow and Recker (2012) [12] present an estimation process for the weights by the inverse optimization technique. Based on this method, Kang et al. (2013) [23] formulate an activity-based network design problem (NDP) as a bi-level problem with two layers: NDP (upper) and HAPP (lower). Xu et al. (2017) [41] propose an estimation method for the parameters in the objective function for HAPP based on a random utility framework. The method uses HAPP to generate travel-activity patterns and personalizes them to construct an alternative choice set for a mixed-logit model.

To enhance the ability of simulating mode choice behavior in the HAPP framework, Chow and Djavadian (2015) [11] develop the multimodal HAPP (mHAPP) and apply it to enumerate an alternative choice set for a mixed logit model that represents an activity scheduling process. Although mHAPP succeeds in representing a multimodal transportation system, it does not model AVs. It is noteworthy that Khayati (2018) [25] proposes the first attempt to evaluate AVs among the HAPP family models. He develops the HAPPAV framework and further estimates the impacts of SAV. His approach is very similar to that of this study; however, the HAPPAV is formulated only to simulate a situation where only AVs are available. Moreover, it does not assume that agents in the simulation compare AVs to other transportation modes and combine them to achieve a more efficient travel-activity pattern. As mentioned above, HAPP has probably received the most intensive attention as a foundation for explaining complex travel behavior among existing activity-based models. These extensions have been aimed at incorporating multiple aspects of travel behaviors such as rescheduling process and destination choice. Moreover, several methods to estimate parameters of the objective function have been developed. Some studies enhance the multimodality of the HAPP framework in addition to CVs, but none of them intends to evaluate AVs in the existences of other transportation modes. This research namely aims to develop a framework which evaluates a household's AV adoption by describing the comparison between CV and AV. Further, it attempts to illustrate travel-activity patterns in multimodal transportation systems with AVs by changing the concept of the problem and reformulating it.

Chapter 3

HAPP formulation

3.1 The General Formulation and Concept of HAPP

The initial formulation of HAPP by Recker (1995) [35] models the generation process of household travel-activity patterns as a routing problem in which vehicles and household members are required to "pick up" activities distributed over space and to ultimately "deliver" them to their home following an optimal set of travel-activity paths. This problem is expressed as a MILP; the general mathematical form of HAPP for household i during a certain time period is expressed as

$$\min \quad Z = \boldsymbol{b}' \cdot \boldsymbol{X} \tag{O1}$$

subject to

$$\boldsymbol{A}\boldsymbol{X} \leq \boldsymbol{c}$$

where

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{X}^v \\ - \\ \boldsymbol{H} \\ - \\ \boldsymbol{T} \end{bmatrix}, \boldsymbol{X}^v, = \left[X^v_{uw} = \begin{cases} 0 \\ 1 \end{cases} \right], \boldsymbol{H}, = \left[H^j_{uw} = \begin{cases} 0 \\ 1 \end{cases} \right], \boldsymbol{T} = [T_u \geq 0],$$

$\boldsymbol{b}$ and $\boldsymbol{c}$ are vectors of real numbers, and $\boldsymbol{A}$ is a matrix of real numbers. The descriptions of the variables are listed below.

$\boldsymbol{b}$: A vector of coefficients determining the relative weight of each decision variable in the objective function.

X^v_{uw}: Binary decision variable equal to unity if vehicle v travels from activity u to activity w, and zero otherwise.

H^j_{uw}: Binary decision variable equal to unity if household member j travels from activity u to activity w, and zero otherwise.

T_u: The time at witch participation in activity u begins.

In this formulation, Z is regarded as the disutility of the household travel-activity pattern defined by the vector of decision variables. The optimal routes obtained by solving this problem is regarded as the most desirable travel-activity pattern during the time period.

I do not repeat specific terms for the objective function and constraints in detail here but note some of the assumptions employed by Recker (1995) [35]. The original formulation assumes the case of CVs; each vehicle is constrained to travel along with its driver and remains parked until an activity in which the driver participates ends. Also, more importantly, an activity is expressed as one pair of pick-up and delivery trips. Hence, the pick-up trip and the corresponding delivery trip to an activity must be done by an identical vehicle or member.

That is, each activity end (start or completion) can be accessed only by the same vehicle or household member.

3.2 Reformulation of HAPP

Alternatively, when a household member uses an AV for a trip to an activity, she may let her AV be used by others after arriving at the location but then requires it to pick her up after finishing the activity. From another point of view, the AV may not stay until its passenger ends an activity and, instead, may wander around to pick up and deliver other passengers while the activity is being executed. Furthermore, by utilizing AVs, a member can be delivered and picked up by different vehicles. According to these examples, in contrast to the previous HAPP assumption, an AV may access an activity location "twice", or different vehicles may access the same activity.

To represent the possible travel-activity pattern only realized by AVs, this research revises HAPP formulation by dividing one activity to two "pairs of pick-up and delivery" nodes (i.e. one from home to the activity location and the other from the activity location to home). Figure 3.1 illustrates the two different concepts regarding how to represent the execution of an activity in the original and revised HAPP frameworks.

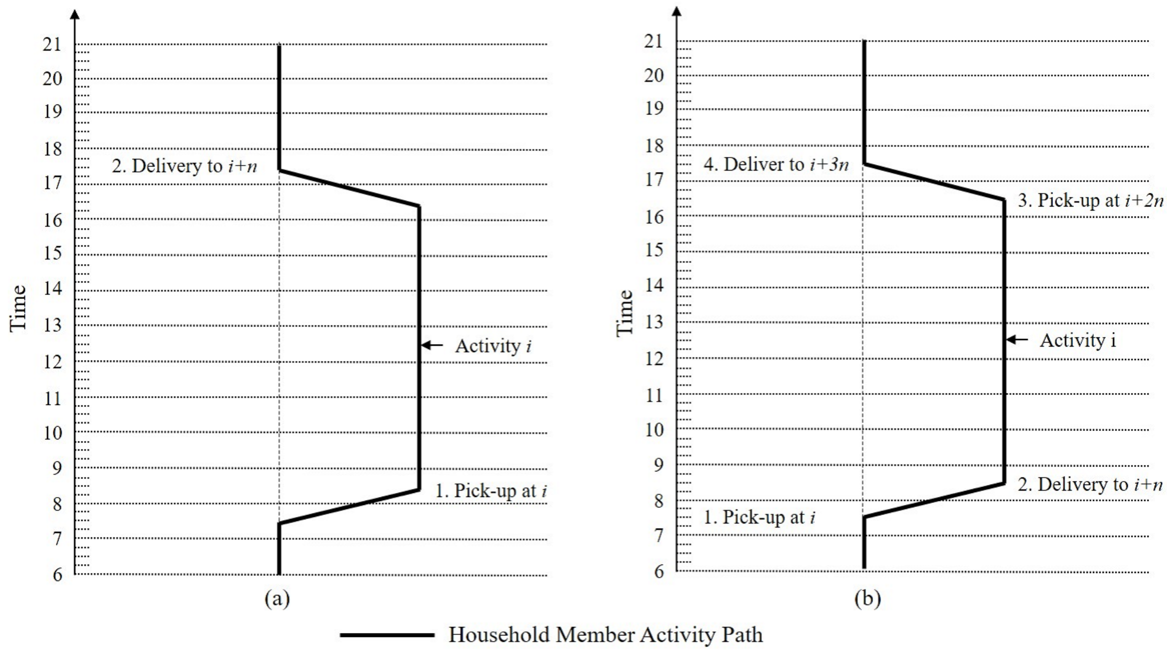

Figure 3.1: Conceptual representation of an activity execution in HAPP (a) Previous formulation (b) Revised formulation

This revision enables the problem to illustrate trips to and from an activity separately. For the new formulation for AVs, this study introduces the notations regarding activity locations below:

$V_c = \{1, 2, ..., v, ..., \lvert V_c\rvert\}$:	The set of conventional vehicles which serve travelers.
$V_a = \{\lvert V_c\rvert + 1, \lvert V_c\rvert + 2, ..., \lvert V_c\rvert + v, ..., \lvert V_c\rvert + \lvert V_a\rvert\}$:	The set of autonomous vehicles which serve travelers.
$V = V_c \cup V_a$:	The set of vehicles which serve travelers.
$\eta = \{1, 2, ..., j, ..., \lvert\eta\rvert\}$:	The set of household members.
$A = \{1, 2, ..., i, ..., n\}$:	The set of out-of-home activities scheduled to be completed by travelers in the household.

$\tilde{P}^{+} = \{1, 2, ..., i, ..., n\}$:	The set designating origin from which the trip for each activity departs. (It is noted that the physical location of each element of $\tilde{P}^{+}$ is each individual's home.)
$\tilde{P}^{-} = \{n+1, n+2, ..., n+i, ..., 2n\}$:	The set designating location at which each activity begins.
$\underset{\sim}{P}^{+} = \{2n+1, 2n+2, ..., 2n+i, ..., 3n\}$:	The set designating location at which each activity ends.
$\underset{\sim}{P}^{-} = \{3n+1, 3n+2, ..., 3n+i, ..., 4n\}$:	The set designating ultimate destination to which the return-to-home trip from each activity ends. (It is noted that the physical location of each element of $\underset{\sim}{P}^{-}$ is home.)
$P^{+} = \tilde{P}^{+} \cup \underset{\sim}{P}^{+}$:	The set of activity pick-up locations.
$P^{-} = \tilde{P}^{-} \cup \underset{\sim}{P}^{-}$:	The set of activity drop-off locations.
$P = P^{+} \cup P^{-}$:	The set of activity locations.
$N = \{0, P, 4n+1\}$:	The set of all nodes, including those associated with initial departure and final return to home.

This notation basically follows that of Solomon and Desrosiers (1988) [40], but classifies activity locations into four sets two of which are pick-up location sets and the others of which are delivery location sets. The trip(s) between pick-up location of activity $i \in \tilde{P}^{+}$ and delivery location of $i + n \in \tilde{P}^{-}$ corresponds to a trip to pick up (or access) activity i in the previous notation. Similarly, the delivery (or returning) trip of activity i to home trip is expressed as a pick-up and delivery trip(s) between location $i + 2n \in \underset{\sim}{P}^{+}$ and location

$i + 3n \in \underset{\sim}{P}^{-}$.

The rest of the notations for the reformulation are shown below:

$T_0^v, T_{4n+1}^v \quad v \in V$:	The times at which vehicle v first departs from its origin and finally arrives at its destination respectively.
$\bar{T}_0^j, \bar{T}_{4n+1}^j \quad v \in V$:	The times at which a household member j first departs from its origin and finally arrives at its destination respectively.
$[a_i, b_i]$:	The time window of available start times for activity i. (Note: b_i must precede the closing of the availability of activity i by an amount equal to or greater than the duration of the activity.)
$[a_{i+n}, b_{i+n}]$:	The time windows for the return-home arrival from activity i.
$[a_0, b_0]$:	The departure time window for the beginning of the travel day.
$[a_{4n+1}, b_{4n+1}]$:	The arrival time window by which time all members of the household must complete their travel.
$\bar{a}_0^j$:	The earliest possible departure time for household member j.
$\bar{b}_{4n+1}^j$:	The latest possible return home time for household member j
s_i:	The duration of activity i.
t_{uw}:	The travel time from the time-space location of activity u to the time-space location of activity w.
c_{uw}^v:	The travel cost from the time-space location of activity u to the time-space location of activity w by vehicle v.
Υ_i^v:	The total accumulation of passengers on vehicle v immediately following completion activity i.
Y_i^j:	The total accumulation of activities on a particular tour by household member j immediately following completion activity i.
d_i:	The demand function for activity i.
D^v:	The maximum number of passengers on vehicle v.

D^j:	The maximum number of sojourns in any tour by household member j.
Ω_ν^v:	The subset of activities that cannot be performed by vehicle/person v.
Ω_H^j:	The subset of activities that cannot be performed by household member j.

I note that they are the same as corresponding ones in preceding HAPP research except that the destination of the return home trip is denoted $4n+1$ due to the increase in the number of activity locations.

This change in the concept of HAPP also requires modifying some of the constraints used in the previous HAPP formulation, as well as, adding new ones. According to Recker (1995) [35], the constraints for HAPP mathematical programming are categorized into six groups: (1) temporal constraints on the vehicles, (2) temporal constraints on the household members performing the activities, (3) spatial connectivity constraints on the vehicles, (4) spatial connectivity constraints on the household members, (5) capacity, budget and participation constraints and (6) vehicle and household member coupling constraints. Based on this categorization, the following subsections describes the revised constraints. The constraints noted in this section apply only to CVs in the household; the constraint set considering AVs is introduced in the next chapter.

(1) Vehicle temporal constraints

The temporal constraints determine the participation time in each activity. They are determined by the order in which vehicles arrives at the activities. These constraints include time-window constrains as well. The constraints for the new formulation are

$$T_u + s_u + t_{u,u+n} \leq T_{u+n}, u \in P^+ \cup \tilde{P}^- \tag{C1.1}$$

$$T_u + s_u + t_{uw} - T_w \leq (1 - X^v_{uw})M, \forall u, w \in P, \forall v \in V \tag{C1.2}$$

$$T^v_0 + s_0 + t_{0,w} - T_w \leq (1 - X^v_{0,w})M, \forall w \in P^+, \forall v \in V \tag{C1.3}$$

$$T_u + t_{u,4n+1} - T^v_{4n+1} \leq (1 - X^v_{u,4n+1})M, \forall u \in P^-, \forall v \in V \tag{C1.4}$$

$$a_{u-n} \leq T_u \leq b_{u-n}, \forall u \in \tilde{P}^- \cup \underset{\sim}{P}^+ \tag{C1.5}$$

$$a^v_0 \sum_{w \in N} X^v_{0,w} \leq T^v_0 \leq b^v_0 \sum_{w \in N} X^v_{0,w}, \forall v \in V \tag{C1.6}$$

$$a^v_{4n+1} \sum_{w \in N} X^v_{0,w} \leq T^v_{4n+1} \leq b^v_{4n+1} \sum_{w \in N} X^v_{0,w}, \forall v \in V \tag{C1.7}$$

where M is a large number. The factor $\sum_{w \in N} X^v_{0,w}$ on both sides of (C1.6) and (C1.7) ensures vehicles' departure and arrival times not to affect the objective function in case that they are not used.

(2) Household member temporal constraints

These constraints work similar to the previous ones of vehicles to determine the activity participation times. The only difference is that they consider the household member's traveling order.

$$T_u + s_u + t_{uw} - T_w \leq (1 - H^j_{uw})M, \forall u, w \in P, \forall j \in \eta \tag{C2.1}$$

$$T^j_0 + s_0 + t_{0w} - T_w \leq (1 - H^j_{0w})M, \forall w \in \tilde{P}^+, \forall j \in \eta \tag{C2.2}$$

$$T_u + s_u + t_{u,4n+1} - \bar{T}^j_{4n+1} \leq (1 - H^j_{u,4n+1})M, \forall u \in \underset{\sim}{P}^-, \forall j \in \eta \tag{C2.3}$$

$$\bar{a}^j_0 \sum_{w \in N} H^j_{0,w} \leq \bar{T}^j_0 \leq M \sum_{w \in N} H^j_{0,w}, \forall j \in \eta \tag{C2.4}$$

$$\bar{T}^j_{4n+1} \leq \bar{b}^j_{4n+1} \sum_{w \in N} H^j_{0,w}, \forall j \in \eta \tag{C2.5}$$

Temporal constraints on vehicles and household members are almost identical to those of the previous formulation with some exceptions; for example, the final destination is indexed as $4n + 1$. It is also noted that, since the actual time of participation in activity u is T_{u+n}, constraint (C1.5) uses a_{u-n} and b_{u-n} instead of using u as subscript. Time window constraints (C2.4) and (C2.5) also makes $\bar{T}_0^j$ and $\bar{T}_{4n+1}^j$ zero, respectively, when household member j makes no trip.

(3) Spatial connectivity constraints on the vehicles

These constraints ensure that a vehicle to traverses a feasible path without any unnecessary trip:

$$\sum_{v \in V} \sum_{w \in N} X_{uw}^v = 1, \forall u \in P^+ \tag{C3.1}$$

$$\sum_{w \in N} X_{uw}^v - \sum_{w \in N} X_{wu}^v = 0, \forall u \in P, \forall v \in V \tag{C3.2}$$

$$\sum_{w \in P^+} X_{0,w}^v = 1, \forall v \in V \tag{C3.3}$$

$$\sum_{u \in P^-} X_{u,4n+1}^v = 1, \forall v \in V \tag{C3.4}$$

$$\sum_{w \in N} X_{wu}^v - \sum_{w \in N} X_{w,u+n}^v = 0, \forall u \in P^+, \forall v \in V \tag{C3.5}$$

$$\sum_{w \in P^- \cup \underset{\sim}{P}^+} X_{0,w}^v = 0, \forall v \in V \tag{C3.6}$$

$$\sum_{u \in N} X_{u,0}^v = 0, \forall v \in V \tag{C3.7}$$

$$\sum_{u \in P^+ \cup \tilde{P}^-} X_{u,4n+1}^v = 0, \forall v \in V \tag{C3.8}$$

$$\sum_{w \in N} X_{4n+1,w}^v = 0, \forall v \in V. \tag{C3.9}$$

In addition to the spatial restrictions defined by the constraints above, household members and vehicles must pick up the activities and deliver them by themselves in the modified formulation. These constraints are expressed as

$$\sum_{v \in V} X^v_{u,u+n} = 1, \forall \tilde{P}^-. \tag{C3.10}$$

Furthermore, the new formulation requires the constraints below so that the pick-ups and deliveries are done in an appropriate sequence:

$$\sum_{u \in \tilde{P}+} X^v_{u,2n+u} = 0, \forall v \in V \tag{C3.11}$$

$$\sum_{w \in \tilde{P}+} X^v_{2n+w,w} = 0, \forall v \in V \tag{C3.12}$$

$$\sum_{u \in \tilde{P}+} X^v_{u,3n+u} = 0, \forall v \in V \tag{C3.13}$$

$$\sum_{w \in \tilde{P}+} X^v_{3n+w,w} = 0, \forall v \in V \tag{C3.14}$$

$$\sum_{u \in \tilde{P}-} X^v_{u,2n+u} = 0, \forall v \in V \tag{C3.15}$$

$$\sum_{w \in \tilde{P}-} X^v_{2n+w,w} = 0, \forall v \in V \tag{C3.16}$$

$$\sum_{w \in \tilde{P}-} X^v_{n+w,w} = 0. \forall v \in V \tag{C3.17}$$

(4) Spatial connectivity constraints on the household members

In a similar manner to the spatial connectivity constraints on vehicles, these constraints ensure that travel paths of household members are feasible:

$$\sum_{j \in \eta} \sum_{w \in N} H^j_{uw} = 1, \forall u \in P^+ \tag{C4.1}$$

$$\sum_{w \in N} H^j_{uw} - \sum_{w \in N} H^j_{wu} = 0, \forall u \in P, \forall j \in \eta \tag{C4.2}$$

$$\sum_{w \in \tilde{P}^+} H^j_{0,w} = 1, \forall j \in \eta \tag{C4.3}$$

$$\sum_{u \in \underset{\sim}{P}^-} H^j_{u,4n+1} = 1, \forall j \in \eta \tag{C4.4}$$

$$\sum_{w \in N} H^j_{wu} - \sum_{w \in N} H^j_{w,u+n} = 0, \forall u \in P^+, \forall j \in \eta \tag{C4.5}$$

$$\sum_{j \in \eta} H^j_{u,u+n} = 1, \forall u \in \tilde{P}^- \tag{C4.6}$$

$$\sum_{w \in \underset{\sim}{P}^+ \cup P^-} H^j_{0,w} = 0, \forall j \in \eta \tag{C4.7}$$

$$\sum_{u \in N} H^j_{u,0} = 0, \forall j \in \eta \tag{C4.8}$$

$$\sum_{u \in P^+ \cup \tilde{P}^-} H^j_{u,4n+1} = 0, \forall j \in \eta \tag{C4.9}$$

$$\sum_{u \in N} H^j_{4n+1,w} = 0, \forall j \in \eta \tag{C4.10}$$

While the meanings of most of the connectivity constraints have been unchanged from the original formulation, constraint (C4.7) prevent members from accessing not only delivery locations but also pick-up location set $\underset{\sim}{P}^+$ from home. Constraint (C4.8) likewise prohibits home return trip from delivery location set $\tilde{P}^-$ as well as pick-up location sets. Moreover, for the same reason as the additional constraints on vehicles, the constraints below are added.

$$\sum_{u \in \tilde{P}^+} H^j_{u,2n+u} = 0, \forall j \in \eta \tag{C4.11}$$

$$\sum_{w \in \tilde{P}^+} H^j_{2n+w,w} = 0, \forall j \in \eta \tag{C4.12}$$

$$\sum_{u \in \tilde{P}^+} H^j_{u,3n+u} = 0, \forall j \in \eta \tag{C4.13}$$

$$\sum_{w \in \tilde{P}^+} H^j_{3n+w,w} = 0, \forall j \in \eta \tag{C4.14}$$

$$\sum_{u \in \tilde{P}^-} H^j_{u,2n+u} = 0, \forall j \in \eta \tag{C4.15}$$

$$\sum_{w \in \tilde{P}^-} H^j_{2n+w,w} = 0, \forall j \in \eta \tag{C4.16}$$

$$\sum_{w \in \tilde{P}^-} H^j_{n+w,w} = 0, \forall j \in \eta \tag{C4.17}$$

$$\sum_{w \in \underset{\sim}{P}^-} H^j_{uw} = 0, \forall j \in \eta, \forall u \in \tilde{P}^+ \tag{C4.18}$$

(5) Capacity budget and participation constraints

These constraints describe the numbers of activities or passengers that a household member or a vehicle, respectively, can hold at a time. Those for household members are

$$H^j_{uw} = 1 \Rightarrow Y^j_u + d_w = Y^j_w, \forall j \in \eta, u \in P, w \in \tilde{P}^+ \tag{C5.1}$$

$$H^j_{uw} = 1 \Rightarrow Y^j_u - d_{w-n} = Y^j_w, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^- \tag{C5.2}$$

$$H^j_{uw} = 1 \Rightarrow Y^j_u = Y^j_w, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^+ \cup \tilde{P}^- \tag{C5.3}$$

$$H^j_{0w} = 1 \Rightarrow d_w = Y^j_w, \forall j \in \eta, \forall w \in \tilde{P}^+ \tag{C5.4}$$

$$0 \le Y^j_u \le D^j, \forall j \in \eta, \forall u \in P^+. \tag{C5.5}$$

The first four of these are rewritten as

$$Y^j_u + d_w - Y^j_w \le (1 - H^j_{uw})M, \forall j \in \eta, u \in P, w \in \tilde{P}^+ \tag{C5.1a}$$

$$Y^j_u + d_w - Y^j_w \ge (H^j_{uw} - 1)M, \forall j \in \eta, u \in P, w \in \tilde{P}^+ \tag{C5.1b}$$

$$Y^j_u - d_{w-n} - Y^j_w \le (1 - H^j_{uw})M, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^-, \tag{C5.2a}$$

$$Y^j_u - d_{w-n} - Y^j_w \ge (H^j_{uw} - 1)M, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^-, \tag{C5.2b}$$

$$Y_u^j - Y_w^j \leq (1 - H_{uw}^j)M, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^+ \cup \tilde{P}^-, \tag{C5.3a}$$

$$Y_u^j - Y_w^j \geq (H_{uw}^j - 1)M, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^+ \cup \tilde{P}^-, \tag{C5.3b}$$

$$d_w - Y_w^j \leq (1 - H_{0,w}^j)M, \forall j \in \eta, w \in \tilde{P}^+ \tag{C5.4a}$$

$$d_w - Y_w^j \geq (H_{0,w}^j - 1)M, \forall j \in \eta, w \in \tilde{P}^+. \tag{C5.4b}$$

Those on vehicles are a little more complicated because, under the formulation in this thesis, vehicles do not always pick up a passenger when they pick up an activity. They are only restricted to pick up a household member when they start a trip; that is, when they make a non-zero distance trip. This condition is ensured by the constraints below:

$$X_{uw}^v = 1 \Rightarrow \begin{cases} \Upsilon_u^v + d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{u'\in N} t_{wu'}H_{wu'}^j > 0 \text{ or } w \in \underset{\sim}{P}^+ \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^+ \tag{C5.6}$$

$$X_{uw}^v = 1 \Rightarrow \begin{cases} \Upsilon_u^v - d_{w-n} = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{u'\in N} t_{wu'}H_{wu'}^j > 0 \text{ or } w \in \tilde{P}^- \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^- \tag{C5.7}$$

$$X_{0w}^v = 1 \Rightarrow \begin{cases} d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N} t_{w\tilde{u}}H_{w\tilde{u}}^j > 0 \\ 0 = \Upsilon_w^v & \text{otherwise} \end{cases}, \forall v \in V, \forall w \in \tilde{P}^+ \tag{C5.8}$$

$$0 \leq \Upsilon_u^v \leq D^v, \forall v \in V, \forall u \in P^+. \tag{C5.9}$$

The additional condition $\sum_{j\in\eta}\sum_{\tilde{u}\in N} t_{w\tilde{u}}H_{w\tilde{u}}^j > 0$ ensures that a vehicle is required to pick up a passenger when picking up an activity w where the passenger starts a non-zero distance trip. Accordingly, the first five of these should be rewritten as

$$\Upsilon_u^v + d_w \cdot \left(1 - \mathbb{1}\left\{\sum_{j\in\eta}\sum_{u'\in N} t_{wu'} H_{wu'}^j = 0\right\}\right) - \Upsilon_w^v \leq (1 - X_{uw}^v)M, \quad \forall v \in V, \forall u \in P, \forall w \in \tilde{P}^+, \tag{C5.6a}$$

$$\Upsilon_u^v + d_w \cdot \left(1 - \mathbb{1}\left\{\sum_{j\in\eta}\sum_{u'\in N} t_{wu'} H_{wu'}^j = 0\right\}\right) - \Upsilon_w^v \geq (X_{uw}^v - 1)M, \quad \forall v \in V, \forall u \in P, \forall w \in \tilde{P}^+, \tag{C5.6b}$$

$$\Upsilon_u^v + d_w - \Upsilon_w^v \leq (1 - X_{uw}^v)M, \forall v \in V, \forall u \in P, \forall w \in \underset{\sim}{P}^+, \tag{C5.6c}$$

$$\Upsilon_u^v + d_w - \Upsilon_w^v \geq (X_{uw}^v - 1)M, \forall v \in V, \forall u \in P, \forall w \in \underset{\sim}{P}^+, \tag{C5.6d}$$

$$\Upsilon_u^v - d_{w-n} \cdot 1 \left(1 - \mathbb{1}\left\{\sum_{j\in\eta}\sum_{u'\in N} t_{wu'} H_{wu'}^j = 0\right\}\right) - \Upsilon_w^v \leq (1 - X_{uw}^v)M, \quad \forall v \in V, \forall u \in P, \forall w \in \underset{\sim}{P}^-, \tag{C5.7a}$$

$$\Upsilon_u^v - d_{w-n} \cdot 1 \left(1 - \mathbb{1}\left\{\sum_{j\in\eta}\sum_{u'\in N} t_{wu'} H_{wu'}^j = 0\right\}\right) - \Upsilon_w^v \geq (X_{uw}^v - 1)M, \quad \forall v \in V, \forall u \in P, \forall w \in \underset{\sim}{P}^-, \tag{C5.7b}$$

$$\Upsilon_u^v - d_w - \Upsilon_w^v \leq (1 - X_{uw}^v)M, \forall v \in V, \forall u \in P, w \in \tilde{P}^- \tag{C5.7c}$$

$$\Upsilon_u^v - d_w - \Upsilon_w^v \geq (X_{uw}^v - 1)M, \forall v \in V, \forall u \in P, w \in \tilde{P}^- \tag{C5.7d}$$

$$d_w \cdot \left(1 - \mathbb{1}\left\{\sum_{j\in\eta}\sum_{\tilde{u}\in N} t_{w\tilde{u}} H_{w\tilde{u}}^j = 0\right\}\right) - \Upsilon_w^v \leq (1 - X_{0,w}^v)M, \forall v \in V, \forall w \in \tilde{P}^+ \tag{C5.8a}$$

$$d_w \cdot \left(1 - \mathbb{1}\left\{\sum_{j\in\eta}\sum_{\tilde{u}\in N} t_{w\tilde{u}} H_{w\tilde{u}}^j = 0\right\}\right) - \Upsilon_w^v \geq (X_{0,w}^v - 1)M, \forall v \in V, \forall w \in \tilde{P}^+ \tag{C5.8b}$$

where $\mathbb{1}\{\ \cdot\}$ equals unity if the expression in the braces is true and zero otherwise.

Participation constraints below prevent vehicles or household members from executing predetermined sets of activities.

$$\sum_{u \in N} \sum_{w \in \Omega_{\nu}^{v}} X_{uw}^{v} = 0, \forall v \in V \tag{C5.10a}$$

$$\sum_{u \in N} \sum_{w \in \Omega_{\nu}^{v}} X_{u,w+2n}^{v} = 0, \forall v \in V \tag{C5.10b}$$

$$\sum_{u \in N} \sum_{w \in \Omega_{H}^{j}} H_{uw}^{j} = 0, \forall j \in \eta \tag{C5.11a}$$

$$\sum_{u \in N} \sum_{w \in \Omega_{H}^{j}} H_{u,w+2n}^{j} = 0, \forall j \in \eta \tag{C5.11b}$$

Constraints (C5.10b) and (C5.11b) are necessary to forbid picking up an undelivered activity.

(6) Vehicle and household member coupling constraints

In previous HAPP formulations, coupling constraints ensure that a household member and a vehicle travel simultaneously. However, the revised formulation allows AVs to travel with no passenger. However, a household member still has to move together with a vehicle, and a CV also needs a driver.

Additionally, the original version of HAPP assumes that all activities are picked up out of home; thus, all of the trips have non-zero distance which requires vehicles and household members travel together. Alternatively, it is possible that the new formulation induces zero-distance trips because activities are generally picked up at home at first; for example, from home (0) to pick-up locations ($\tilde{P}^{+}$). For non-zero distance trips, we do not have to impose coupling constraints on household members.

These complications no longer allow using the same coupling constraints as in the original formulation of HAPP. To construct new coupling constraints, it is assumed that people need to use a vehicle for trips with non-zero travel time. Mathematically, such a constraint for household members are expressed as

$$H_{uw}^{j} = 1 \text{ and } t_{uw} > 0 \Rightarrow \sum_{v \in V} X_{uw}^{v} = 1, \forall j \in \eta, \forall u, w \in P, \tag{C6.1}$$

and, that for vehicles is

$$X_{uw}^{v} = 1 \text{ and } t_{uw} > 0 \Rightarrow \sum_{j \in \eta} H_{uw}^{j} = 1, \forall v \in V, \forall u, w \in P. \tag{C6.2}$$

More practically, they can be rewritten as

$$\sum_{v \in V} X_{uw}^{v} - 1 \leq (1 - H_{uw}^{j})M + \frac{1}{Mt_{uw} + m}, \forall j \in \eta, \forall u, w \in P, \tag{C6.1a}$$

$$\sum_{v \in V} X_{uw}^{v} - 1 \geq (H_{uw}^{j} - 1)M - \frac{1}{Mt_{uw} + m}, \forall j \in \eta, \forall u, w \in P, \tag{C6.1b}$$

$$\sum_{j \in \eta} H_{uw}^{j} - 1 \leq (1 - X_{uw}^{v})M + \frac{1}{Mt_{uw} + m}, \forall v \in V, \forall u, w \in P, \tag{C6.2a}$$

$$\sum_{j \in \eta} H_{uw}^{j} - 1 \geq (X_{uw}^{v} - 1)M - \frac{1}{Mt_{uw} + m}, \forall v \in V, \forall u, w \in P, \tag{C6.2b}$$

where m is a small number such as 0.00001.

Next, the constraints below ensure that at least one vehicle is dispatched whenever household members make trips from their home.

$$\sum_{v \in V} \sum_{w \in P} X_{0,w}^{v} \leq \sum_{j \in \eta} \sum_{w \in P} H_{0w}^{j} \tag{C6.3}$$

$$\sum_{v \in V} \sum_{w \in P} X_{0,w}^{v} \geq \sum_{j \in \eta} \sum_{w \in P} H_{0w}^{j} - \eta + 1 \tag{C6.4}$$

Note that a vehicle is assumed to be able to accommodate only one passenger at this point of the study.

3.3 An Example to Validate the Revised Formulation

To show that the new formulation is comparable to the original HAPP, this section shows an example based on the same parameters used in the original study (Recker, 1995) [35].

Case 1: A Household with two CVs (Replication of case 4B in Recker (1995) with the new formulation)

First, to verify the proposed formulation, case 4B in the former study (Recker, 1995) [35] is replicated as a base situation. This case simulates travel-activity patterns of a household of two members owning two conventional vehicles. There are three activity out-of-home activity locations ($i = 1, 2, 3$). The parameters for this example are shown in the appendix.

The objective function for this case is

$$\min Z = \sum_{v \in V} \sum_{u \in N} \sum_{w \in N} c_{uw} X_{uw}^{v} + \sum_{u \in \tilde{P}^{-}} (T_{u+n} - T_{u}) + \sum_{v \in V} (T_{4n+1}^{v} - T_{0}^{v}) + \sum_{v \in V} \sum_{w \in P^{+}} K X_{0,w}^{v} \quad \text{(O2)}$$

where $K = 100$, which is the same value as used in the original study by Recker (1995) [35].

Figure 3.2 shows the resultant optimal travel-activity pattern for the household obtained by utilizing ILOG CPLEX. I note that the starting and ending times of activity 2 are different from those in the corresponding case in the former study because the time-window constraints allows for arbitrariness in departure time as long as the pattern satisfies the temporal constraints; nevertheless, the solution has the same value of the objective function.

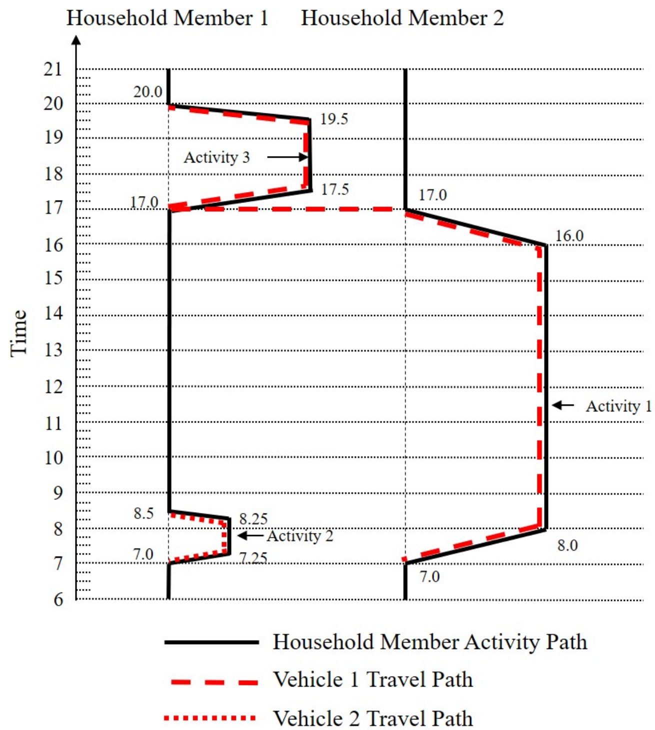

Figure 3.2: Travel-Activity Pattern for Case 1 (with two CVs)

Chapter 4

Extending HAPP to Facilitate Evaluation of AVs

4.1 An Extension and Example to Represent AVs

This section presents an extension to the reformulated HAPP model to simulate travel-activity patterns in which an AV is introduced to a household. The remaining sections of this chapter evaluate the viability of AVs based on this extension.

Case 2: A Household with only an AV

Case 2 considers a simple situation in which an AV has replaced the two CVs in the same household as in case 1. Since an AV travels more flexibly than a CV, it is necessary to relax some of the constraints as well as to include additional ones to the original formulation. Even if this AV is used by one household member, for example, it can travel to pick up the other member without waiting for the first one to finish an activity.

(1) Vehicle temporal constraints

First, since AVs do not have to stay and might immediately depart somewhere to pick up another passenger even after it delivers a passenger to an activity location, temporal window constraint (C1.2) is rewritten as

$$T_u + t_{uw} - T_w \leq (1 - X^v_{uw})M, \forall u, w \in P, \forall v \in V_a, \tag{C1.2'}$$

which does not consider the duration of delivered activity u.

(3) Spatial connectivity constraints on the vehicles

Next, if delivered by an AV, a household member is not necessarily picked up by the same one after she completes an activity. Therefore, we add a constraint

$$\sum_{v \in V} \sum_{w \in N} X^v_{wu} - \sum_{v \in V} \sum_{w \in N} X^v_{w,u+n} = 0, \forall u \in \tilde{P}^-. \tag{C3.18}$$

As the last extension for this case, AVs can not only pick up an activity at home but also a completed activity out of home. Similarly, they can return home just after delivering an activity to be executed. Hence, for AVs, the constraints (C3.6) and (C3.8) are replaced with

$$\sum_{w \in P^-} X^v_{0,w} = 0, \forall v \in V_a, \tag{C3.6'}$$

$$\sum_{u \in P^+} X^v_{u,4n+1} = 0, \forall v \in V_a. \tag{C3.8'}$$

In addition, to allow AVs to be free to make a trip while its passenger is participating in activity, constraint (C3.10) and (C6.2) are not required for AVs.

An illustrative example for the extension in this case uses the same parameters as those in

Case 1, except that the household is limited to have only one AV (and no CVs). Additionally, AVs and household members do not have to either start or complete activities for the travel day at the same time. Thus, the objective function is redefined as

$$\begin{aligned}\min Z = &\sum_{v\in V}\sum_{u\in N}\sum_{w\in N} c_{uw}X_{uw}^{v} + \sum_{u\in\tilde{P}^-}(T_{u+n}-T_u) + \sum_{v\in V}(T_{4n+1}^{v}-T_0^{v}) \\ &+\sum_{v\in V}\sum_{w\in P^+} KX_{0,w}^{v} + \sum_{j\in\eta}(\bar{T}_{4n+1}^{j}-\bar{T}_0^{j})\end{aligned} \tag{O3}$$

whose last term represents the total temporal extent of activities of household members in the travel day.

Figure 4.1 shows the result for this problem. It illustrates that the AV first delivers member 2 to activity 1 but does not stay there so as to autonomously pick up member 1 and deliver him to activity 2 and 3. After member 1 completes his activities and returns to home, the AV finally goes to pick up member 2 without a driver and then deliver her to their home. In contrast to the previous case, this extension successfully depicts the characteristic of an AV.

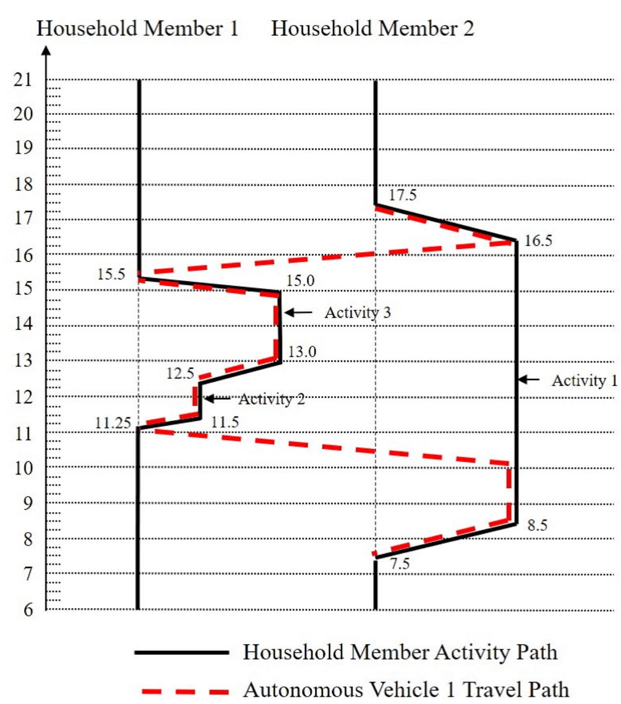

Figure 4.1: Travel-Activity Pattern for Case 2 (with one AV)

4.2 Examples to Analyze the Viability of AV

The former two examples verify the new formulation's capability of depicting a travel-activity patterns for a household with a CV or AV; this section assesses the validity of the proposed framework on the economic viability analysis for AV.

Case 3: A household choosing either CVs or an AV

When AVs become practically available, households will face the choice of purchasing either a CV or an AV. They might, furthermore, consider purchase of an AV in lieu of any existing CVs. To analyze these choices, this case considered in this section simulates a situation in which the household with two members has an option; i.e., replacing their CVs with an AV. As we see in the case 2, a CV and an AV may lead to different "optimal" travel patterns even if the household members execute the same activity sets. An AV is presumed to enable the household to have more convenient activity patterns than a CV, notwithstanding that an AV, perhaps the most innovative transportation mode in a century, should be more expensive than a CV. Additionally, an AV's convenience might mean more distance traveled by autonomous pick-up trips and result in a higher expenditure for traveling. Therefore, to decide which vehicle to buy, the household will likely compare the cost of possessing CVs to that of an AV, taking into account their probable travel miles.

First, let us suppose a household comparing one CV to one AV. Since HAPP can simulate household activity patterns within a day, this analysis uses the vehicles' cost per mile and cost per day for the comparison. A household considers the relative value of AV to CV; thus, its comparison is based on the ratios of the two costs of AV over those of CV. By changing AV's cost while fixing the operating costs of CV, we evaluate the household's travel-activity pattern and choice of vehicle under several values of the two ratios.

The objective function is again modified for the purpose of the viability analysis. First, since the previous examples do not consider traveling distance but only time, it is necessary to assume average travel speed in the following analysis. Thus, the first term of (O2) is replaced with

$$\sum_{v \in V_c} \sum_{u \in N} \sum_{w \in N} c_c v_{\text{ave}} t_{uw} X_{uw}^v + \sum_{v \in V_a} \sum_{u \in N} \sum_{w \in N} c_a v_{\text{ave}} t_{uw} X_{uw}^v$$

where c_c and c_a are the costs per mile for CV and AV, respectively, and v_{ave} the average vehicle speed. In addition, the last term of (O2) is replaced with

$$\sum_{v \in V_c} \sum_{w \in P^+} K_c X_{0,w}^v + \sum_{v \in V_a} \sum_{w \in P^+} K_a X_{0,w}^v$$

where K_c is the ownership cost of a CV, and K_a is that of an AV. Consequently, we have

$$\begin{aligned} \min Z = & \sum_{v \in V_c} \sum_{u \in N} \sum_{w \in N} c_c v_{\text{ave}} t_{uw} X_{uw}^v + \sum_{v \in V_a} \sum_{u \in N} \sum_{w \in N} c_a v_{\text{ave}} t_{uw} X_{uw}^v + \sum_{u \in \tilde{P}^-} (T_{u+n} - T_u) \\ & + \sum_{v \in V} (T_{4n+1}^v - T_0^v) + \sum_{v \in V_c} \sum_{w \in P^+} K_c X_{0,w}^v + \sum_{v \in V_a} \sum_{w \in P^+} K_a X_{0,w}^v + \sum_{j \in \eta} (\bar{T}_{4n+1}^j - \bar{T}_0^j) \end{aligned} \tag{O4}$$

for the objective function.

To make the situation realistic, the values for the parameters are specified as below:

- Cost per mile c_c: 16.97 cents (Medium Sedan) [1]
- Cost per day K_c: \$15.41 (Medium Sedan) [1]
- Average speed: v_{ave} : 28.87 miles/h (Private Vehicle Average Commute Speed) [3]

This case also follows the same parameters used in the previous examples but allows for choices of two types of vehicles; i.e., vehicles are allowed to be "unchosen" if they do not comport to the optimal activity pattern. Then, constraints (C3.3) and (C3.4) are relaxed as

$$\sum_{w \in P^+} X^v_{0,w} \leq 1, \forall v \in V \tag{C3.3'}$$

$$\sum_{u \in P^-} X^v_{u,4n+1} \leq 1, \forall v \in V. \tag{C3.4'}$$

Moreover, since CVs might not be used to visit all the activities, constraint (C3.10) is modified to be

$$\sum_{v \in V_c} X^v_{u,u+n} \leq 1, \forall \tilde{P}^-. \tag{C3.10'}$$

Figure 4.2 shows an optimal travel-activity pattern with one CV. The other pattern with one AV is exactly the same as in case 2. This result indicates that having one CV leads to the household having a different activity pattern from that with by an AV.

The household chooses either of the two travel-activity patterns depending on AV's costs. Figure 4.3 plots the set of decision switching points for the household to choose either a CV or an AV. For the combination of the ratios below the line, the household would choose to have an AV and vice versa. Although the pattern of CV has fewer travel miles than that of AV, the cost per day of AV can be about 1.4 times as high as CV's keeping AV to be a feasible alternative mode for the household when fixing cost per mile ratios at 1. The reason for the household preferring an AV is that household member 1 has longer travel day in order to complete all the activities assigned to him with only a CV than with a single AV in the household. However, it should be noted that the weight of this out-of-home time term is predefined, meaning that it is arbitrary relative to the cost parameters.

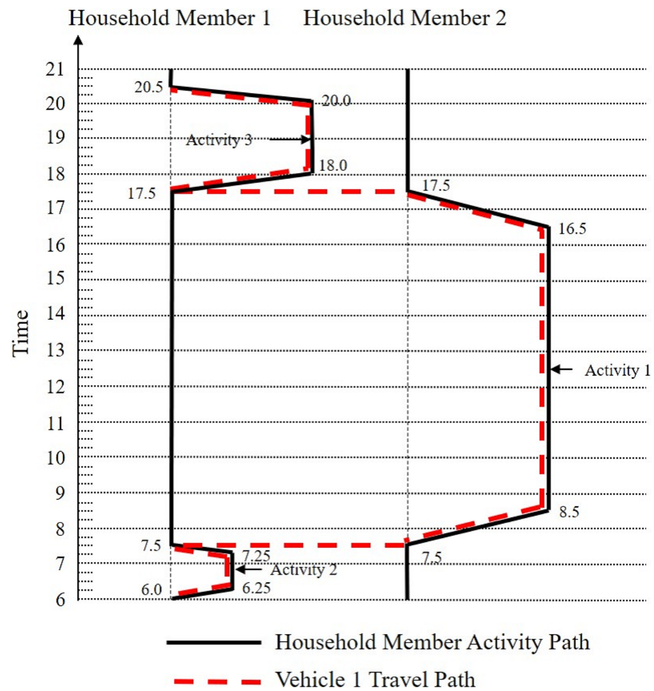

Figure 4.2: Travel-Activity Pattern for Case 3A (with one CV)

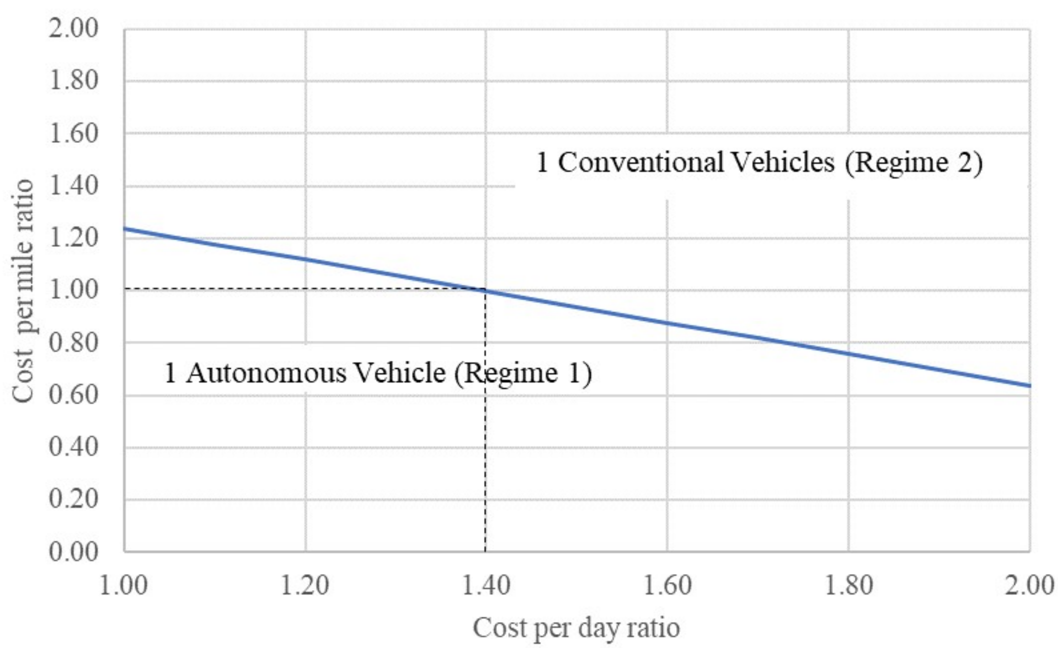

Figure 4.3: Plot of Decision Switching Points Regarding Vehicle Costs for Case 3A

The next case study assumes the same household choosing either two CVs or one AV under the combinations of different ratios of the two costs. To make the activity pattern unavailable for one CV but possible for two CVs, this case modifies the activity time window constraints on activities 2 and 3 to be

$$[a_2, b_2] = [10, 21], [a_3, b_3] = [12, 13].$$

Figure 4.4 illustrates the optimized travel-activity pattern with two CVs. The pattern with one AV is the same as the previous two cases. Contrary to case 3A, household members have the same activity patterns in both situations.

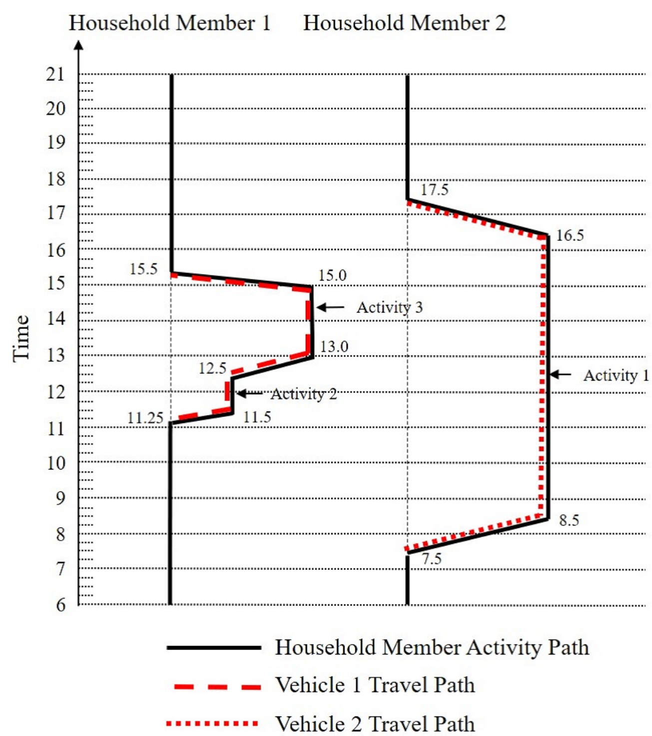

Figure 4.4: Travel-Activity Pattern for Case 3B (with two CVs)

Figure 4.5 similarly plots a set of decision switching points between the two patterns above. When cost per mile ratio is one, the threshold of cost per day ratio is around 1.64, which is not twice as large as 1.4 in Case 3A. This ratio is slightly higher than that in case 3A because, even though AV's cost per day is half of the cost of CV, total miles traveled of AV are longer. Furthermore, since the optimal travel-activity patterns of the household members are identical in both of the regimes, owning two CVs is more advantageous to having one CV in that they can offer more convenience in activity participation time, resulting in lowering term $\sum_{j\in\eta}(\bar{T}^j_{4n+1} - \bar{T}^j_0)$ in the objective function. This fact also reduces the difference in the cost per day ratio between case 3A and 3B.

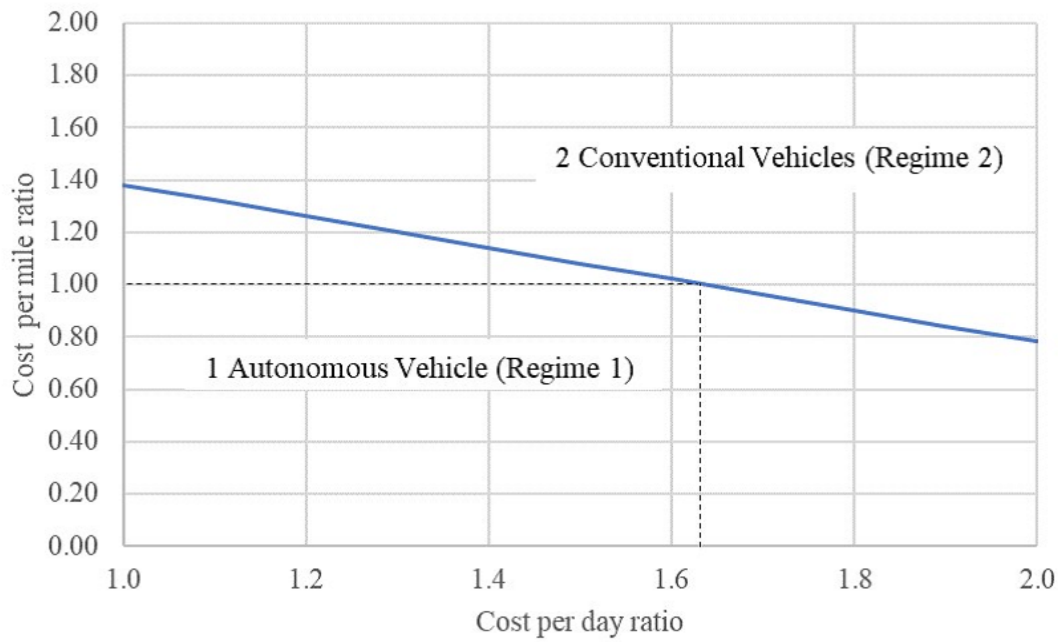

Figure 4.5: Plot of Decision Switching Points Regarding Vehicle Costs for Case 3B

Case 4: A household with an AV and discretionary parking alternatives

An AV can be idle and parked somewhere if its next trip is to pick up a household member at completion of an activity occurring at the place where it is parked. In such a case, it is reasonable for the owner to assign a better place for his AV to stay because AVs may automatically travel to a less expensive parking lot than that of the place in which the activity is being performed. In this example, an AV traveling to this inexpensive parking lot is regarded to participate in a "discretionary" activity resulting from a choice of parking that depends on the parking cost.

Modeling discretionary activities

To represent the parking behavior of AVs, this case first describes how the HAPP framework represents discretionary activities in general. First, to differentiate activities, decompose activity nodes $P = P_M \cup P_D$ where P_M and P_D represent sets of mandatory and discretionary activities, respectively. Furthermore, there can be two types of discretionary activity: (1) an activity which a vehicle must complete or (2) an activity which a household member must complete. Let us respectively denote the node sets for these two types P_{D_1} and P_{D_2}. Accordingly, the node sets introduced in Chapter 3 are now expressed as

$$
\begin{aligned}
&\tilde{P}^+ = \tilde{P}^+_M \cup \tilde{P}^+_D = \tilde{P}^+_M \cup \tilde{P}^+_{D_1} \cup \tilde{P}^+_{D_2} \\
&\tilde{P}^- = \tilde{P}^-_M \cup \tilde{P}^-_D = \tilde{P}^-_M \cup \tilde{P}^-_{D_1} \cup \tilde{P}^-_{D_2} \\
&\underset{\sim}{P}^+ = \underset{\sim}{P}^+_M \cup \underset{\sim}{P}^+_D = \underset{\sim}{P}^+_M \cup \underset{\sim}{P}^+_{D_1} \cup \underset{\sim}{P}^+_{D_2} \\
&\underset{\sim}{P}^- = \underset{\sim}{P}^-_M \cup \underset{\sim}{P}^-_D = \underset{\sim}{P}^-_M \cup \underset{\sim}{P}^-_{D_1} \cup \underset{\sim}{P}^-_{D_2}.
\end{aligned}
$$

The other notations related to these ones are shown in the appendix.

(3) Spatial connectivity constraints on the vehicles

Based on the notation above, some of the constraints are relaxed in order to represent discretionary activities. Constraint (C3.1) is rewritten as

$$\sum_{v \in V} \sum_{w \in N'} X^v_{uw} = 1, \forall u \in P^+_M. \tag{C3.1}$$

$$\sum_{v \in V} \sum_{w \in N'} X^v_{uw} \leq 1, \forall u \in P^+_D. \tag{C3.1'b}$$

Automatic parking by AVs will be an example for the first type of discretionary activity. If an AV decides to execute such a discretionary activity, or in other words, finds a better place to park itself, it must stay there until it finishes the activity. An extra constraint on AVs,

$$\sum_{u \in N} X^v_{uw} = X^v_{w,w+n}, \forall v \in V_a, \forall w \in \tilde{P}^-_{D_1} \tag{C3.19}$$

ensures this condition.

(4) Spatial connectivity constraints on the household members

For household members avoid accessing these activities, constraints (C4.1) and (C4.6) are modified to be

$$\sum_{j \in \eta} \sum_{w \in N} H^j_{uw} = 1, \forall u \in P^+_M \tag{C4.1}$$

$$\sum_{j \in \eta} \sum_{w \in N} H^j_{uw} \leq 1, \forall u \in P^+_D \tag{C4.1'}$$

$$\sum_{j \in \eta} H^j_{u,u+n} = 1, \forall u \in \tilde{P}^-_M \tag{C4.6}$$

$$\sum_{j \in \eta} H^j_{u,u+n} \leq 1, \forall u \in \tilde{P}^-_D. \tag{C4.6'}$$

For a discretionary activity of type (2) mentioned above, a constraint

$$\sum_{u \in N} H^j_{uw} = H^j_{w,w+n}, \forall j \in \eta, \forall w \in \tilde{P}^-_{D_2} \tag{C4.19}$$

ensures that the member who delivers a discretionary activity completes it.

In addition, if a discretionary activity is temporary parking, this activity is restricted to be available only for AVs; thus, parking activities are placed into activity sets unavailable for household members and CVs.

Modeling automatic parking behavior

Next, this case study focuses on modeling AVs' automatic parking behavior. While the passenger is being engaged in one activity, its AV must complete the discretionary trips for parking by making a "subtour" originating from and returning to the place where the passenger is doing the activity. Thus, additional constraints are needed to represent this subtour behavior. In order to restrict a subtour pattern to terminate within the duration of an activity, let $u' \in \tilde{P}^+_{D_1}$ be an index of an activity executed within a subtour from activity u. Since the subtour for u' must be completed between the beginning and end of the activity u from which it originates, then we need the additional constraints below:

$$T_{u+n} \leq T_{u'}, \forall u \in \tilde{P}^+ \tag{C1.8}$$

$$T_{u'+3n} \leq T_{u+2n}, \forall u \in \tilde{P}^+. \tag{C1.9}$$

This case further requires calculating total parking time to compare parking cost; nevertheless, it is not always straightforward to obtain it. After delivering a passenger, for example, an AV possibly stays at its activity location but does not stay for entire duration of the activity, or it arrives at a pick-up location earlier than actual activity pick-up time. These times are also included in total parking time in addition to the duration of an executed activity. To identify the total parking time, we introduce variables τ_u^a and τ_u^b that respectively represent the waiting time after delivery and before pick-up at the place of activity u. The reason why these variables work is that an outcome of HAPP sometimes contains arbitrary pick-up or delivery time. For example, when $T_u + s_u + t_{uw} < T_w$ for a trip between delivery location u and pick-up location w, a vehicle for this trip wait for a certain period $T_w - (T_u + s_u + t_{uw})$ either after the delivery or before the pick-up that is $T_w - (T_u + s_u + t_{uw}) = \tau_u^a$ or τ_u^b. Then, to determine when an AV waits in that condition, letting $k_u < 0$ $(u \in P)$ be a parking fee per hour at the place of activity u, the rules below are applied:

$$\sum_{v \in V} X_{uw}^v = 1 \text{ and } t_{uw} > 0 \text{ and } u \in P^+$$
$$\Rightarrow \begin{cases} \tau_u^a = T_w - (T_u + s_u + t_{uw}), \tau_w^b = 0 & \text{if } k_u \leq k_w \text{ and } w \in P^+ \\ \tau_u^a = 0, \tau_w^b = T_w - (T_u + s_u + t_{uw}) & \text{otherwise} \end{cases} \tag{C1.10}$$

$$\sum_{v \in V} X_{uw}^v = 1 \text{ and } t_{uw} > 0 \text{ and } u \in P^-$$
$$\Rightarrow \begin{cases} \tau_u^a = 0, \tau_w^b = T_w - (T_u + s_u + t_{uw}) & \text{if } k_u \leq k_w \text{ and } w \in P^+ \\ \tau_u^a = T_w - (T_u + s_u + t_{uw}), \tau_w^b = 0 & \text{otherwise} \end{cases} \tag{C1.11}$$

$$\sum_{v \in V} X_{uw}^v = 1 \text{ and } t_{uw} = 0 \Rightarrow \tau_u^a = T_w - (T_u + s_u), \tau_w^b = 0, \forall u \in P, \forall w \in P. \tag{C1.12}$$

$$\sum_{v \in V} X_{uw}^v = 0 \Rightarrow \tau_u^a = 0, \tau_w^b = 0, \forall u \in P, \forall w \in P. \tag{C1.13}$$

The pragmatical expressions for these constraints are shown in the appendix. Note that all the constraints presented in Case 3 and 4 are summarized in the appendix as well. This revised HAPP model is entitled as HAPPAV2 in tribute to Khayati (2018) [25].

Finally, to take advantage of the variables introduced above, the term $\sum_{u \in P} k_u(\tau_u^a + \tau_u^b)$ is added to the objective function. The added term expresses the total parking fee that a vehicle can be imposed for the activity day. Naturally, since a household is supposed to have no parking cost at their home, $k_0 = 0$. (Precisely, parking cost at home should be included in housing cost.) Hence, the objective function is

$$\begin{aligned}\min Z = &\sum_{v\in V_c}\sum_{u\in N}\sum_{w\in N} c_c v_{\text{ave}} t_{uw} X^v_{uw} + \sum_{v\in V_a}\sum_{u\in N}\sum_{w\in N} c_a v_{\text{ave}} t_{uw} X^v_{uw} + \sum_{u\in\tilde{P}^-}(T_{u+n} - T_u)\\ &+ \sum_{v\in V}(T^v_{4n+1} - T^v_0) + \sum_{v\in V_c}\sum_{w\in P^+} K_c X^v_{0,w} + \sum_{v\in V_a}\sum_{w\in P^+} K_a X^v_{0,w} + \sum_{j\in\eta}(\bar{T}^j_{4n+1} - \bar{T}^j_0) \quad \text{(O5)}\\ &+ \sum_{u\in P} k_u(\tau^a_u + \tau^b_u).\end{aligned}$$

This case explores the traveling behavior of an AV relative to the parking cost for each activity location. In this example, it is supposed that a vehicle parking at the locations of activities 2 and 3 will be imposed a parking fee while parking at home for free. To simulate this situation, we add extra activities only available for AVs assuming that they are done at home but picked up at the location of activities 2 or 3. For the return trip, the delivered activity is picked up at home and then delivered to the location of activities 2 or 3. These discretionary activities are indexed $i = 4$ and 5. Since activities 4 and 5 are unavailable for household members, the activities are added to $\Omega^j_H(j = 1, 2)$. In addition, we extend the duration of activity 3 to 2.5 hours to make the example more interesting. The analysis allows the household one AV and other settings are the same to case 3B. Note that no matter how much the cost per day of AV is, it does not affect the result because the household inevitably chooses to use the assigned AV to participate in activities.

Figure 4.6 shows the thresholds in which the AV changes its routing behavior for different cost per mile ratio. For each ratio, there are four regimes of different travel-activity paths. Figure 4.7 illustrates the paths corresponding to the four regimes. As parking fee increases, household member 1 shifts his activity into later period so as to reduce total parking time sacrificing the total out-of-home time for vehicle. In regime 4, the AV does not park at the place of activity 2.

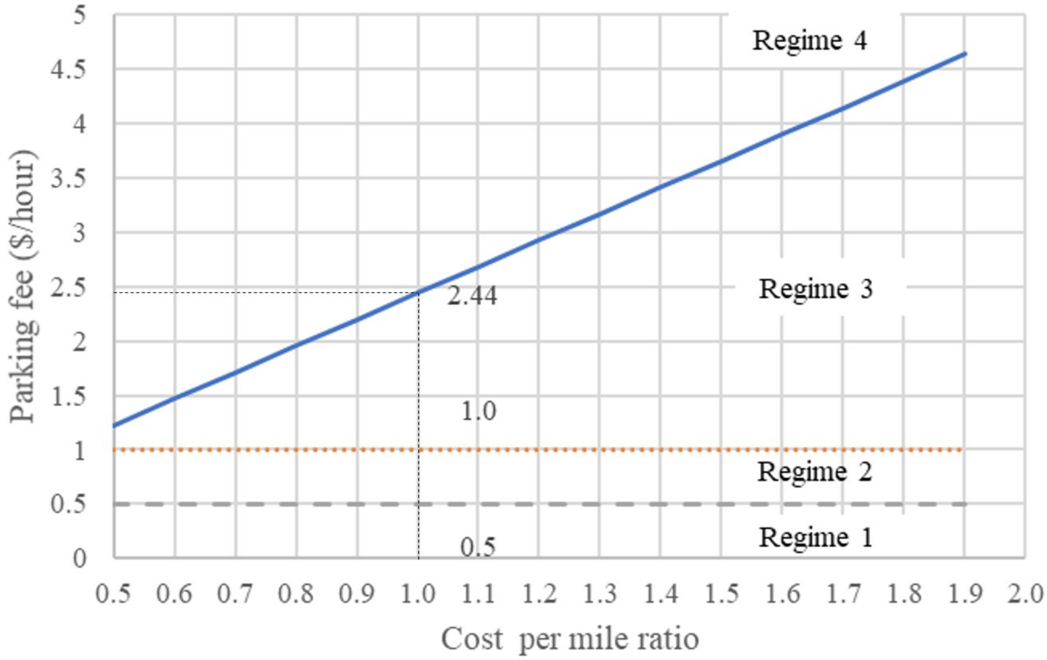

Figure 4.6: Parking Fee Sensitivity Analysis for Case 4A

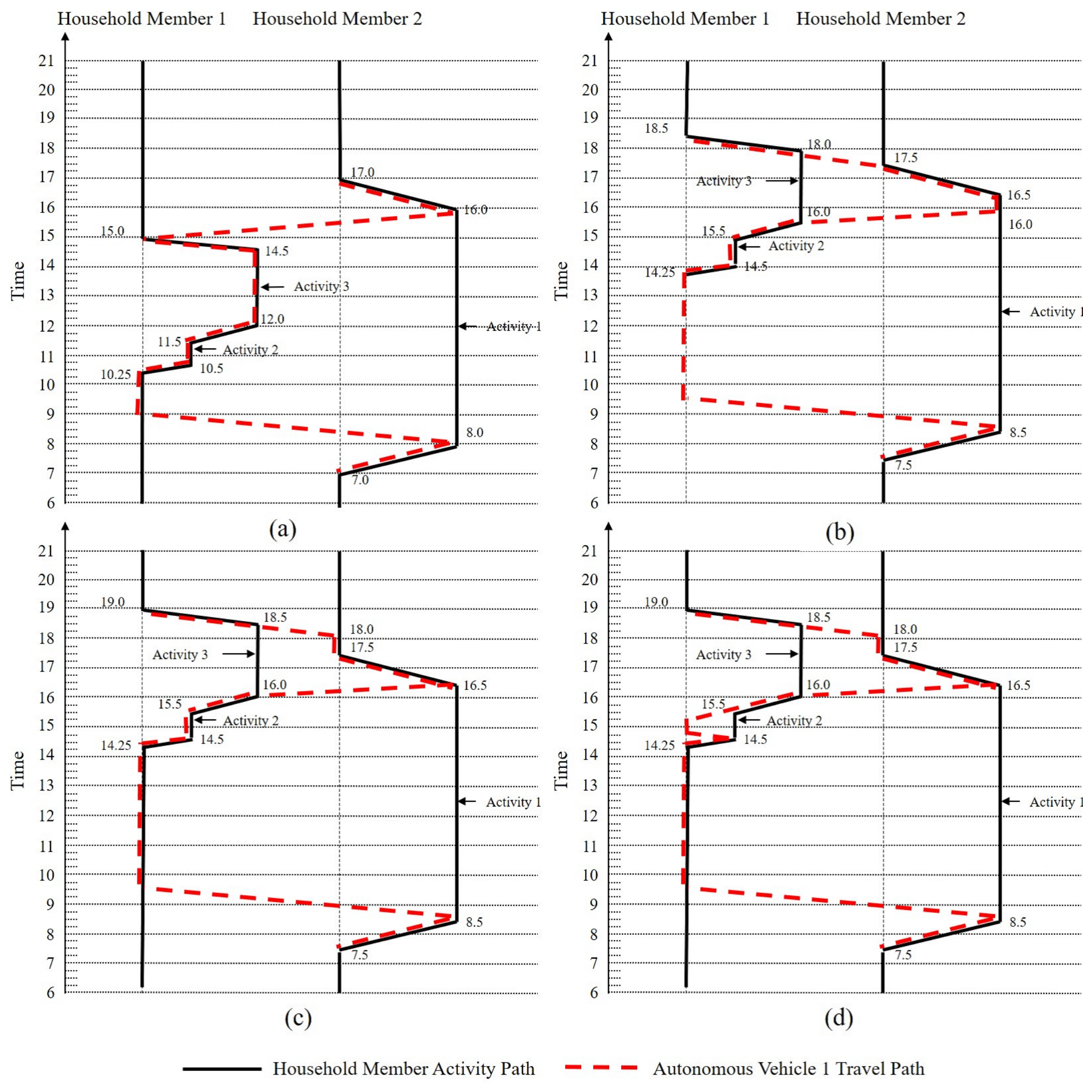

Figure 4.7: Household Travel-Activity Patterns for Case 4A with one AV under Different Parking Fee (a) Regime 1 (b) Regime 2 (c)Regime 3 (d)Regime 4

Next, other time window constraints used in cases 1 to 3A are applied. Figure 4.8 shows different pattern switching points on each cost per mile ratio under these constraints. In this case, there are three regimes of traveling pattern with the same household activity paths. Figure 4.9 portrays the routing patterns corresponding to the three regimes. When imposed relatively lower parking fee to cost per mile, the AV naturally stays at both locations of activities 2 and 3. As the fee becomes higher, the AV voluntarily opts to park at home leaving from activity 3's location or then both of the out-of-home locations.

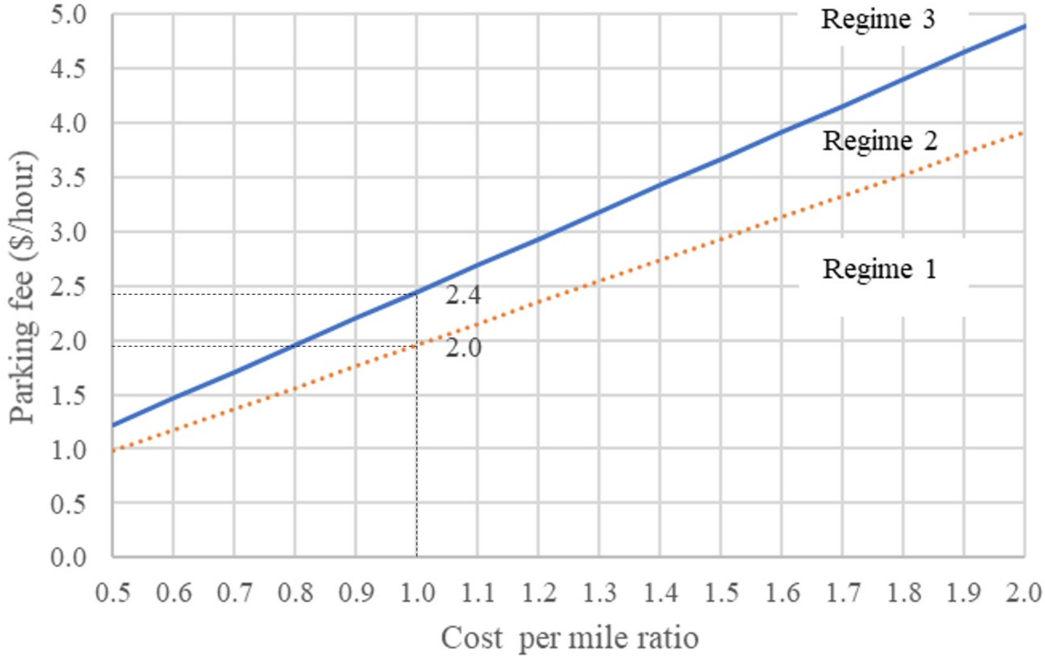

Figure 4.8: Parking Fee Sensitivity Analysis for Case 4B

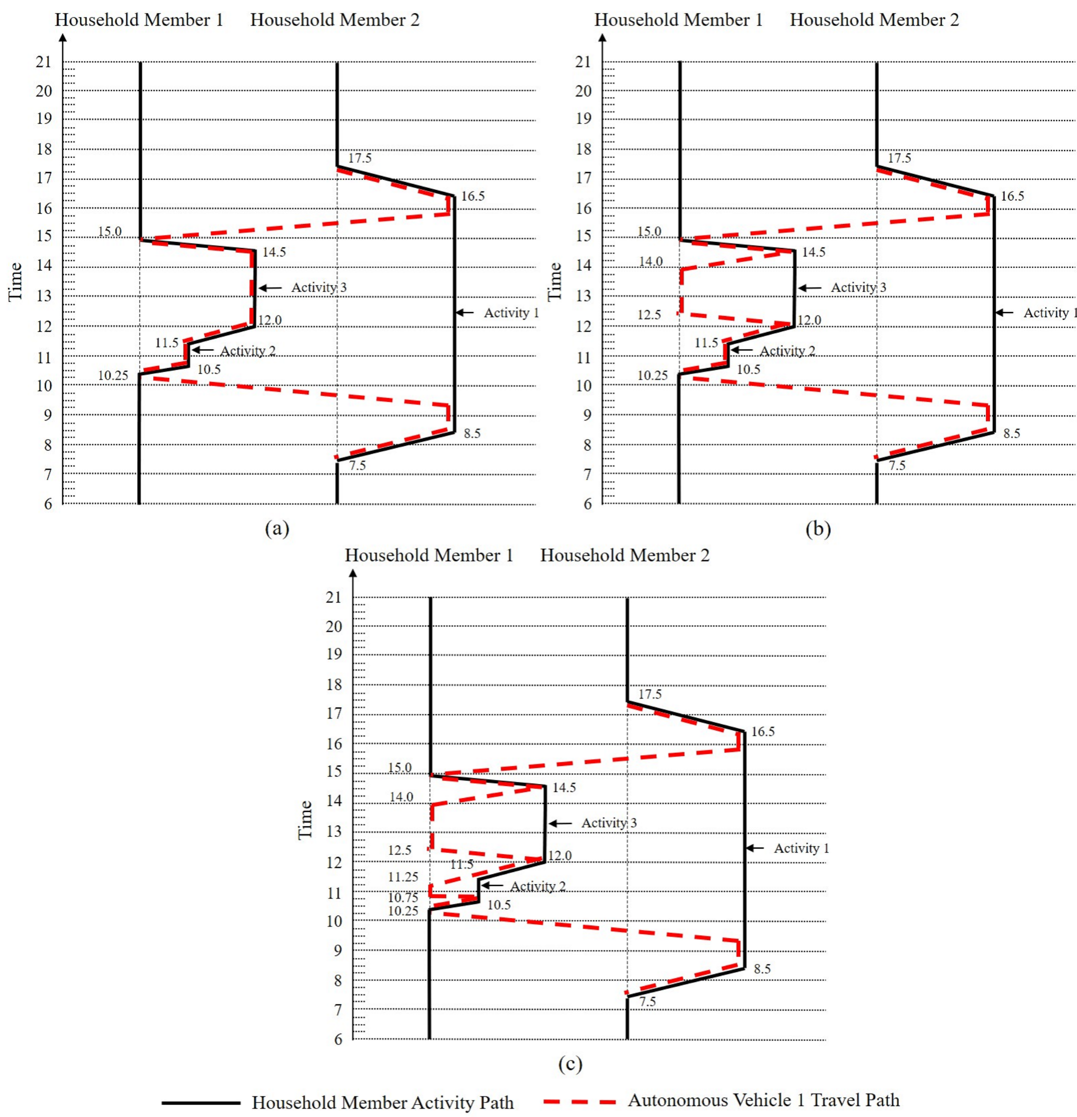

Figure 4.9: Household Travel-Activity Patterns for Case 4B with one AV under Different Parking Fee (a) Regime 1 (b) Regime 2 (c)Regime 3

In the end, Figure 4.10 shows total vehicle miles traveled obtained in the four cases presented above. From the result of cases 3A and 3B, it is seen that introducing AV possibly increases total miles traveled in these simple examples. Moreover, from those of cases 4A an 4B, the higher the parking cost is, the farther the AV travels. This result consequently implies that charging higher parking fee may cause AVs to travel more and lead to a higher environmental burden.

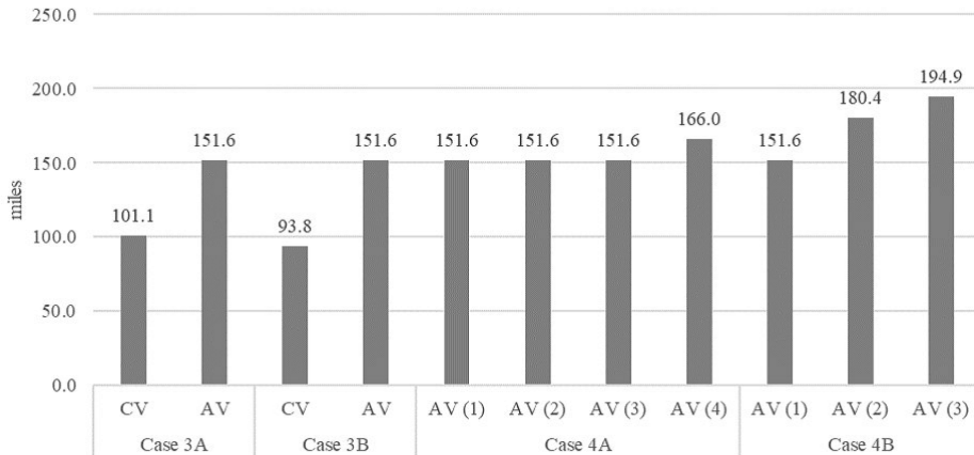

Figure 4.10: Total Traveling Distance Comparison (The numbers in parentheses indicate each regime)

Chapter 5

Further Extensions

Mobility as a Service (MaaS) is a concept of transportation business that is attracting attention from both practitioners and researchers. In contrast to traditional contract systems of transportation, under this concept transportation service providers are expected to offer ”packaged” services which avail users diverse modes. Accordingly, MaaS providers are required to ensure connectivity among different modes such that, for example, travelers can reduce waiting time or fares when transferring from one to another.

Under such multimodal services, AVs could work either as a feeder transit mode to public transit systems or a main transportation mode for an entire trip. Whereas they can provide door-to-door service like CVs and bikes, they do not need a parking spot at stations thanks to the autonomous parking function. Although AVs could potentially be a menace to existing transportation services, this feature of AVs could also enhance their level of service and eventually help to realize a more desirable multimodal transportation system, in which travelers can jointly utilize multiple transportation modes to execute more efficient travel-activity patterns.

Multimodal transportation systems incorporating AVs would likely change travelers' behavior and eventually affect the decision-making process in transportation planning. In spite of the optimism about such modern transportation services, very few evaluation methodologies have been developed for them. The need for an evaluation framework, to gauge the effect of such services is obvious.

This section is aimed at developing an evaluation framework for multimodal systems incorporating AVs by extending the revised HAPP formulation described in the previous sections. The following examples demonstrate how the HAPP framework can represent travel-activity patterns in multimodal transportation systems with AVs.

5.1 Extensions and Examples to Facilitate Evaluation of Multimodal Transportation Systems

This subsection first introduces the gradual reformulations of HAPP to represent transportation modes other than CVs and AVs. The following hypothetical case studies incrementally incorporate such private modes as bikes, walk, rideshare or taxi, and public transit into the HAPP framework.

Case 5: Adding Various Private Modes

The revised HAPP formulation presented above only considers CVs and AVs as travelers' transportation means. However, in reality, we frequently travel by other private modes; for example, by bike. Bikes share almost the same characteristics with CVs since they must travel with a rider. The significant differences between bikes and CVs are in speeds and travel costs; i.e. bicycle users will experience longer travel time but pay a lower cost. Although other private modes such as scooters can offer a different level of service from those of CVs and bikes, the following reformulation will be able to evaluate these modes in the same way once bikes are incorporated in the framework. The following example modifies the formulation so that it illustrates a situation in which travelers can choose different private modes with different levels of service.

(1) Vehicle temporal constraints

In the previous HAPP formulation, all travelers and vehicles are assumed to refer to the same travel time/cost matrices to determine the disutility of travel-activity patterns. If travelers have several options for their transportation modes, this assumption is no longer applicable; otherwise, they will refer to different times associated with the used mode for an OD pair. To allow for this choice, several temporal constraints are modified as:

$$T_u + s_u + \min_{\forall v \in V} t^v_{u,u+n} \leq T_{u+n}, \forall u \in P^+ \cup \tilde{P}^- \tag{C1.1}$$

$$T_u + s_u + t^v_{uw} - T_w \leq (1 - X^v_{uw})M, \forall u, w \in P, \forall v \in V_c \tag{C1.2}$$

$$T_u + t^v_{uw} - T_w \leq (1 - X^v_{uw})M, \forall u, w \in P, \forall v \in V_a \tag{C1.2'}$$

$$T^v_0 + s_0 + t^v_{0,w} - T_w \leq (1 - X^v_{0,w})M, \forall w \in P^+, \forall v \in V \tag{C1.3}$$

$$T_u + t^v_{u,4n+1} - T^v_{4n+1} \leq (1 - X^v_{u,4n+1})M, \forall u \in P^-, \forall v \in V \tag{C1.4}$$

where $t^v_{uw}, \forall u, w \in N$ is vehicle v's travel time between u and w. Accordingly, those for parking time are rewritten as

$$\sum_{v \in V} t^v_{uw} X^v_{uw} = 1 > 0 \text{ and } u \in P^+$$
$$\Rightarrow \begin{cases} \tau^u_a = T_w - (T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw}), \tau^w_b = 0 & \text{if } k_u \leq k_w \text{ and } w \in P^+ \\ \tau^u_a = 0, \tau^w_b = T_w - (T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw}) & \text{otherwise} \end{cases} \tag{C1.10}$$

$$\sum_{v\in V} t_{uw}^v X_{uw}^v = 1 > 0 \text{ and } u \in P^-$$

$$\Rightarrow \begin{cases} \tau_a^u = 0, \tau_b^w = T_w - (T_u + s_u + \sum_{v\in V} t_{uw}^v X_{uw}^v) & \text{if } k_u \leq k_w \text{ and } w \in P^+ \\ \tau_a^u = T_w - (T_u + s_u + \sum_{v\in V} t_{uw}^v X_{uw}^v), \tau_b^w = 0 & \text{otherwise} \end{cases} \tag{C1.11}$$

$$\sum_{v\in V} X_{uw}^v = 1 \text{ and } \min_{\forall v\in V} t_{uw}^v = 0 \Rightarrow \tau_a^u = T_w - (T_u + s_u), \tau_b^w = 0, \forall u \in P, \forall w \in P. \tag{C1.12}$$

(2) Household member temporal constraints

In a similar manner, some of the temporal constraints for household members are rewritten as

$$H_{uw}^j = 1 \Rightarrow T_u + s_u + \sum_{v\in V} t_{uw}^v X_{uw}^v \leq T_w, \forall u, w \in P, \forall j \in \eta \tag{C2.1}$$

$$H_{0,w}^j = 1 \Rightarrow T_0^j + s_0 + \sum_{v\in V} t_{0,w}^v X_{0,w}^v \leq T_w, \forall w \in P, \forall j \in \eta \tag{C2.2}$$

$$H_{u,4n+1}^j = 1 \Rightarrow T_u + \sum_{v\in V} t_{u,4n+1}^v X_{u,4n+1}^v \leq T_{4n+1}^j, \forall u \in P, \forall j \in \eta \tag{C2.3}$$

that are equivalent to

$$T_u + s_u + \sum_{v\in V} t_{uw}^v X_{uw}^v - T_w \leq (1 - H_{uw}^j)M, \forall u, w \in P, \forall j \in \eta \tag{C2.1}$$

$$T_0^j + s_0 + \sum_{v\in V} t_{0,w}^v X_{0,w}^v - T_w \leq (1 - H_{0w}^j)M, \forall w \in \tilde{P}^+, \forall j \in \eta \tag{C2.2}$$

$$T_u + s_u + \sum_{v\in V} t_{u,4n+1}^v X_{u,4n+1}^v - \bar{T}_{4n+1}^j \leq (1 - H_{u,4n+1}^j)M, \forall u \in \utilde{P}^-, \forall j \in \eta. \tag{C2.3}$$

(5) Capacity budget and participation constraints

Some of the capacity budget constraints for vehicles consider travel time to determine whether the concerned trip has non-zero distance. They should be modified as

$$X_{uw}^{v} = 1 \Rightarrow \begin{cases} \Upsilon_u^v + d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N}\min_{\forall v\in V} t_{w\tilde{u}}^{v} H_{w\tilde{u}}^{j} > 0 \text{ or } w \in \utilde{P}^{+} \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^{+} \qquad \text{(C5.6)}$$

$$X_{uw}^{v} = 1 \Rightarrow \begin{cases} \Upsilon_u^v - d_{w-n} = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N}\min_{\forall v\in V} t_{w\tilde{u}}^{v} H_{w\tilde{u}}^{j} > 0 \text{ or } w \in \tilde{P}^{-} \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^{-} \qquad \text{(C5.7)}$$

$$X_{0w}^{v} = 1 \Rightarrow \begin{cases} d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N}\min_{\forall v\in V} t_{w\tilde{u}}^{v} H_{w\tilde{u}}^{j} > 0 \\ 0 = \Upsilon_w^v & \text{otherwise} \end{cases}, \forall v \in V, \forall w \in \tilde{P}^{+} \quad \text{(C5.8)}$$

(6) Vehicle and household member coupling constraints

Likewise, it is necessary to modify the coupling constraints which consider travel time:

$$H_{uw}^{j} = 1 \text{ and } \min_{\forall v\in V} t_{uw}^{v} > 0 \Rightarrow \sum_{v\in V} X_{uw}^{v} = 1, \forall j \in \eta, \forall u, w \in P, \qquad \text{(C6.1)}$$

$$X_{uw}^{v} = 1 \text{ and } \min_{\forall v\in V} t_{uw}^{v} > 0 \Rightarrow \sum_{j\in\eta} H_{uw}^{j} = 1, \forall v \in V_c, \forall u, w \in P. \qquad \text{(C6.2)}$$

To verify that the modified formulation works as expected, this case demonstrates an example of a simple situation, in which a household member only commutes to work and has two options for commuting: a bike or CV. It is apparent that the bike has lower costs but larger travel times than those of CVs. Specifically, the bike ownership cost is set to be one dollar per day, and no per-mile travel cost is needed to use bike. The travel time for cars is 0.5 hours, and that for bikes is 0.75 hours between the home and the workplace. Figure 5.1 depicts this arrangement. The duration and time-window of the activity is set to be the same as those of activity 1 in the previous cases.

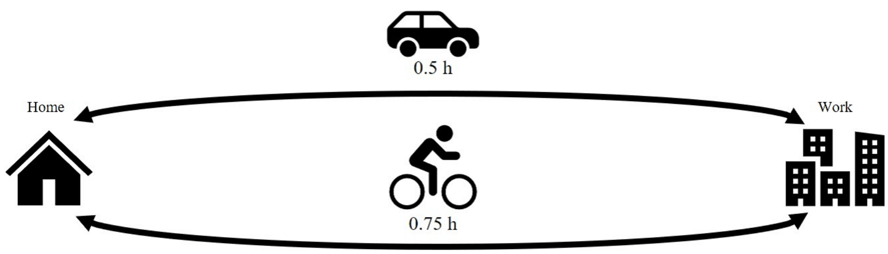

Figure 5.1: Setting for Case 5

Let t_{uw}^v, c_c^v, and K_c^v be the travel time, cost per time, and ownership cost of vehicle v, respectively. Using these parameters, the objective function for this case is simplified to be

$$\min Z = \sum_{v \in V_c} \sum_{u \in N} \sum_{w \in N} c_c^v v_{\text{ave}} t_{uw}^v X_{uw}^v + \sum_{v \in V_c} \sum_{w \in P^+} K_c^v X_{0,w}^v + \beta \sum_{j \in \eta} (\bar{T}_{4n+1}^j - \bar{T}_0^j) \tag{O6}$$

where β is an arbitrary parameter, which represents the value of time of the household member; one with larger β will pay more to reduce travel time than one with smaller β. By changing this β, the following example can illustrate different mode choice behavior of the member.

Figure 5.2 plots the solutions for this problem. They are quite simple but show that the reformulated model is capable of representing mode choice behavior as intended. In this arrangement, if a household member has β smaller than 38.6, he will choose a bike. Conversely, if β is larger than the threshold, he will use a car.

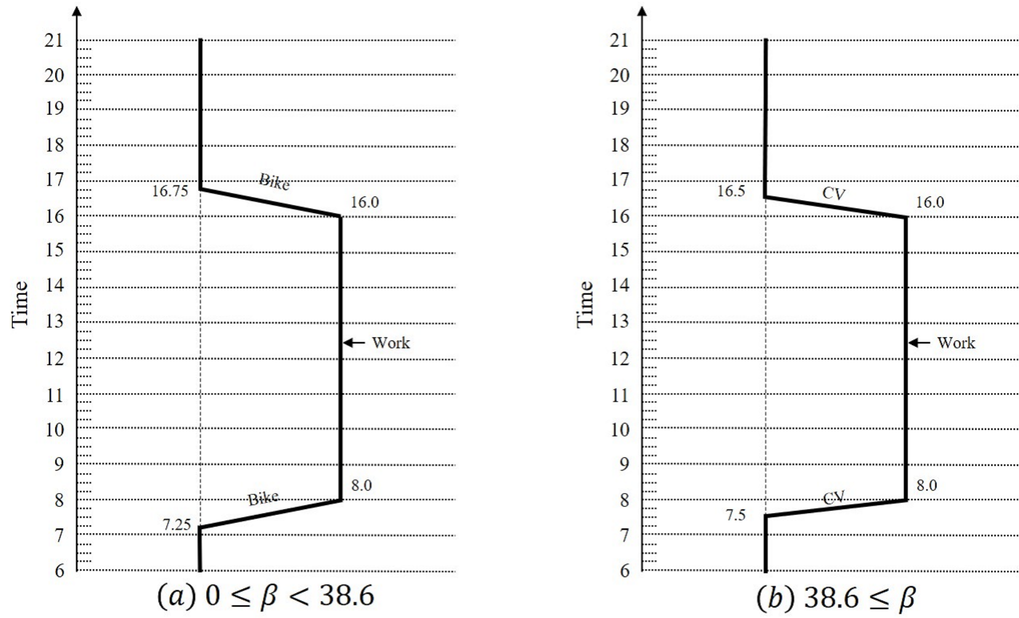

Figure 5.2: Possible Travel-Activity Patterns in Case 5

Case 6: Adding Walking

It is obvious that we do not always rely on transportation technologies when we make a trip; in other words, travelers do not have to use any "modes" for some short trips. That is, walking should be regarded as a way of traveling in urban settings. To enable the HAPP framework to simulate walking trips, additional modifications to the constraints are needed.

(2) Household member temporal constraints

The household member temporal constraints need to be differentiated depending on whether the member uses a certain private mode or walks because the term $\sum_{v \in V} t_{uw}^v X_{uw}^v$ in (C2.1), for example, is zero when he chooses to walk, and travel time would not be reflected. Therefore, they are rewritten as

$$H^j_{uw} = 1 \text{ and } \sum_{v \in V} X^v_{uw} = 1 \Rightarrow T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw} \leq T_w, \forall u, w \in P, \forall j \in \eta \tag{C2.1a}$$

$$H^j_{uw} = 1 \text{ and } \sum_{v \in V} X^v_{uw} = 0 \Rightarrow T_u + s_u + t^h_{uw} \leq T_w, \forall u, w \in P, \forall j \in \eta \tag{C2.1b}$$

$$H^j_{0,w} = 1 \text{ and } \sum_{v \in V} X^v_{0,w} = 1 \Rightarrow T^j_0 + s_0 + \sum_{v \in V} t^v_{0,w} X^v_{0,w} \leq T_w, \forall w \in P, \forall j \in \eta \tag{C2.2a}$$

$$H^j_{0,w} = 1 \text{ and } \sum_{v \in V} X^v_{0,w} = 0 \Rightarrow T^j_0 + s_0 + t^h_{0,w} \leq T_w, \forall w \in P, \forall j \in \eta \tag{C2.2b}$$

$$H^j_{u,4n+1} = 1 \text{ and } \sum_{v \in V} X^v_{u,4n+1} = 1 \Rightarrow T_u + \sum_{v \in V} t^v_{u,4n+1} X^v_{u,4n+1} \leq T^j_{4n+1}, \forall u \in P, \forall j \in \eta \tag{C2.3a}$$

$$H^j_{u,4n+1} = 1 \text{ and } \sum_{v \in V} X^v_{u,4n+1} = 0 \Rightarrow T_u + t^h_{u,4n+1} \leq T^j_{4n+1}, \forall u \in P, \forall j \in \eta. \tag{C2.3b}$$

where t^h_{uw} is the travel time on foot between u and w. To be implemented, they have to be expressed in the following manner:

$$T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw} - T_w \leq (1 - H^j_{uw})M, \forall u, w \in P, \forall j \in \eta \tag{C2.1a}$$

$$T_u + s_u + t^h_{uw}(1 - \sum_{v \in V} X^v_{uw}) - T_w \leq (1 - H^j_{uw})M, \forall u, w \in P, \forall j \in \eta \tag{C2.1b}$$

$$T^j_0 + s_0 + \sum_{v \in V} t^v_{0,w} X^v_{0,w} - T_w \leq (1 - H^j_{0,w})M, \forall w \in P, \forall j \in \eta \tag{C2.2a}$$

$$T^j_0 + s_0 + t^h_{0,w}(1 - \sum_{v \in V} X^v_{0,w}) - T_w \leq (1 - H^j_{0,w})M, \forall w \in P, \forall j \in \eta \tag{C2.2b}$$

$$T_u + \sum_{v \in V} t^v_{u,4n+1} X^v_{u,4n+1} - T^j_{4n+1} \leq (1 - H^j_{u,4n+1})M, \forall u \in P, \forall j \in \eta \tag{C2.3a}$$

$$T_u + t^h_{u,4n+1}(1 - \sum_{v \in V} X^v_{u,4n+1}) - T^j_{4n+1} \leq (1 - H^j_{u,4n+1})M, \forall u \in P, \forall j \in \eta. \tag{C2.3b}$$

(6) Vehicle and household member coupling constraints

For walkable OD pairs, household members need to consider not using vehicles. For such pairs, the coupling constraints are relaxed. In particular, (C6.1) is redefined to be

$$H^j_{uw} = 1 \Rightarrow \sum_{v \in V} X^v_{uw} = 1, \forall j \in \eta, \forall (u, w) \in \mathbb{P}^2_v \tag{C6.1}$$

where $\mathbb{P}^2_v$ is a set of OD pairs between which travelers cannot walk. It should be noted that constraint (C6.4) is no longer applicable because household members do not have to use private modes when they to/from out-of-home activities.

In a similar setting, in which the working place is located closer to home than that of the previous case, the following example verifies the reformulation embracing walking. The household member is allowed to either bike or walk between home and the working place, while the objective function is set to be the same as before. The member choosing to walk does not have to pay any cost but experiences longer travel time. In this scenario, biking takes half an hour, and walking takes 0.75 hours.

Figure 5.3 displays this example's result, which clearly shows that walking is incorporated in the HAPP framework without adding a new decision variable. The threshold β value for the two patterns is 2.0, which implies that few people will probably walk in this situation.

Case 7: Adding Rideshare

In the last few years, rideshare companies have become essential mobility providers in many cities around the world thanks to the sophisticated mobile apps. By offering flexible services, they will be playing an influential role among other advanced transportation services in the future. The characteristic of rideshare is that it can provide door-to-door service while

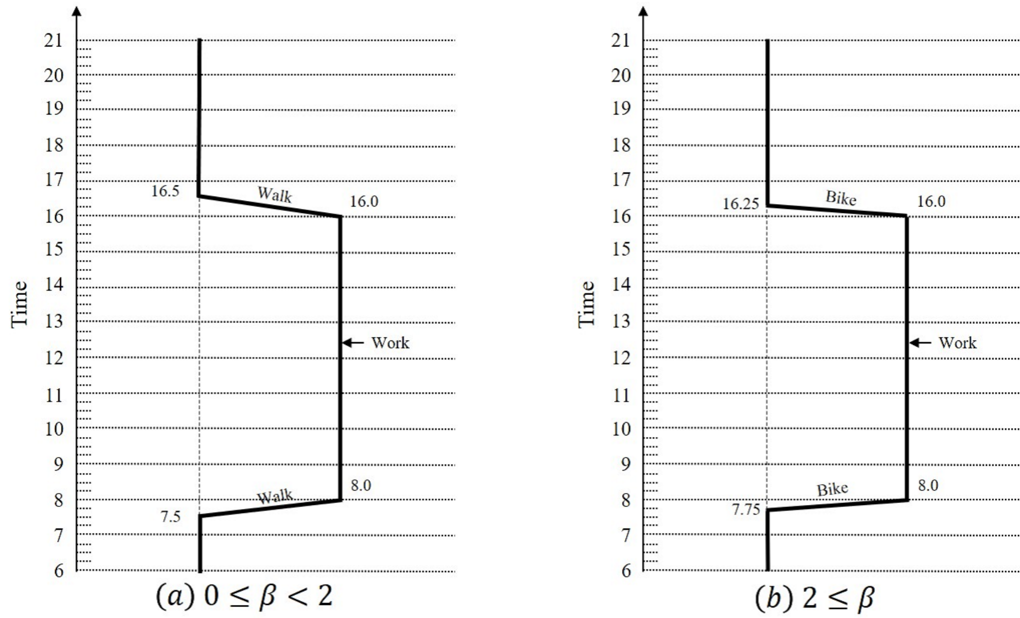

Figure 5.3: Possible Travel-Activity Patterns in Case 6

avoiding driving and ownership cost. Since household members do not have to travel together with a vehicle for their home-based tour, it is not necessary to consider either connectivity and coupling constraint to represent rideshare trips in HAPP.

Since rideshare differs from other private vehicles, we cannot use the same constraints on it. Thus, another decision variable is introduced to differentiate rideshare from private vehicle. Let $R^j_{uw}, \forall j \in 1, ..., \eta$, be a binary decision variable that indicates whether or not household member j uses ride share from u to w. Note that it is not assumed that this variable represents vehicle traveling; therefore, connectivity constraints are not imposed on R^j_{uw}.

Additionally, rideshare is presumed to be always available for travelers at this point of the research. In reality, this assumption will be too optimistic because rideshare services are limited and cannot always serve passengers when demand is very high, but considering stochastic availability of rideshare is left for future study. Conventional taxis can be represented simply by adding a similar binary decision variable and imposing the following constraints on them. They are differentiated only by their level of service.

(2) Household member temporal constraints

Let t^r_{uw} be the travel time between u to w on rideshare to discriminate it from those for private vehicles. Using this variable, temporal constraints on household member are again revised as

$$H^j_{uw} = 1 \text{ and } \sum_{v \in V} X^v_{uw} = 1 \Rightarrow T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw} \leq T_w, \forall u, w \in P, \forall j \in \eta \tag{C2.1a}$$

$$H^j_{uw} = 1 \text{ and } \sum_{v \in V} X^v_{uw} = 0 \Rightarrow \begin{cases} T_u + s_u + t^h_{uw} \leq T_w, \text{ if } R^j_{uw} = 0 \\ T_u + s_u + t^r_{uw} \leq T_w, \text{ if } R^j_{uw} = 1 \end{cases}, \forall u, w \in P, \forall j \in \eta \tag{C2.1b}$$

$$H^j_{0,w} = 1 \text{ and } \sum_{v \in V} X^v_{0,w} = 1 \Rightarrow T^j_0 + s_0 + \sum_{v \in V} t^v_{0,w} X^v_{0,w} \leq T_w, \forall w \in P, \forall j \in \eta \tag{C2.2a}$$

$$H^j_{0,w} = 1 \text{ and } \sum_{v \in V} X^v_{0,w} = 0 \Rightarrow \begin{cases} T^j_0 + s_0 + t^h_{0,w} \leq T_w, \text{ if } R^j_{0,w} = 0 \\ T^j_0 + s_0 + t^r_{0,w} \leq T_w, \text{ if } R^j_{0,w} = 1 \end{cases}, \forall w \in P, \forall j \in \eta \tag{C2.2b}$$

$$H^j_{u,4n+1} = 1 \text{ and } \sum_{v \in V} X^v_{u,4n+1} = 1 \Rightarrow T_u + \sum_{v \in V} t^v_{u,4n+1} X^v_{u,4n+1} \leq T^j_{4n+1}, \forall u \in P, \forall j \in \eta \tag{C2.3a}$$

$$H^j_{u,4n+1} = 1 \text{ and } \sum_{v \in V} X^v_{u,4n+1} = 0 \Rightarrow \begin{cases} T_u + t^h_{u,4n+1} \leq T^j_{4n+1}, \text{ if } R^j_{u,4n+1} = 0 \\ T_u + t^r_{u,4n+1} \leq T^j_{4n+1}, \text{ if } R^j_{u,4n+1} = 1 \end{cases}, \quad \forall u \in P, \forall j \in \eta, \tag{C2.3b}$$

some of which can be expressed as

$$T_u + s_u + t^h_{uw}(1 - \sum_{v \in V} X^v_{uw} - R^j_{uw}) - T_w \leq (1 - H^j_{uw})M, \forall u, w \in P, \forall j \in \eta \tag{C2.1b}$$

$$T_0^j + s_0 + t_{0,w}^h(1 - \sum_{v \in V} X_{0,w}^v - R_{0,w}^j) - T_w \leq (1 - H_{0,w}^j)M, \forall w \in P, \forall j \in \eta \tag{C2.2b}$$

$$T_u + t_{u,4n+1}^h(1 - \sum_{v \in V} X_{u,4n+1}^v - R_{u,4n+1}^j) - T_{4n+1}^j \leq (1 - H_{u,4n+1}^j)M, \forall u \in P, \forall j \in \eta. \tag{C2.3b}$$

(6) Vehicle and household member coupling constraints

For an unwalkable OD pair, a household member will use either a car or a rideshare. Coupling constraint (C6.1) accordingly turns out to be

$$H_{uw}^j = 1 \Rightarrow \sum_{v \in V} X_{uw}^v + R_{uw}^j = 1, \forall j \in \eta, \forall (u,w) \in \mathbb{P}_v^2. \tag{C6.1}$$

In addition, to prevent ride share services from making unnecessary zero-time trips, a constraint

$$R_{uw}^j \leq t_{uw}^r M, \quad \forall j \in \eta, \forall u, w \in N \tag{C6.5}$$

is required.

This reformulation is also verified in the same situation as presented in Case 6, but an option of rideshare is added. A term representing fares for rideshare $\sum_{j \in \eta} \sum_{u \in N} \sum_{w \in N} c_{uw}^R R_{uw}^j$ is added to the objective function:

$$\begin{aligned} \min Z = &\sum_{v \in V_c} \sum_{u \in N} \sum_{w \in N} c_c^v v_{\text{ave}} t_{uw}^v X_{uw}^v + \sum_{v \in V_c} \sum_{w \in P^+} K_c^v X_{0,w}^v + \beta \sum_{j \in \eta} (\bar{T}_{4n+1}^j - \bar{T}_0^j) \\ &+ \sum_{j \in \eta} \sum_{u \in N} \sum_{w \in N} c_{uw}^R R_{uw}^j \end{aligned} \tag{O7}$$

where c_{uw}^R is a cost for using rideshare between u and w. As we can see from Figure 5.4, there are three possible patterns in this setting; however, rideshare is preferable only for one with a much higher value of β.

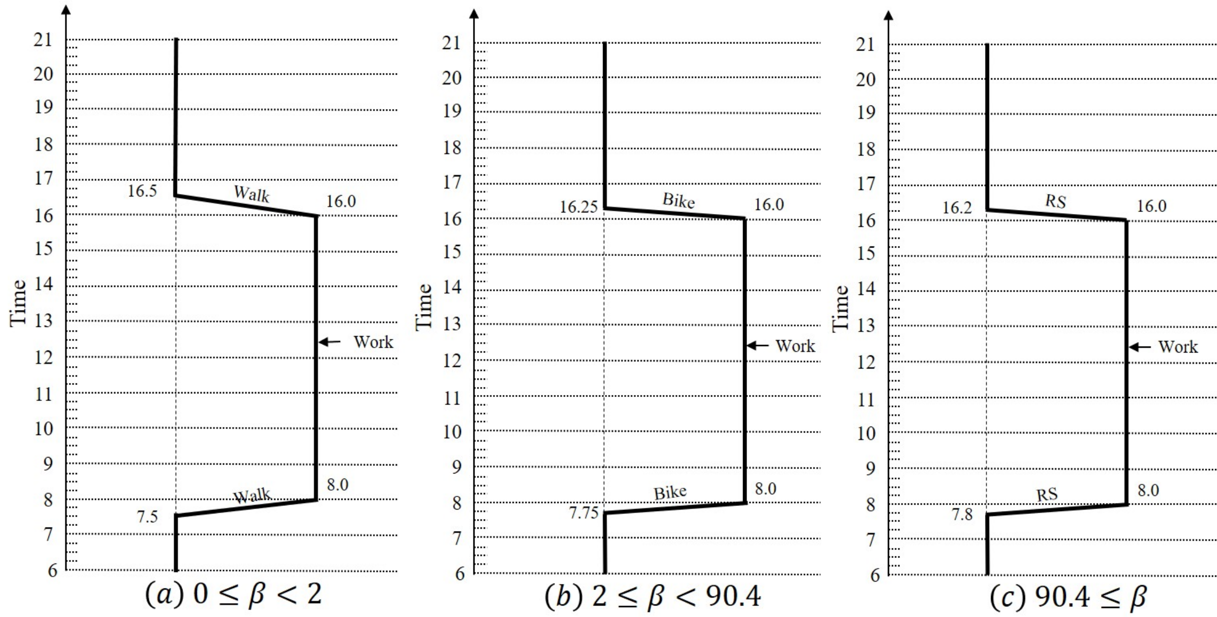

Figure 5.4: Possible Travel-Activity Patterns in Case 7

Case 8: Adding Public Transit

Thanks to its higher capacity, public transit (PT) can be expected to still be playing an important role in urban transportation systems of metropolitan cities even after AVs become available. Thus, we need to model PT in this HAPP framework in order to investigate the utility of AVs in such urban contexts. A trip by PT, unlike trips by other door-to-door transportation modes incorporated so far, usually consists of at least three segments: access and egress parts before and after the main part with PT, respectively. PT namely requires travelers to use different modes in order to complete their whole trip. Since modes for access and egress can be any available mode other than PT, we need to consider multiple combinations of modes to represent a PT trip. In the multimodal HAPP formulation discussed above, one trip is regarded as one link assigned with one mode. It is possible to make one link represent one combination of multiple modes; however, this representation will be computationally burdensome because the number of possible mode combinations for one trip will be larger and larger as the number of available modes increases. Moreover, it cannot capture PT's important characteristic that its schedule is fixed, while access and egress segments are flexible in time.

Hence, it is necessary to represent separate segments and schedule of PT trips. To satisfy these requirements for PT trips, this research employs an idea that the main segment of PT trip is considered as an "activity". Remember that, in the reformulated HAPP developed in the previous cases, an activity is expressed by two different pick-up or delivery nodes both of which are located at the same position, and that travelers can make trips to and from these nodes by different modes. Then, let us suppose that these two nodes of an activity are located at different positions. In this way, it appears that one who is executing the activity will be automatically move from one node to another as if she is using a PT mode. These separate nodes are accordingly thought to be stations or stops of PT, and the duration of the activity turns out to be travel time for the main segment of a PT trip. Pick-up or delivery trips for the activity are therefore regarded as access-egress trips. This concept of representing PT is illustrated in Figure 5.5. Furthermore, thinking of PT trip as activity has another advantage; we can impose time-window constraints to represent schedules of PT. in other words, departure and arrival times of PT are translated into temporal constraints of starting and ending times of an activity, respectively. Specifically, we can express departure time as the latest time in an activity beginning time window and arrival time as the earliest time in an activity ending time window.

To discriminate PT trips from other discretionary activities, denote a node set for PT trips as $P_P \subseteq P_{D_2}$ such that $P_P = \tilde{P}_P^+ \cup \tilde{P}_P^- \cup \underset{\sim}{P}_P^+ \cup \underset{\sim}{P}_P^-$ where $\tilde{P}_P^+ \subseteq \tilde{P}_{D_2}^+$, $\tilde{P}_P^- \subseteq \tilde{P}_{D_2}^-$, $\underset{\sim}{P}_P^+ \subseteq \underset{\sim}{P}_{D_2}^+$, and $\underset{\sim}{P}_P^+ \subseteq \underset{\sim}{P}_{D_2}^+$.

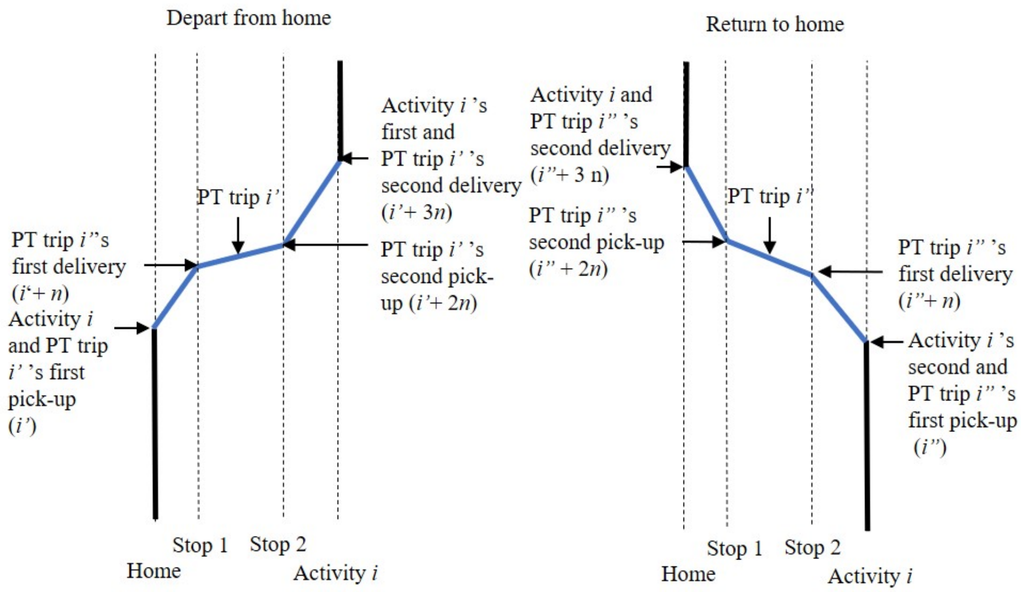

Figure 5.5: Illustration of the PT Trip Representation in HAPP

Considering the fact that PT does not allow vehicles to ride on it, we need

$$X^v_{u,u+n} = 0, \forall v \in V, \forall u \in \tilde{P}^-_P \tag{C3.20}$$

on vehicles. Since PT trips are considered as discretionary activities of type (2) introduced Case 4, constraint (C4.19) ensures that a household member who delivers a discretionary activity completes it (i.e. completes a travel on PT). Furthermore, it is meaningless that vehicles access or egress from a station without dropping off or picking up a passenger, respectively. Thus, coupling constraints

$$\sum_{u \in P} X^v_{u,w} \leq \sum_{j \in \eta} \sum_{u \in P} H^j_{u,w}, \forall v \in V, \forall w \in \tilde{P}^-_P \tag{C6.6}$$

$$\sum_{w \in P} X^v_{u,w} \leq \sum_{j \in \eta} \sum_{w \in P} H^j_{u,w}, \forall v \in V, \forall u \in \underset{\sim}{P}^+_P \tag{C6.7}$$

are added to prevent the useless accesses/egresses. All of the constraints defined to incorporate various modes discussed above are shown in the appendix.

Representing PT trips requires no more reformulations to those presented above but necessitates expansion of input data. Specifically, to add one PT service such as bus service from one stop to another, we need to add one "activity" with two ends at different positions. The duration of this activity corresponds to the travel time between the two ends. The schedules of the PT services are reflected by its time window constraints. For example, those for a bus trip i' departing from a stop at 7 am and arriving at another at 7:30 am are expressed as

$$[a_{i'}, b_{i'}] = [0, 7], [a_{i'+n}, b_{i'+n}] = [7.5, 24].$$

To illustrates PT trips with the reformulated HAPP, let us suppose that the setting in Case 6 is enhanced with a public transit line. This setting is shown in Figure 5.6. The public transit is operated under a fixed schedule, and its fare is 2.5 dollars per ride. The stops are accessible only on foot. The term representing fares for PT is included in the objective

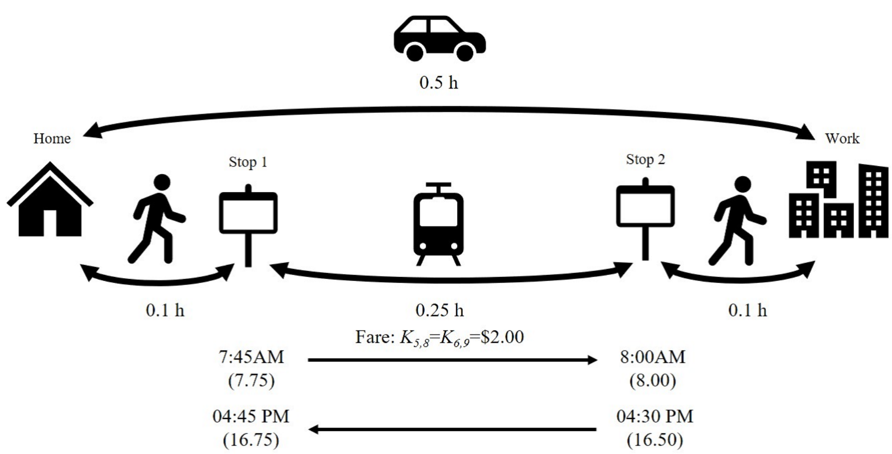

Figure 5.6: Setting for Case 8A

function:

$$\min Z = \sum_{v\in V_c}\sum_{u\in N}\sum_{w\in N} c_c^v v_{\text{ave}} t_{uw}^v X_{uw}^v + \sum_{v\in V_c}\sum_{w\in P^+} K_c^v X_{0,w}^v + \beta \sum_{j\in\eta}(\bar{T}_{4n+1}^j - \bar{T}_0^j)$$
$$+ \sum_{j\in\eta}\sum_{u\in N}\sum_{w\in N} c_{uw}^R R_{uw}^j + \sum_{j\in\eta}\sum_{u\in\tilde{P}_D^-} c_{u,u+n}^P H_{u,u+n}^j \tag{O8}$$

where $c^P_{u,u+n}$ represents a fare for using PT between u and $u+n$. The possible travel-activity patterns are displayed in Figure 5.7. This result successfully demonstrates the PT trip representation in the HAPP framework. It also clearly shows that PT services between the two locations make it more likely for the person to give up using a car even if he has a relatively high value of time.

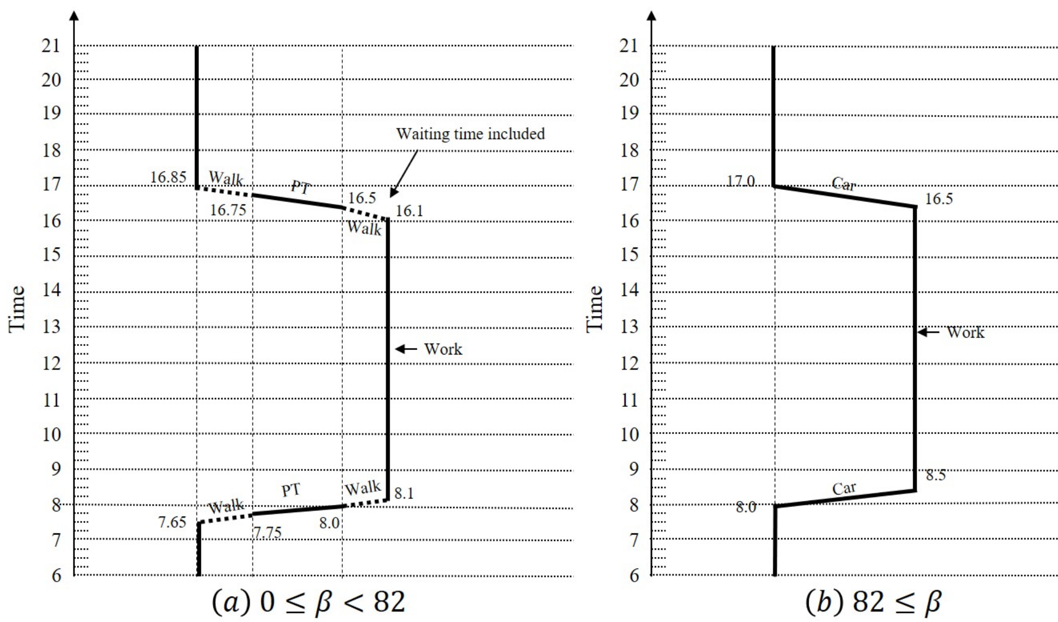

Figure 5.7: Possible Travel-Activity Patterns in Case 8A

The next example, say Case 8B, allows for multimodal access to stop 1 in the setting shown in Figure 5.6. The member is allowed to access the stop by bike as well as on foot from his home but has to pay two dollars for parking fee when he left bike at the stop. Biking takes 0.05 hours between his home and the stop.

Figure 5.8 shows that there are three patterns, two of which have different feeder modes to and from stop 1. This result ensures that the reformulation is capable of representing the multimodality in accesses/egresses for PT. Additionally, the result that people with greater value of time will use PT than in the previous example implies that improving feeder service will have an impact on the demand for PT.

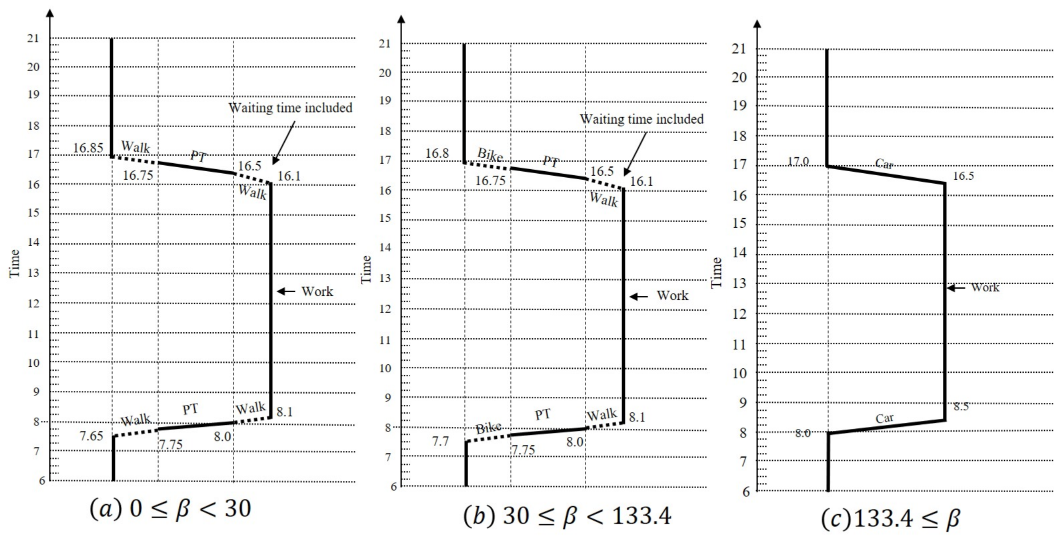

Figure 5.8: Possible Travel-Activity Patterns in Case 8B

5.2 Examples to Evaluate Multimodal Transportation Systems with AVs

The reformulated HAPP can eventually evaluate multimodal transportation systems with AVs. Let us call this framework "multimodal HAPP with AV (mHAPPAV)" for convenience. Although the examples presented in this section thus far are so simple that we may analytically find a solution by hand, this subsection examines more sophisticated transportation arrangements and exemplifies cumulative evaluations of multimodal transportation systems with AVs by mHAPPAV.

Case 9A: AVs Coordinating with Public Transit

This case shows that mHAPPAV simulates AVs coordinating with PT. The parameters employed for this case are almost identical to those used in Cases 1 - 4 except that a public transit line is added between home and activity 1. Figure 5.9 illustrates this arrangement including the schedule for PT. The household members are supposed to be able to walk between home and Stop 1, stop 2 and activity 1, and home and Activity 2. They can use two CVs and an AV as well as Case 3, but the per-mile cost for AV is fixed to be the same as that of CVs. Travel times for walking are assumed to be five times as longer as those of cars for simplicity. Additionally, the household members have to pay three dollars for each ride on PT. Parking cost for vehicle at stop 1 is again ten dollars per day. Objective function (O8) is also used for this case.

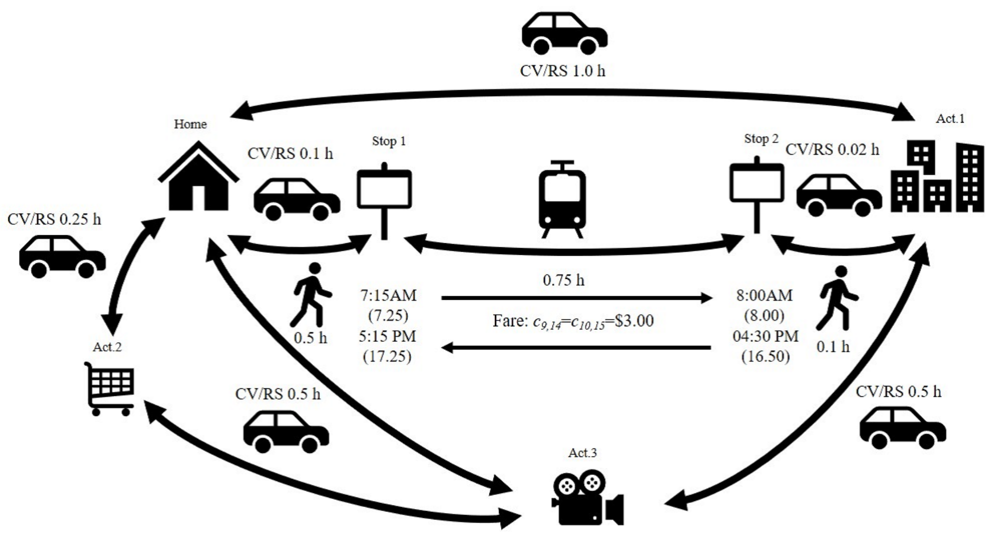

Figure 5.9: Setting for Case 9

Figure 5.10 displays five possible patterns, say (a) - (e), realized depending on two parameters: the value of time of the household and the price of AVs. Patterns (c) and (e) are the same as those obtained in Case 3 as well. The AV is used in patterns (d) and (e); particularly in pattern (d), household member 2 uses the AV as a feeder to PT, showing that mHAPPAV can represent the coordination between the AV and PT.

In the following, this case carries out a sensitivity analysis concerning the household's choice of these patterns by changing the parameters: the value of time β and the ratio of the price of AV to that of CV. To simplify the analysis, the price of CV is assumed to be constant: 15.41 dollars per day. Figure 5.11 shows how a set of parameters is associated with each pattern.

Each regime in Figure 5.11 corresponds to the pattern with the same index in Figure 5.10. If an AV is not available to the household or is much more expensive than a CV, only patterns (a), (b), and (c) are possible. This time, household member 2 uses PT for activity 1 if β is below 25.21. If the ownership cost per day of AV is less than 1.72 times as much as that of CV, pattern (d) becomes preferable for the household. When the ratio is 1.6, for example, a household with β smaller than forty would be better off by taking patterns using PT (i.e (a), (b), and (d)). That is, AVs could help to increase the attractiveness of travel-activity patterns using PT for households with a higher value of time when their price is low enough. From another point of view, coordinating with PT would make AVs more viable than when competing with CVs by themselves.

Case 9B: AVs Competing with Rideshares

Finally, Case 9B allows rideshares to enter the transportation system presented in Case 9A. Since rideshare services are already available in many cities, it is useful to consider their impacts on the potential utility of AVs; they can either compete or coordinate with private AVs depending on conditions. This case investigates under which circumstance owing an AV is preferable to owing CVs in the presence of rideshare services.

The setting for this case is the same as that of Case 9a except that ridershare is available between every pair of activities. As to the LOS of ridershare, rideshare passengers should pay fixed fare for each use while the travel times for them are identical to those for other vehicles. The fares for rideshare are presumed as in Table 5.1.

In addition to the five patterns in Figure 5.10, there can be two more travel-activity patterns with rideshare. They are shown in Figure 5.12 and denoted (f) and (g). In both of them, household member 2 utilizes rideshare along with PT to commute to activity 1 so that he can avoid the waiting time he would have if he commuted there by PT. In pattern (g), he uses an AV only for egress from stop 1.

Table 5.1: Fare for Rideshare in Case 9B

c^r_{uw} (\$)	0	1	2	3	4 (Stop 1)	5 (Stop 2)
0	0	17.9	6.65	10.4	6.1	17.9
1	17.9	0	47.9	10.4	17.9	6.1
2	6.65	17.9	0	10.4	6.65	17.9
3	10.4	10.4	10.4	0	10.4	10.4
4 (Stop 1)	6.1	17.9	6.65	10.4	0	16.4
5 (Stop 2)	17.9	6.1	17.9	10.4	16.4	0

The household members choose one of the seven patterns, concerning the price of AV and the household's value of time parameter as well as in Case 9a. Figure 5.13 displays the seven regimes corresponding to the seven patterns. The shapes of these regimes for the large value of β are different from those in the previous case, while those of regimes for (a), (b), and (d) are the same. This result indicates that introducing rideshare services will reduce the demand among people with higher value of time for AVs. This is because, even when the price of AV is relatively high, it is still unnecessary for the household desiring less travel time to own two CVs thanks to the rideshare and PT services.

All in all, the two cases demonstrate that mHAPPAV is capable of investigating adaptation behavior for AVs in a realistic situation with multimodal transportation systems. The analyses in the last two cases consider the availability of other transportation modes and households' heterogeneous values of time. They show that these factors would strongly affect households' decisions to incorporate AVs, as well as the cost of AVs. It is implied that we finally need to consider the availability of various transportation modes other than CVs when we examine the utility of AVs in actual settings.

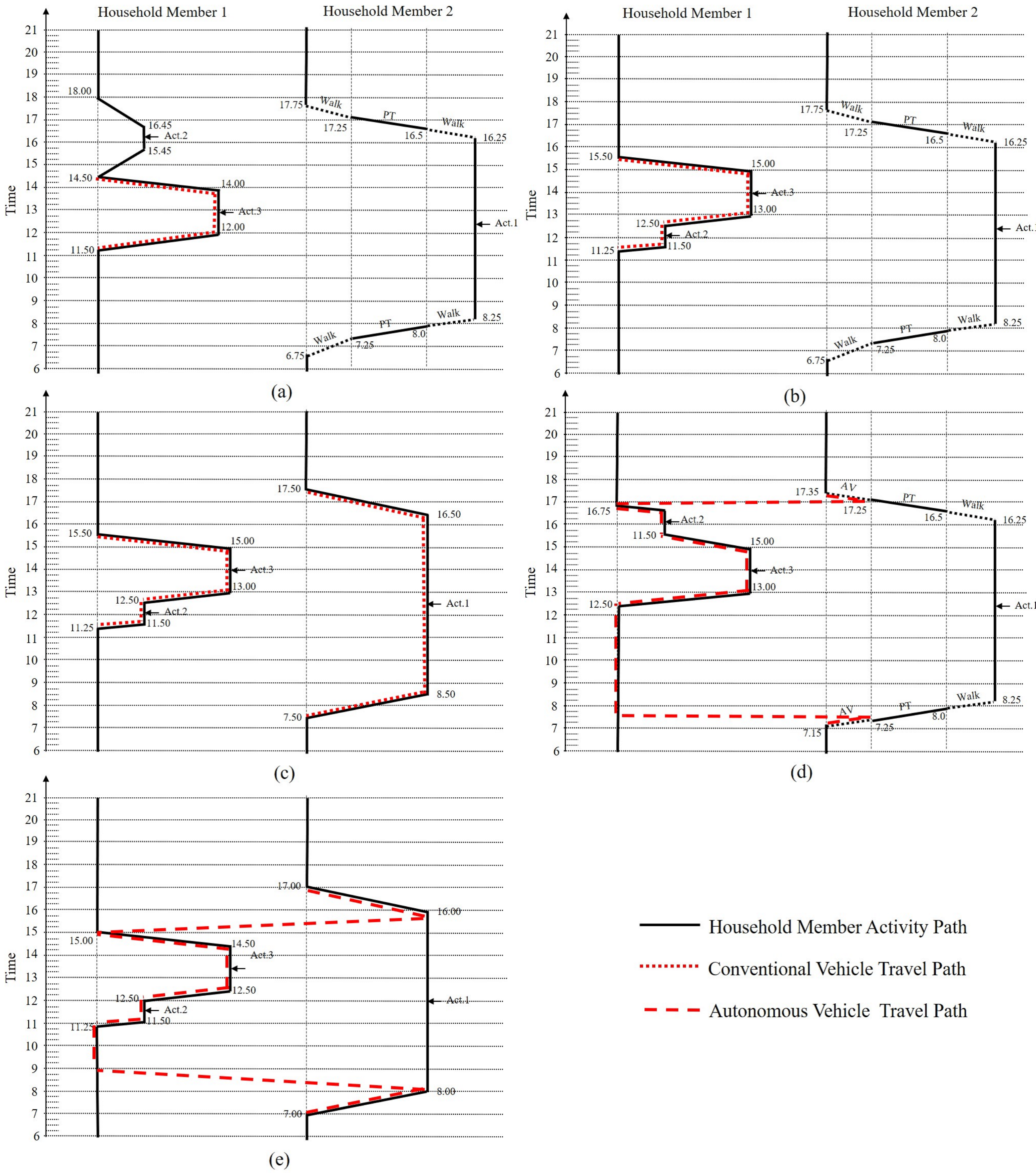

Figure 5.10: Possible Travel-Activity Patterns in Case 9A

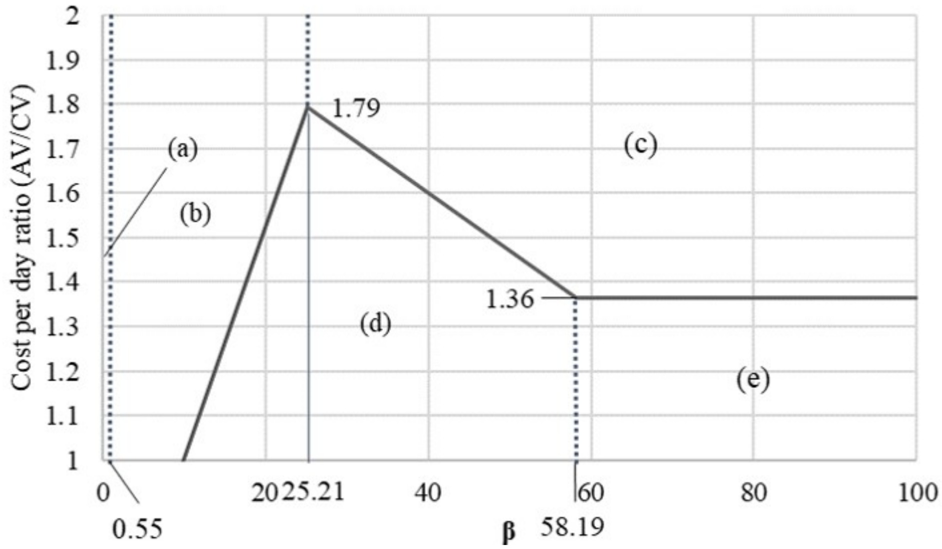

Figure 5.11: Travel-Activity Pattern Analysis Regarding AV Ownership Cost and Time-value Parameter for Case 9A

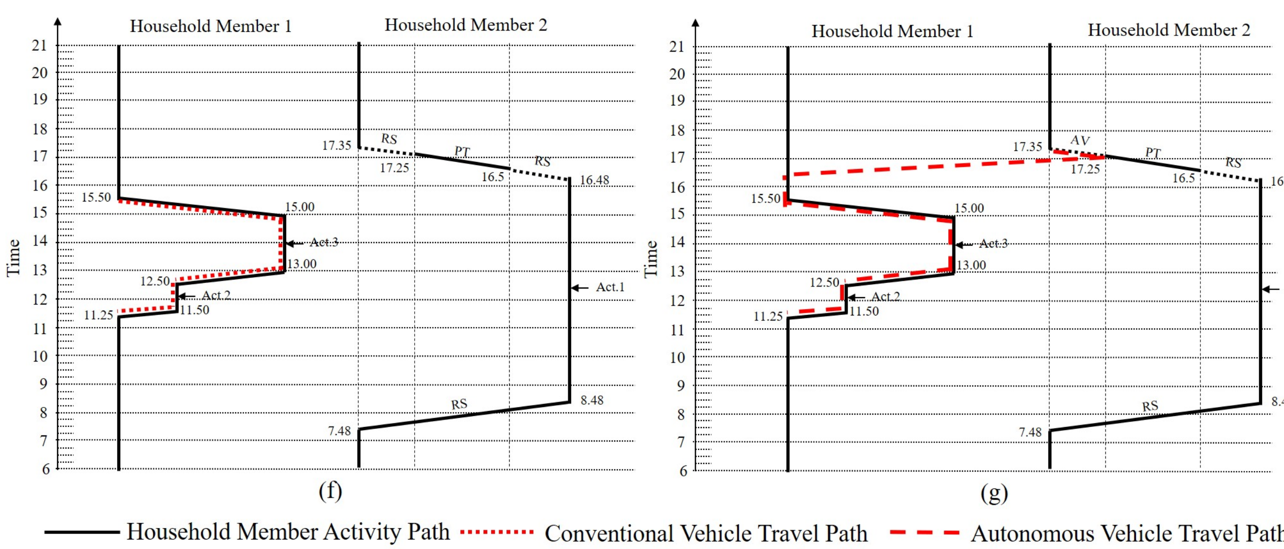

Figure 5.12: Additional Possible Travel-Activity Patterns in Case 9B

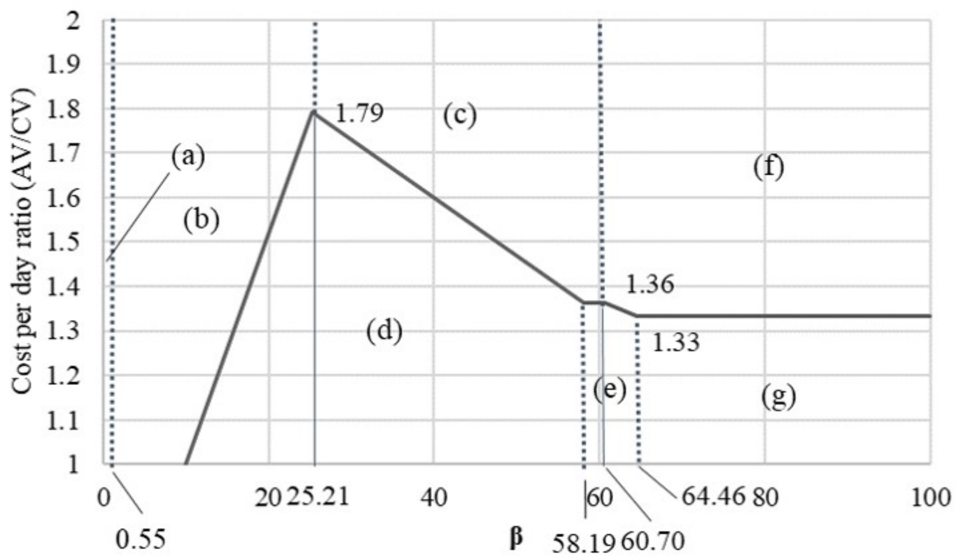

Figure 5.13: Travel-Activity Pattern Analysis Regarding AV Ownership Cost and Time-value Parameter for Case 9A

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The ”smart city” concept has been addressed in recent years. Even though the definition of the term is not concrete, the concept assumes an urban system whose components are designed to work concertedly to achieve a certain objective and a desirable environment. AVs are expected to be an essential means of traveling in the smart city. This unprecedented transportation mode would make the smart city concept more promising but even more complicated than the cities of today. Accordingly, the tools for designing such a complex city with AVs are needed.

Planning or managing urban transportation systems must begin with understanding them based on rigorous analytical theories. The same is the case for those in the smart cities. To capture the behavioral aspects of urban environments, traditional ABA has been developed as the most comprehensive behavioral theory for travel demand analysis. This approach provides a sound theoretical basis for analyzing the demand side of urban transportation systems. However, even though many models have been developed based on this approach, only a few of them have been employed to evaluate either multimodal transportation systems or AVs.

This research focuses on HAPP among the existing ABMs and reformulates it to evaluate the viability of AVs under various settings with multimodal transportation modes. AVs are expected to provide, for example, disabled people with mobility and, moreover, everyone with higher quality of life free from stressful driving. Nonetheless, they may induce negative influence on our lives. As shown in Chapter 4, AVs will probably cause more VMT than CVs due to their zero occupancy trips. In that sense, they might rather be detrimental than be beneficial for the society in terms of environmental burden. Hence, without any insights of the whole impacts of AVs, we cannot establish an effective strategy for AV operation. In this context, this research proposes a basic tool, which explicitly depicts what activity pattern would be desirable for a household purchasing an AV, to evaluate such a new mobility option. The feature of this model helps to forecast traveling behavior after private AVs become available. Households will want to make a sensible choice of whether they purchase AVs or still rely on CVs. This decision can be guided by the framework presented in this study because it illustrates a specific context where AVs are useful for the household in terms of its ownership costs. In addition, the examples shown in Case 4 reveal that the proposed model can be used to analyze management or policies. It is shown that imposing parking fee can induce extra AV traveling and higher environmental cost. Even though this analysis is based on hypothetical arrangements, a similar kind of investigation could be considered when managing smart cities in which AVs would probably be dominating.

The AV not only adds a kind of transportation mode but also leads to a new concept of mobility service. Society has also embraced innovative transportation services other than AVs. Ridesharing services, such as Uber and Lyft, have already affected traveler behavior in a large number of cities. Electric vehicles and shared mobility have already come into practice. Further, MaaS will finally form a new entity of urban transportation system including these transportation services as well as conventional ones.

This thesis develops mHAPPAV, a new model that enhances the HAPP framework's multimodality and applicability in more realistic settings. It successfully incorporates different types of private vehicles, walking, ridesharing and public transit into the model in addition to CV and AV. This extension enables the HAPP framework to evaluate multimodal transportation systems and, moreover, AVs coordinating or competing with other transportation modes. To date, mHAPPAV is the only framework that can illustrate travel -activity patterns with a combination of multiple modes including AVs.

6.2 Future work

The most probable issue that we will face when applying the proposed framework to real data is computational. Because the original HAPP is generally categorized as an MILP within the subset of the NP-hard optimization problems, its requirement for computational time will be intractable when it is applied to a large problem. mHAPPAV furthermore adds decision variables representing various transportation modes to the original model and, thus, requires more effort to find a solution than the original one. It is important to solve a problem in a feasible time, especially when mHAPPAV is used in practice. In the context of demand forecasting, solving problems for numerous households and aggregating the solutions are required. Consequently, an efficient solution method is needed for the effective applications of the proposed framework.

Next, this research uses some prescribed parameters in the objective functions. Some of the examples in Chapter 5 show possible different travel-activity patterns depending on a parameter expressing the value of time for a household. Thus, it is necessary to estimate these parameter values to simulate realistic activity-travel patterns in actual applications.

While the estimation method suggested by preceding research, such as those by Recker et al. (2008) [34], Chow and Recker (2013) [12] and Xu et al. (2017) [41], can be applicable, those methods are conventionally based on behavioral data sampled from a household travel survey. However, when we apply mHAPPAV to households whose travel-activity patterns have not yet been observed, it is necessary to infer behavioral parameters based only on their attributes. Therefore, we have to develop a parameter inference framework while considering the availability of behavioral or personal data.

Third, this research does not explicitly represent shared ride of vehicles. Allowing for shared ride on AVs will lead to different travel-activity patterns from those obtained in this research and higher viability of them. Furthermore, it is crucial to evaluate shared mobility services that will grow to be a key transportation service in the future. Since an AV likely will be more expensive than a CV, SAV systems will probably make sharing vehicle services more common than current ones. Although this research optimistically assumes that rideshares can always serve passengers, rideshare services in reality have variable levels of service, which affects travelers' decision making. Their services are also determined by the demand level for themselves. Therefore, in order to evaluate shared mobility services, dynamic representation of transportation systems should be considered in the HAPP framework.

Finally, the mHAPPAV framework is directly developed from the original HAPP model by Recker (1995) [35]; that is, it does not model other behavioral aspects, for example, rescheduling and location choice, which previous studies concerned HAPP have formulated. Including these travel behaviors will enhance the model's capability of evaluating a wider variety of policies and services. Because mHAPPAV is merely a reformulation of the original HAPP, the extensions above can be built into it—this thesis offers a rigorous foundation for an operational tool to evaluate advanced transportation systems.

Bibliography

[1] AAA. YOUR DRIVING COSTS, 2017.

[2] T. Adler and M. Ben-Akiva. A theoretical and empirical model of trip chaining behavior. *Transportation Research Part B: Methodological*, 13(3):243–257, 1979.

[3] U. S. D. o. T. F. H. Administration. Summary of Travel Trends: 2009 National Household Travel Survey, 2009.

[4] T. A. Arentze and H. J. P. Timmermans. A learning-based transportation oriented simulation system. *Transportation Research Part B: Methodological*, 38(7):613–633, 2004.

[5] J. Auld and A. Mohammadian. Activity planning processes in the Agent-based Dynamic Activity Planning and Travel Scheduling (ADAPTS) model. *Transportation Research Part A: Policy and Practice*, 46(8):1386–1403, 2012.

[6] J. Auld, V. Sokolov, and T. S. Stephens. Analysis of the Effects of Connected–Automated Vehicle Technologies on Travel Demand. *Transportation Research Record: Journal of the Transportation Research Board*, 2625:1–8, 2017.

[7] C. Bhat, J. Guo, S. Srinivasan, and A. Sivakumar. Comprehensive Econometric Microsimulator for Daily Activity-Travel Patterns. *Transportation Research Record: Journal of the Transportation Research Board*, 1894:57–66, 2004.

[8] J. L. Bowman. *The Day Activity Schedule Approach to Travel Demand Analysis*. PhD thesis, Massachusetts Institute of Technology, 1998.

[9] J. L. Bowman and M. E. Ben-Akiva. Activity-based disaggregate travel demand model system with activity schedules. *Transportation Research Part A: Policy and Practice*, 35(1):1–28, 2001.

[10] F. S. F. S. Chapin. *Human activity patterns in the city : things people do in time and in space*. New York : Wiley, 1974.

[11] J. Y. J. Chow and S. Djavadian. Activity-based market equilibrium for capacitated multimodal transport systems. *Transportation Research Part C: Emerging Technologies*, 59:2–18, 2015.

[12] J. Y. J. Chow and W. W. Recker. Inverse optimization with endogenous arrival time constraints to calibrate the household activity pattern problem. *Transportation Research Part B: Methodological*, 46(3):463–479, 2012.

[13] D. Ettema, A. Borgers, and H. Timmermans. SMASH (Simulation Model of Activity Scheduling Heuristics): Some Simulations. *Transportation Research Record*, 1551(1):88–94, 1996.

[14] D. J. Fagnant and K. Kockelman. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, 77:167–181, 2015.

[15] D. J. Fagnant and K. M. Kockelman. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies*, 40:1–13, 2014.

[16] L. P. Gan and W. Recker. A mathematical programming formulation of the household activity rescheduling problem. *Transportation Research Part B: Methodological*, 42(6):571–606, 2008.

[17] L. P. Gan and W. Recker. Stochastic Preplanned Household Activity Pattern Problem with Uncertain Activity Participation (SHAPP). *Transportation Science*, 47(3):439–454, 2013.

[18] T. Gärling, T. Kalén, J. Romanus, M. Selart, and B. Vilhelmson. Computer Simulation of Household Activity Scheduling. *Environment and Planning A: Economy and Space*, 30(4):665–679, 1998.

[19] K. G. Goulias, C. R. Bhat, R. M. Pendyala, Y. Chen, R. Paleti, K. C. Konduri, T. Lei, S. Y. Yoon, G. Huang, and H.-H. Hu. Simulator of Activities, Greenhouse Emissions, Networks, and Travel (SimAGENT) in Southern California. 2012.

[20] T. Hägerstrand. WHAT ABOUT PEOPLE IN REGIONAL SCIENCE? *Papers in Regional Science*, 24(1):7–24, 1970.

[21] M. Hyland and H. S. Mahmassani. Dynamic autonomous vehicle fleet operations: Optimization-based strategies to assign AVs to immediate traveler demand requests. *Transportation Research Part C: Emerging Technologies*, 92:278–297, 2018.

[22] P. M. Jones, M. C. Dix, M. I. CLARKE, and I. G. Heggie. *Understanding travel behaviour*. Gower Publishing, Brookfield, Vt United States, 1983.

[23] J. E. Kang, J. Y. J. Chow, and W. W. Recker. On activity-based network design problems. *Transportation Research Part B: Methodological*, 57:398–418, 2013.

[24] J. E. Kang and W. Recker. The location selection problem for the household activity pattern problem. *Transportation Research Part B: Methodological*, 55:75–97, 2013.

[25] Y. Khayati. *Household Use of Emerging Vehicle Technologies: Modeling Framework and Traveler Adaptation*. PhD thesis, The State University of New York at Buffalo, 2018.

[26] R. Kitamura and S. Fujii. Two Computational Process Models Of Activity-Travel Behavior. Theoretical Foundations of Travel Choice Modeling. *Theoretical Foundations of Travel Choice Modeling*, pages 251–279, 1998.

[27] R. Kitamura, A. Kikuchi, S. Fujii, and T. Yamamoto. *An Overview of PCATS/DEBNetS Micro-simulation System: Its Development, Extension, and Application to Demand Forecasting*, pages 371–399. Springer US, Boston, MA, 2005.

[28] L. Kröger, T. Kuhnimhof, and S. Trommer. Does context matter? A comparative study modelling autonomous vehicle impact on travel behaviour for Germany and the USA. *Transportation Research Part A: Policy and Practice*, 2018.

[29] B. Lenntorp. *Paths in space-time environments: A timegeographic study of movement possibilities of individuals*. Lund studies in geography : Ser. B., Human geography. Royal University of Lund, Department of Geography, 1976.

[30] N. Masoud and R. Jayakrishnan. Autonomous or driver-less vehicles: Implementation strategies and operational concerns. *Transportation Research Part E: Logistics and Transportation Review*, 108:179–194, 2017.

[31] M. G. McNally and C. R. Rindt. The Activity-Based Approach. In *Handbook of Transport Modelling*, chapter 4, pages 55–73. 2007.

[32] R. Pendyala, R. Kitamura, A. Kikuchi, T. Yamamoto, and S. Fujii. Florida Activity Mobility Simulator: Overview and Preliminary Validation Results. *Transportation Research Record: Journal of the Transportation Research Board*, 1921:123–130, 2005.

[33] S. Rasouli and H. Timmermans. Activity-based models of travel demand: promises, progress and prospects. *International Journal of Urban Sciences*, 18(1):31–60, 2014.

[34] W. Recker, J. Duan, and H. Wang. Development of an Estimation Procedure for an Activity-Based Travel Demand Model. *Computer-Aided Civil and Infrastructure Engineering*, 23(7):483–501, 2008.

[35] W. W. Recker. The household activity pattern problem: General formulation and solution. *Transportation Research Part B: Methodological*, 29(1):61–77, 1995.

[36] W. W. Recker. A bridge between travel demand modeling and activity-based travel analysis. *Transportation Research Part B: Methodological*, 35(5):481–506, 2001.

[37] W. W. Recker, M. G. McNally, and G. S. Root. A model of complex travel behavior: Part I—Theoretical development. *Transportation Research Part A: General*, 20(4):307–318, 1986.

[38] W. W. Recker, M. G. McNally, and G. S. Root. A model of complex travel behavior: Part II—An operational model. *Transportation Research Part A: General*, 20(4):319–330, 1986.

[39] M. J. Roorda, E. J. Miller, and K. M. N. Habib. Validation of TASHA: A 24-h activity scheduling microsimulation model. *Transportation Research Part A: Policy and Practice*, 42(2):360–375, 2008.

[40] M. M. Solomon and J. Desrosiers. Survey Paper—Time Window Constrained Routing and Scheduling Problems. *Transportation Science*, 22(1):1–13, 1988.

[41] Z. Xu, J. E. Kang, and R. Chen. A Random Utility Based Estimation Framework for the Household Activity Pattern Problem. *Transportation Research Procedia*, 23:809–826, 2017.

[42] W. Zhang, S. Guhathakurta, and E. B. Khalil. The impact of private autonomous vehicles on vehicle ownership and unoccupied VMT generation. *Transportation Research Part C: Emerging Technologies*, 90:156–165, 2018.

Appendix A

A.1 Notation for Indexes

$V_c = \{1, 2, ..., v, ..., \|V_c\|\}$:	The set of conventional vehicles which serve travelers.
$V_a = \{\|V_c\| + 1, \|V_c\| + 2, ..., \|V_c\| + v, ..., \|V_c\| + \|V_a\|\}$:	The set of autonomous vehicles which serve travelers.
$V = V_c \cup V_a$:	The set of vehicles which serve travelers.
$\eta = \{1, 2, ..., j, ..., \|\eta\|\}$:	The set of household members.
$A = \{1, 2, ..., i, ..., n\}$:	The set of out-of-home activities scheduled to be completed by travelers in the household.
$A_M = \{1, 2, ..., i, ..., m\}$:	The set of out-of-home mandatory activities scheduled to be completed by travelers in the household.
$A_D = \{m + 1, ..., i, ..., n\}$:	The set of out-of-home discretionary activities scheduled to be completed by travelers in the household.

$A_{D_1} = \{m+1, ..., i, ..., \tilde{m}\}, \tilde{m} = m + m_{D_1}$: The set of out-of-home discretionary activities of type 1 scheduled to be completed by travelers in the household.

$A_{D_2} = \{\tilde{m}+1, ..., i, ..., n\}$: The set of out-of-home discretionary activities of type 2 scheduled to be completed by travelers in the household.

$A_P = \{\tilde{m}+1, ..., i, ..., \tilde{m}+m_P\}, \tilde{m}+m_P \leq n$: The set of PT activities scheduled to be completed by travelers in the household.

$\tilde{P}^+ = \{1, 2, ..., i, ..., n\}$: The set designating origin from which the trip for each activity departs.

$\tilde{P}^- = \{n+1, n+2, ..., n+i, ..., 2n\}$: The set designating location at which each activity begins.

$\underset{\sim}{P}^+ = \{2n+1, 2n+2, ..., 2n+i, ..., 3n\}$: The set designating location at which each activity ends.

$\underset{\sim}{P}^- = \{3n+1, 3n+2, ..., 3n+i, ..., 4n\}$: The set designating the ultimate destination of the return-to-home trip for each activity.

$\tilde{P}_M^+ = \{1, 2, ..., i, ..., m\}$: The set designating origin from which the trip for each mandatory activity departs.

$\tilde{P}_M^- = \{n+1, n+2, ..., n+i, ..., n+m\}$: The set designating location at which each mandatory activity begins.

$\underset{\sim}{P}_M^+ = \{2n+1, 2n+2, ..., 2n+i, ..., 2n+m\}$: The set designating location at which each mandatory activity ends.

$\underset{\sim}{P}_M^- = \{3n+1, 3n+2, ..., 3n+i, ..., 3n+m\}$: The set designating the ultimate destination of the return-to-home trip for each mandatory activity.

$\tilde{P}_{D_1}^+ = \{m+1, m+2, ..., i, ..., \tilde{m}\}$: The set designating origin from which the trip for each type 1 discretionary activity departs.

$\tilde{P}_{D_1}^- = \{n+m+1, n+m+2, ..., n+m+i, ..., n+\tilde{m}\}$: The set designating location at which each type 1 discretionary activity begins.

$\underset{\sim}{P}_{D_1}^+ = \{2n+m_{D_1}+1, 2n+m_{D_1}+2, ..., 2n+m_{D_1}+i, ..., 2n+\tilde{m}\}$: The set designating location at which each type 1 discretionary activity ends.

$\underset{\sim}{P}_{D_1}^- = \{3n+m_{D_1}+1, 3n+m_{D_1}+2, ..., 3n+m_{D_1}+i, ..., 3n+\tilde{m}\}$: The set designating the ultimate destination of the return-to-home trip for each type 1 discretionary activity.

$\tilde{P}_{D_2}^+ = \{\tilde{m}+1, \tilde{m}+2, ..., i, ..., n\}$: The set designating origin from which the trip for each type 2 discretionary activity departs.

$\tilde{P}_{D_2}^- = \{n+\tilde{m}+1, n+\tilde{m}+2, ..., n+\tilde{m}+i, ..., 2n\}$:

The set designating location at which each type 2 discretionary activity begins.

$\underset{\sim}{P}^{+}_{D_2} = \{2n + \tilde{m} + 1, 2n + \tilde{m} + 2, ..., 2n + \tilde{m} + i, ..., 3n\}$:

The set designating location at which each type 2 discretionary activity ends.

$\underset{\sim}{P}^{-}_{D_2} = \{3n + \tilde{m} + 1, 3n + \tilde{m} + 2, ..., 3n + \tilde{m} + i, ..., 4n\}$:

The set designating the ultimate destination of the return-to-home trip for each type 2 discretionary activity.

$\tilde{P}^{+}_{P} = \{\tilde{m} + 1, \tilde{m} + 2, ..., i, ..., \tilde{m} + m_P\} \subseteq \tilde{P}^{+}_{D_2}$: The set designating origin from which the trip for each PT activity departs.

$\tilde{P}^{-}_{P} = \{n + \tilde{m} + 1, n + \tilde{m} + 2, ..., n + \tilde{m} + i, ..., n + \tilde{m} + m_P\} \subseteq \tilde{P}^{-}_{D_2}$:

The set designating location at which each PT activity begins.

$\underset{\sim}{P}^{+}_{P} = \{2n + \tilde{m} + 1, 2n + \tilde{m} + 2, ..., 2n + \tilde{m} + i, ..., 2n + \tilde{m} + m_P\} \subseteq \underset{\sim}{P}^{+}_{D_2}$:

The set designating location at which each PT activity ends.

$\underset{\sim}{P}^{-}_{P} = \{3n + \tilde{m} + 1, 3n + \tilde{m} + 2, ..., 3n + \tilde{m} + i, ..., 3n + \tilde{m} + m_P\} \subseteq \underset{\sim}{P}^{-}_{D_2}$:

The set designating the ultimate destination of the return-to-home trip for each PT activity.

$\tilde{P}_D^+ = \tilde{P}_{D_1}^+ \cup \tilde{P}_{D_2}^+$:	The set designating origin from which the trip for each discretionary activity departs.
$\tilde{P}_D^- = \tilde{P}_{D_1}^- \cup \tilde{P}_{D_2}^-$:	The set designating location at which each discretionary activity begins.
$\utilde{P}_D^+ = \utilde{P}_{D_1}^+ \cup \utilde{P}_{D_2}^+$:	The set designating location at which each discretionary activity ends.
$\utilde{P}_D^- = \utilde{P}_{D_1}^- \cup \utilde{P}_{D_2}^-$:	The set designating the ultimate destination of the return-to-home trip for each discretionary activity.
$P^+ = \tilde{P}^+ \cup \utilde{P}^+$:	The set of activity pick-up locations.
$P^- = \tilde{P}^- \cup \utilde{P}^-$:	The set of activity drop-off locations.
$P = P^+ \cup P^-$:	The set of activity locations.
$N = \{0, P, 4n+1\}$:	The set of all nodes, including those associated with initial departure and final return to home.

A.2 Notation for Variables

X_{uw}^v:	Binary decision variable equal to unity if vehicle v travels from activity u to activity w, and zero otherwise.
H_{uw}^j:	Binary decision variable equal to unity if household member j travels from activity u to activity w, and zero otherwise.
R_{uw}^j:	Binary decision variable equal to unity if household member j travels from activity u to activity w on rideshare, and zero otherwise.

T_u: The time at witch participation in activity u begins.

T_0^v, T_{4n+1}^v: The times at which vehicle v first departs from its origin and finally arrives at its destination respectively.

$\bar{T}_0^j, \bar{T}_{4n+1}^j$: The times at which a household member j first departs from its origin and finally arrives at its destination respectively.

$[a_i, b_i]$: The time window of available start times for activity i. (Note: b_i must precede the closing of the availability of activity i by an amount equal to or greater than the duration of the activity.)

$[a_{i+n}, b_{i+n}]$: The time windows for the return-home arrival from activity i.

$[a_0, b_0]$: The departure time window for the beginning of the travel day.

$[a_{4n+1}, b_{4n+1}]$: The arrival time window by which time all members of the household must complete their travel.

$\bar{a}_0^j$: The earliest possible departure time for household member j.

$\bar{b}_{4n+1}^j$: The latest possible return home time for household member j

t_{uw}^v: The travel time from the time-space location of activity u to the time-space location of activity w by vehicle v.

t_{uw}^H: The travel time from the time-space location of activity u to the time-space location of activity w on foot .

c_{uw}^v: The travel cost from the time-space location of activity u to the time-space location of activity w by vehicle v.

c_{uw}^P: The fare from the time-space location of activity u to the time-space location of activity w by public transit.

c_{uw}^R: The fare from the time-space location of activity u to the time-space location of activity w by rideshare.

Υ_i^v: The total accumulation of passengers on vehicle v immediately following completion activity i.

Y_i^j:	The total accumulation of activities on a particular tour by household member j immediately following completion activity i.
d_i:	The demand function for activity i.
D^v:	The maximum number of passengers on vehicle v.
D^j:	The maximum number of sojourns in any tour by household member j.
Ω_ν^v:	The subset of activities that cannot be performed by vehicle/person v.
Ω_H^j:	The subset of activities that cannot be performed by household member j.
τ_i^a:	The waiting time after activity i is picked up or delivered.
τ_i^b:	The waiting time before activity i is picked up or delivered.
$\mathbb{P}_v^2$:	The set of OD pairs between which travelers cannot walk.

A.3 Parameters for Case 1-4

Travel time and cost between activity locations

Table A.3: Travel Time

t_{uw}	0	1	2	3
0	0.00	1.00	0.25	0.50
1	1.00	0.00	1.00	0.50
2	0.25	1.00	0.00	0.50
3	0.50	0.50	0.50	0.00

Table A.4: Travel Cost

c_{uw}	0	1	2	3
0	0.00	2.00	1.00	1.00
1	2.00	0.00	1.00	1.00
2	1.00	1.00	0.00	0.50
3	1.00	1.00	0.50	0.00

Activity durations

$$[s_1, s_2, s_3] = [8, 1, 2]$$

The time availability windows and corresponding return-home windows

$$\begin{bmatrix} a_1, b_1 \\ a_2, b_2 \\ a_3, b_3 \end{bmatrix} = \begin{bmatrix} 8, 8.5 \\ 6, 21 \\ 12, 13 \end{bmatrix}, \begin{bmatrix} a_{1+n}, b_{1+n} \\ a_{2+n}, b_{2+n} \\ a_{3+n}, b_{3+n} \end{bmatrix} = \begin{bmatrix} 17, 19 \\ 10, 21 \\ 12, 21 \end{bmatrix}$$

Initial departure and end of travel day windows

$$[a_0, b_0] = [6, 20], [a_{4n+1}, b_{4n+1}] = [6, 21]$$

$$[\bar{a}_0, \bar{b}_0] = [\bar{a}_{4n+1}, \bar{b}_{4n+1}] = [6, 22]$$

Subsets of unperformed activities

$$\Omega_\nu^1 = \{1, 3\}, \Omega_\nu^2 = \{2\}$$

$$\Omega_H^1 = \{1\}, \Omega_H^2 = \{2, 3\}$$

A.4 Constraints for HAPPAV2

(1) Vehicle temporal constraints

$$T_u + s_u + t_{u,u+n} \leq T_{u+n}, u \in P^+ \cup \tilde{P}^- \tag{C1.1}$$

$$T_u + s_u + t_{uw} - T_w \leq (1 - X^v_{uw})M, \forall u, w \in P, \forall v \in V_c \tag{C1.2}$$

$$T_u + t_{uw} - T_w \leq (1 - X^v_{uw})M, \forall u, w \in P, \forall v \in V_a \tag{C1.2'}$$

$$T^v_0 + s_0 + t_{0,w} - T_w \leq (1 - X^v_{0,w})M, \forall w \in P^+, \forall v \in V \tag{C1.3}$$

$$T_u + t_{u,4n+1} - T^v_{4n+1} \leq (1 - X^v_{u,4n+1})M, \forall u \in P^-, \forall v \in V \tag{C1.4}$$

$$a_{u-n} \leq T_u \leq b_{u-n}, \forall u \in \tilde{P}^- \cup \underset{\sim}{P}^+ \tag{C1.5}$$

$$a^v_0 \sum_{w \in N} X^v_{0,w} \leq T^v_0 \leq b^v_0 \sum_{w \in N} X^v_{0,w}, \forall v \in V \tag{C1.6}$$

$$a^v_{4n+1} \sum_{w \in N} X^v_{0,w} \leq T^v_{4n+1} \leq b^v_{4n+1} \sum_{w \in N} X^v_{0,w}, \forall v \in V \tag{C1.7}$$

Subtour duration constraints

$$T_{u+n} \leq T_{u'}, \forall u \in \tilde{P}^+ \tag{C1.8}$$

$$T_{u'+3n} \leq T_{u+2n}, \forall u \in \tilde{P}^+. \tag{C1.9}$$

Constraints for calculating parking time

$$\sum_{v \in V} X^v_{uw} = 1 \text{ and } t_{uw} > 0 \text{ and } u \in P^+$$
$$\Rightarrow \begin{cases} \tau^a_u = T_w - (T_u + s_u + t_{uw}), \tau^b_w = 0 & \text{if } k_u \leq k_w \text{ and } w \in P^+ \\ \tau^a_u = 0, \tau^b_w = T_w - (T_u + s_u + t_{uw}) & \text{otherwise} \end{cases} \tag{C1.10}$$

$$\sum_{v \in V} X_{uw}^{v} = 1 \text{ and } t_{uw} > 0 \text{ and } u \in P^{-}$$

$$\Rightarrow \begin{cases} \tau_u^a = 0, \tau_w^b = T_w - (T_u + s_u + t_{uw}) & \text{if } k_u \leq k_w \text{ and } w \in P^{+} \\ \tau_u^a = T_w - (T_u + s_u + t_{uw}), \tau_w^b = 0 & \text{otherwise} \end{cases} \tag{C1.11}$$

$$\sum_{v \in V} X_{uw}^{v} = 1 \text{ and } t_{uw} = 0 \Rightarrow \tau_u^a = T_w - (T_u + s_u), \tau_w^b = 0, \forall u \in P, \forall w \in P. \tag{C1.12}$$

$$\sum_{v \in V} X_{uw}^{v} = 0 \Rightarrow \tau_u^a = 0, \tau_w^b = 0, \forall u \in P, \forall w \in P. \tag{C1.13}$$

(2) Household member temporal constraints

$$T_u + s_u + t_{uw} - T_w \leq (1 - H_{uw}^{j})M, \forall u, w \in P, \forall j \in \eta \tag{C2.1}$$

$$T_0^j + s_0 + t_{0w} - T_w \leq (1 - H_{0w}^{j})M, \forall w \in \tilde{P}^{+}, \forall j \in \eta \tag{C2.2}$$

$$T_u + s_u + t_{u,4n+1} - \bar{T}_{4n+1}^{j} \leq (1 - H_{u,4n+1}^{j})M, \forall u \in \underset{\sim}{P}^{-}, \forall j \in \eta \tag{C2.3}$$

$$\bar{a}_0^j \sum_{w \in N} H_{0,w}^{j} \leq \bar{T}_0^j \leq M \sum_{w \in N} H_{0,w}^{j}, \forall j \in \eta \tag{C2.4}$$

$$\bar{T}_{4n+1}^{j} \leq \bar{b}_{4n+1}^{j} \sum_{w \in N} H_{0,w}^{j}, \forall j \in \eta \tag{C2.5}$$

(3) Spatial connectivity constraints on the vehicles

$$\sum_{v \in V} \sum_{w \in N} X_{uw}^{v} = 1, \forall u \in P_M^{+} \tag{C3.1}$$

$$\sum_{v \in V} \sum_{w \in N'} X_{uw}^{v} \leq 1, \forall u \in P_D^{+}. \tag{C3.1'}$$

$$\sum_{w \in N} X_{uw}^{v} - \sum_{w \in N} X_{wu}^{v} = 0, \forall u \in P, \forall v \in V \tag{C3.2}$$

$$\sum_{w \in P^+} X^v_{0,w} \leq 1, \forall v \in V \tag{C3.3'}$$

$$\sum_{u \in P^-} X^v_{u,4n+1} \leq 1, \forall v \in V \tag{C3.4'}$$

$$\sum_{w \in N} X^v_{wu} - \sum_{w \in N} X^v_{w,u+n} = 0, \forall u \in P^+, \forall v \in V \tag{C3.5}$$

$$\sum_{w \in P^- \cup \underset{\sim}{P}^+} X^v_{0,w} = 0, \forall v \in V_c \tag{C3.6}$$

$$\sum_{w \in P^-} X^v_{0,w} = 0, \forall v \in V_a \tag{C3.6'}$$

$$\sum_{u \in N} X^v_{u,0} = 0, \forall v \in V \tag{C3.7}$$

$$\sum_{u \in P^+ \cup \tilde{P}^-} X^v_{u,4n+1} = 0, \forall v \in V_c \tag{C3.8}$$

$$\sum_{u \in P^+} X^v_{u,4n+1} = 0, \forall v \in V_a \tag{C3.8'}$$

$$\sum_{w \in N} X^v_{4n+1,w} = 0, \forall v \in V \tag{C3.9}$$

$$\sum_{v \in V_c} X^v_{u,u+n} \leq 1, \forall \tilde{P}^- \tag{C3.10'}$$

$$\sum_{u \in \tilde{P}^+} X^v_{u,2n+u} = 0, \forall v \in V \tag{C3.11}$$

$$\sum_{w \in \tilde{P}^+} X^v_{2n+w,w} = 0, \forall v \in V \tag{C3.12}$$

$$\sum_{u \in \tilde{P}^+} X^v_{u,3n+u} = 0, \forall v \in V \tag{C3.13}$$

$$\sum_{w \in \tilde{P}^+} X^v_{3n+w,w} = 0, \forall v \in V \tag{C3.14}$$

$$\sum_{u \in \tilde{P}^-} X^v_{u,2n+u} = 0, \forall v \in V \tag{C3.15}$$

$$\sum_{w \in \tilde{P}^-} X^v_{2n+w,w} = 0, \forall v \in V \tag{C3.16}$$

$$\sum_{w \in \tilde{P}^-} X^v_{n+w,w} = 0, \forall v \in V \tag{C3.17}$$

$$\sum_{v\in V}\sum_{w\in N} X^v_{wu} - \sum_{v\in V}\sum_{w\in N} X^v_{w,u+n} = 0, \forall u \in \tilde{P}^-. \tag{C3.18}$$

$$\sum_{u\in N} X^v_{uw} = X^v_{w,w+n}, \forall v \in V_a, \forall w \in \tilde{P}^+_{D_1} \tag{C3.19}$$

(4) Spatial connectivity constraints on the household members

$$\sum_{j\in\eta}\sum_{w\in N} H^j_{uw} = 1, \forall u \in P^+_M \tag{C4.1'}$$

$$\sum_{j\in\eta}\sum_{w\in N} H^j_{uw} \leq 1, \forall u \in P^+_D, \tag{C4.1'b}$$

$$\sum_{w\in N} H^j_{uw} - \sum_{w\in N} H^j_{wu} = 0, \forall u \in P, \forall j \in \eta \tag{C4.2}$$

$$\sum_{w\in \tilde{P}^+} H^j_{0,w} = 1, \forall j \in \eta \tag{C4.3}$$

$$\sum_{u\in \tilde{P}^-} H^j_{u,4n+1} = 1, \forall j \in \eta \tag{C4.4}$$

$$\sum_{w\in N} H^j_{wu} - \sum_{w\in N} H^j_{w,u+n} = 0, \forall u \in P^+, \forall j \in \eta \tag{C4.5}$$

$$\sum_{j\in\eta} H^j_{u,u+n} = 1, \forall u \in \tilde{P}^-_M \tag{C4.6}$$

$$\sum_{j\in\eta} H^j_{u,u+n} \leq 1, \forall u \in \tilde{P}^-_D. \tag{C4.6'}$$

$$\sum_{w\in \tilde{P}^+\cup P^-} H^j_{0,w} = 0, \forall j \in \eta \tag{C4.7}$$

$$\sum_{u\in N} H^j_{u,0} = 0, \forall j \in \eta \tag{C4.8}$$

$$\sum_{u\in P^+\cup \tilde{P}^-} H^j_{u,4n+1} = 0, \forall j \in \eta \tag{C4.9}$$

$$\sum_{u\in N} H^j_{4n+1,w} = 0, \forall j \in \eta \tag{C4.10}$$

$$\sum_{u \in \tilde{P}^+} H^j_{u,2n+u} = 0, \forall j \in \eta \tag{C4.11}$$

$$\sum_{w \in \tilde{P}^+} H^j_{2n+w,w} = 0, \forall j \in \eta \tag{C4.12}$$

$$\sum_{u \in \tilde{P}^+} H^j_{u,3n+u} = 0, \forall j \in \eta \tag{C4.13}$$

$$\sum_{w \in \tilde{P}^+} H^j_{3n+w,w} = 0, \forall j \in \eta \tag{C4.14}$$

$$\sum_{u \in \tilde{P}^-} H^j_{u,2n+u} = 0, \forall j \in \eta \tag{C4.15}$$

$$\sum_{w \in \tilde{P}^-} H^j_{2n+w,w} = 0, \forall j \in \eta \tag{C4.16}$$

$$\sum_{w \in \tilde{P}^-} H^j_{n+w,w} = 0, \forall j \in \eta \tag{C4.17}$$

$$\sum_{w \in \underset{\sim}{P}^-} H^j_{uw} = 0, \forall j \in \eta, \forall u \in \tilde{P}^+ \tag{C4.18}$$

$$\sum_{u \in N} H^j_{uw} = H^j_{w,w+n}, \forall j \in \eta, \forall w \in \tilde{P}^-_{D_2} \tag{C4.19}$$

(5) Capacity budget and participation constraints

Capacity constraints on household members

$$H^j_{uw} = 1 \Rightarrow Y^j_u + d_w = Y^j_w, \forall j \in \eta, u \in P, w \in \tilde{P}^+ \tag{C5.1}$$

$$H^j_{uw} = 1 \Rightarrow Y^j_u - d_{w-n} = Y^j_w, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^- \tag{C5.2}$$

$$H^j_{uw} = 1 \Rightarrow Y^j_u = Y^j_w, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^+ \cup \tilde{P}^- \tag{C5.3}$$

$$H^j_{0w} = 1 \Rightarrow d_w = Y^j_w, \forall j \in \eta, \forall w \in \tilde{P}^+ \tag{C5.4}$$

$$0 \leq Y^j_u \leq D^j, \forall j \in \eta, \forall u \in P^+. \tag{C5.5}$$

Capacity constraints on vehicles

$$X_{uw}^{v} = 1 \Rightarrow \begin{cases} \Upsilon_u^v + d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{u'\in N} t_{wu'}H_{wu'}^{j} > 0 \text{ or } w \in \utilde{P}^{+} \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^{+} \quad \text{(C5.6)}$$

$$X_{uw}^{v} = 1 \Rightarrow \begin{cases} \Upsilon_u^v - d_{w-n} = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N} t_{w\tilde{u}}H_{w\tilde{u}}^{j} > 0 \text{ or } w \in \tilde{P}^{-} \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^{-} \quad \text{(C5.7)}$$

$$X_{0w}^{v} = 1 \Rightarrow \begin{cases} d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N} t_{w\tilde{u}}H_{w\tilde{u}}^{j} > 0 \\ 0 = \Upsilon_w^v & \text{otherwise} \end{cases}, \forall v \in V, \forall w \in \tilde{P}^{+} \quad \text{(C5.8)}$$

$$0 \le \Upsilon_u^v \le D^v, \forall v \in V, \forall u \in P^{+}. \quad \text{(C5.9)}$$

Participation constraints

$$\sum_{u\in N}\sum_{w\in\Omega_\nu^v} X_{uw}^{v} = 0, \forall v \in V \quad \text{(C5.10a)}$$

$$\sum_{u\in N}\sum_{w\in\Omega_\nu^v} X_{u,w+2n}^{v} = 0, \forall v \in V \quad \text{(C5.10b)}$$

$$\sum_{u\in N}\sum_{w\in\Omega_H^j} H_{uw}^{j} = 0, \forall j \in \eta \quad \text{(C5.11a)}$$

$$\sum_{u\in N}\sum_{w\in\Omega_H^j} H_{u,w+2n}^{j} = 0, \forall j \in \eta \quad \text{(C5.11b)}$$

(6) Vehicle and household member coupling constraints

$$H_{uw}^{j} = 1 \text{ and } t_{uw} > 0 \Rightarrow \sum_{v\in V} X_{uw}^{v} = 1, \forall j \in \eta, \forall u, w \in P, \quad \text{(C6.1)}$$

$$X_{uw}^v = 1 \text{ and } t_{uw} > 0 \Rightarrow \sum_{j\in\eta} H_{uw}^j = 1, \forall v \in V_c, \forall u, w \in P. \tag{C6.2}$$

$$\sum_{v\in V}\sum_{w\in P} X_{0,w}^v \leq \sum_{j\in\eta}\sum_{w\in P} H_{0w}^j \tag{C6.3}$$

$$\sum_{v\in V}\sum_{w\in P} X_{0,w}^v \geq \sum_{j\in\eta}\sum_{w\in P} H_{0w}^j - \eta + 1 \tag{C6.4}$$

A.5 Constraints for mHAPPAV

(1) Vehicle temporal constraints

$$T_u + s_u + \min_{\forall v \in V} t_{u,u+n}^v \leq T_{u+n}, u \in P^+ \cup \tilde{P}^- \tag{C1.1}$$

$$T_u + s_u + t_{uw}^v - T_w \leq (1 - X_{uw}^v)M, \forall u, w \in P, \forall v \in V_c \tag{C1.2}$$

$$T_u + t_{uw}^v - T_w \leq (1 - X_{uw}^v)M, \forall u, w \in P, \forall v \in V_a \tag{C1.2'}$$

$$T_0^v + s_0 + t_{0,w}^v - T_w \leq (1 - X_{0,w}^v)M, \forall w \in P^+, \forall v \in V \tag{C1.3}$$

$$T_u + t_{u,4n+1}^v - T_{4n+1}^v \leq (1 - X_{u,4n+1}^v)M, \forall u \in P^-, \forall v \in V \tag{C1.4}$$

$$a_{u-n} \leq T_u \leq b_{u-n}, \forall u \in \tilde{P}^- \cup \underset{\sim}{P}^+ \tag{C1.5}$$

$$a_0^v \sum_{w\in N} X_{0,w}^v \leq T_0^v \leq b_0^v \sum_{w\in N} X_{0,w}^v, \forall v \in V \tag{C1.6}$$

$$a_{4n+1}^v \sum_{w\in N} X_{0,w}^v \leq T_{4n+1}^v \leq b_{4n+1}^v \sum_{w\in N} X_{0,w}^v, \forall v \in V \tag{C1.7}$$

Subtour duration constraints

$$T_{u+n} \leq T_{u'}, \forall u \in \tilde{P}^+ \tag{C1.8}$$

$$T_{u'+3n} \leq T_{u+2n}, \forall u \in \tilde{P}^+. \tag{C1.9}$$

Constraints for calculating parking time

$$\sum_{v \in V} t^v_{uw} X^v_{uw} > 0, \text{ and } u \in P^+$$
$$\Rightarrow \begin{cases} \tau^a_u = T_w - (T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw}), \tau^b_w = 0 & \text{if } k_u \leq k_w \text{ and } w \in P^+ \\ \tau^a_u = 0, \tau^b_w = T_w - (T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw}) & \text{otherwise} \end{cases} \tag{C1.10}$$

$$\sum_{v \in V} t^v_{uw} X^v_{uw} > 0 > 0 \text{ and } u \in P^-$$
$$\Rightarrow \begin{cases} \tau^a_u = 0, \tau^b_w = T_w - (T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw}) & \text{if } k_u \leq k_w \text{ and } w \in P^+ \\ \tau^a_u = T_w - (T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw}), \tau^b_w = 0 & \text{otherwise} \end{cases} \tag{C1.11}$$

$$\sum_{v \in V} t^v_{uw} X^v_{uw} > 0 = 0 \Rightarrow \tau^a_u = T_w - (T_u + s_u), \tau^b_w = 0, \forall u \in P, \forall w \in P. \tag{C1.12}$$

$$\sum_{v \in V} X^v_{uw} = 0 \Rightarrow \tau^a_u = 0, \tau^b_w = 0, \forall u \in P, \forall w \in P. \tag{C1.13}$$

(2) Household member temporal constraints

$$H^j_{uw} = 1 \text{ and } \sum_{v \in V} X^v_{uw} = 1 \Rightarrow T_u + s_u + \sum_{v \in V} t^v_{uw} X^v_{uw} \leq T_w, \forall u, w \in P, \forall j \in \eta \tag{C2.1a}$$

$$H^j_{uw} = 1 \text{ and } \sum_{v \in V} X^v_{uw} = 0 \Rightarrow \begin{cases} T_u + s_u + t^h_{uw} \leq T_w, \text{ if } R^j_{uw} = 0 \\ T_u + s_u + t^r_{uw} \leq T_w, \text{ if } R^j_{uw} = 1 \end{cases}, \forall u, w \in P, \forall j \in \eta \tag{C2.1b}$$

$$H^j_{0,w} = 1 \text{ and } \sum_{v \in V} X^v_{0,w} = 1 \Rightarrow T^j_0 + s_0 + \sum_{v \in V} t^v_{0,w} X^v_{0,w} \leq T_w, \forall w \in P, \forall j \in \eta \tag{C2.2a}$$

$$H_{0,w}^{j} = 1 \text{ and } \sum_{v \in V} X_{0,w}^{v} = 0 \Rightarrow \begin{cases} T_0^j + s_0 + t_{0,w}^h \leq T_w, \text{ if } R_{0,w}^j = 0 \\ T_0^j + s_0 + t_{0,w}^r \leq T_w, \text{ if } R_{0,w}^j = 1 \end{cases}, \forall w \in P, \forall j \in \eta \tag{C2.2b}$$

$$H_{u,4n+1}^{j} = 1 \text{ and } \sum_{v \in V} X_{u,4n+1}^{v} = 1 \Rightarrow T_u + \sum_{v \in V} t_{u,4n+1}^{v} X_{u,4n+1}^{v} \leq T_{4n+1}^{j}, \forall u \in P, \forall j \in \eta \tag{C2.3a}$$

$$H_{u,4n+1}^{j} = 1 \text{ and } \sum_{v \in V} X_{u,4n+1}^{v} = 0 \Rightarrow \begin{cases} T_u + t_{u,4n+1}^h \leq T_{4n+1}^j, \text{ if } R_{u,4n+1}^j = 0 \\ T_u + t_{u,4n+1}^r \leq T_{4n+1}^j, \text{ if } R_{u,4n+1}^j = 1 \end{cases}, \quad \forall u \in P, \forall j \in \eta, \tag{C2.3b}$$

$$\bar{a}_0^j \sum_{w \in N} H_{0,w}^j \leq \bar{T}_0^j \leq M \sum_{w \in N} H_{0,w}^j, \forall j \in \eta \tag{C2.4}$$

$$\bar{T}_{4n+1}^j \leq \bar{b}_{4n+1}^j \sum_{w \in N} H_{0,w}^j, \forall j \in \eta \tag{C2.5}$$

(3) Spatial connectivity constraints on the vehicles

$$\sum_{v \in V} \sum_{w \in N} X_{uw}^v = 1, \forall u \in P_M^+ \tag{C3.1}$$

$$\sum_{v \in V} \sum_{w \in N'} X_{uw}^v \leq 1, \forall u \in P_D^+. \tag{C3.1'}$$

$$\sum_{w \in N} X_{uw}^v - \sum_{w \in N} X_{wu}^v = 0, \forall u \in P, \forall v \in V \tag{C3.2}$$

$$\sum_{w \in P^+} X_{0,w}^v \leq 1, \forall v \in V \tag{C3.3'}$$

$$\sum_{u \in P^-} X_{u,4n+1}^v \leq 1, \forall v \in V \tag{C3.4'}$$

$$\sum_{w \in N} X_{wu}^v - \sum_{w \in N} X_{w,u+n}^v = 0, \forall u \in P^+, \forall v \in V \tag{C3.5}$$

$$\sum_{w \in P^- \cup \tilde{P}^+} X^v_{0,w} = 0, \forall v \in V_c \tag{C3.6}$$

$$\sum_{w \in P^-} X^v_{0,w} = 0, \forall v \in V_a \tag{C3.6'}$$

$$\sum_{u \in N} X^v_{u,0} = 0, \forall v \in V \tag{C3.7}$$

$$\sum_{u \in P^+ \cup \tilde{P}^-} X^v_{u,4n+1} = 0, \forall v \in V_c \tag{C3.8}$$

$$\sum_{u \in P^+} X^v_{u,4n+1} = 0, \forall v \in V_a \tag{C3.8'}$$

$$\sum_{w \in N} X^v_{4n+1,w} = 0, \forall v \in V \tag{C3.9}$$

$$\sum_{v \in V_c} X^v_{u,u+n} \leq 1, \forall \tilde{P}^- \tag{C3.10'}$$

$$\sum_{u \in \tilde{P}^+} X^v_{u,2n+u} = 0, \forall v \in V \tag{C3.11}$$

$$\sum_{w \in \tilde{P}^+} X^v_{2n+w,w} = 0, \forall v \in V \tag{C3.12}$$

$$\sum_{u \in \tilde{P}^+} X^v_{u,3n+u} = 0, \forall v \in V \tag{C3.13}$$

$$\sum_{w \in \tilde{P}^+} X^v_{3n+w,w} = 0, \forall v \in V \tag{C3.14}$$

$$\sum_{u \in \tilde{P}^-} X^v_{u,2n+u} = 0, \forall v \in V \tag{C3.15}$$

$$\sum_{w \in \tilde{P}^-} X^v_{2n+w,w} = 0, \forall v \in V \tag{C3.16}$$

$$\sum_{w \in \tilde{P}^-} X^v_{n+w,w} = 0, \forall v \in V \tag{C3.17}$$

$$\sum_{v \in V} \sum_{w \in N} X^v_{wu} - \sum_{v \in V} \sum_{w \in N} X^v_{w,u+n} = 0, \forall u \in \tilde{P}^-. \tag{C3.18}$$

$$\sum_{u \in N} X^v_{uw} = X^v_{w,w+n}, \forall v \in V, \forall w \in \tilde{P}^-_{D_1} \tag{C3.19}$$

$$X^v_{u,u+n} = 0, \forall v \in V, \forall u \in \tilde{P}^-_P \tag{C3.20}$$

(4) Spatial connectivity constraints on the household members

$$\sum_{j\in\eta}\sum_{w\in N} H^j_{uw} = 1, \forall u \in P^+_M \tag{C4.1}$$

$$\sum_{j\in\eta}\sum_{w\in N} H^j_{uw} \le 1, \forall u \in P^+_D, \tag{C4.1'}$$

$$\sum_{w\in N} H^j_{uw} - \sum_{w\in N} H^j_{wu} = 0, \forall u \in P, \forall j \in \eta \tag{C4.2}$$

$$\sum_{w\in \tilde{P}^+} H^j_{0,w} = 1, \forall j \in \eta \tag{C4.3}$$

$$\sum_{u\in \tilde{P}^-} H^j_{u,4n+1} = 1, \forall j \in \eta \tag{C4.4}$$

$$\sum_{w\in N} H^j_{wu} - \sum_{w\in N} H^j_{w,u+n} = 0, \forall u \in P^+, \forall j \in \eta \tag{C4.5}$$

$$\sum_{j\in\eta} H^j_{u,u+n} = 1, \forall u \in \tilde{P}^-_M \tag{C4.6}$$

$$\sum_{j\in\eta} H^j_{u,u+n} \le 1, \forall u \in \tilde{P}^-_D \tag{C4.6'}$$

$$\sum_{w\in \tilde{P}^+\cup P^-} H^j_{0,w} = 0, \forall j \in \eta \tag{C4.7}$$

$$\sum_{u\in N} H^j_{u,0} = 0, \forall j \in \eta \tag{C4.8}$$

$$\sum_{u\in P^+\cup \tilde{P}^-} H^j_{u,4n+1} = 0, \forall j \in \eta \tag{C4.9}$$

$$\sum_{u\in N} H^j_{4n+1,w} = 0, \forall j \in \eta \tag{C4.10}$$

$$\sum_{u\in \tilde{P}^+} H^j_{u,2n+u} = 0, \forall j \in \eta \tag{C4.11}$$

$$\sum_{w\in \tilde{P}^+} H^j_{2n+w,w} = 0, \forall j \in \eta \tag{C4.12}$$

$$\sum_{u \in \tilde{P}^+} H^j_{u,3n+u} = 0, \forall j \in \eta \tag{C4.13}$$

$$\sum_{w \in \tilde{P}^+} H^j_{3n+w,w} = 0, \forall j \in \eta \tag{C4.14}$$

$$\sum_{u \in \tilde{P}^-} H^j_{u,2n+u} = 0, \forall j \in \eta \tag{C4.15}$$

$$\sum_{w \in \tilde{P}^-} H^j_{2n+w,w} = 0, \forall j \in \eta \tag{C4.16}$$

$$\sum_{w \in \tilde{P}^-} H^j_{n+w,w} = 0, \forall j \in \eta \tag{C4.17}$$

$$\sum_{w \in \underset{\sim}{P}^-} H^j_{uw} = 0, \forall j \in \eta \quad \forall u \in \tilde{P}^+ \tag{C4.18}$$

$$\sum_{u \in N} H^j_{uw} = H^j_{w,w+n}, \forall j \in \eta, \forall w \in \tilde{P}^-_{D_2} \tag{C4.19}$$

(5) Capacity budget and participation constraints

Capacity constraints for household members

$$H^j_{uw} = 1 \Rightarrow Y^j_u + d_w = Y^j_w, \forall j \in \eta, u \in P, w \in \tilde{P}^+ \tag{C5.1}$$

$$H^j_{uw} = 1 \Rightarrow Y^j_u - d_{w-n} = Y^j_w, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^- \tag{C5.2}$$

$$H^j_{uw} = 1 \Rightarrow Y^j_u = Y^j_w, \forall j \in \eta, u \in P, w \in \underset{\sim}{P}^+ \cup \tilde{P}^- \tag{C5.3}$$

$$H^j_{0w} = 1 \Rightarrow d_w = Y^j_w, \forall j \in \eta, \forall w \in \tilde{P}^+ \tag{C5.4}$$

$$0 \leq Y^j_u \leq D^j, \forall j \in \eta, \forall u \in P^+ \tag{C5.5}$$

Capacity constraints for vehicles

$$X_{uw}^{v} = 1 \Rightarrow \begin{cases} \Upsilon_u^v + d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N} \min_{\forall v\in V} t_{w\tilde{u}}^v H_{w\tilde{u}}^j > 0 \text{ or } w \in \tilde{P}^+ \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^+ \tag{C5.6}$$

$$X_{uw}^{v} = 1 \Rightarrow \begin{cases} \Upsilon_u^v - d_{w-n} = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N} \min_{\forall v\in V} t_{w\tilde{u}}^v H_{w\tilde{u}}^j > 0 \text{ or } w \in \tilde{P}^- \\ \Upsilon_u^v = \Upsilon_w^v & \text{otherwise} \end{cases},$$

$$\forall v \in V, \forall u \in P, \forall w \in P^- \tag{C5.7}$$

$$X_{0w}^{v} = 1 \Rightarrow \begin{cases} d_w = \Upsilon_w^v & \text{if } \sum_{j\in\eta}\sum_{\tilde{u}\in N} \min_{\forall v\in V} t_{w\tilde{u}}^v H_{w\tilde{u}}^j > 0 \\ 0 = \Upsilon_w^v & \text{otherwise} \end{cases}, \forall v \in V, \forall w \in \tilde{P}^+ \tag{C5.8}$$

$$0 \le \Upsilon_u^v \le D^v, \forall v \in V, \forall u \in P^+ \tag{C5.9}$$

Participation constraints

$$\sum_{u\in N}\sum_{w\in\Omega_\nu^v} X_{uw}^v = 0, \forall v \in V \tag{C5.10a}$$

$$\sum_{u\in N}\sum_{w\in\Omega_\nu^v} X_{u,w+2n}^v = 0, \forall v \in V \tag{C5.10b}$$

$$\sum_{u\in N}\sum_{w\in\Omega_H^j} H_{uw}^j = 0, \forall j \in \eta \tag{C5.11a}$$

$$\sum_{u\in N}\sum_{w\in\Omega_H^j} H_{u,w+2n}^j = 0, \forall j \in \eta \tag{C5.11b}$$

(6) Vehicle and household member coupling constraints

$$H_{uw}^j = 1 \Rightarrow \sum_{v \in V} X_{uw}^v + R_{uw}^j = 1, \forall j \in \eta, \forall (u,w) \in \mathbb{P}_v^2 \tag{C6.1}$$

$$X_{uw}^v = 1 \text{ and } \min_{\forall v \in V} t_{uw}^v > 0 \Rightarrow \sum_{j \in \eta} H_{uw}^j = 1, \forall v \in V_c, \forall u, w \in P \tag{C6.2}$$

$$\sum_{v \in V} \sum_{w \in P} X_{0,w}^v \leq \sum_{j \in \eta} \sum_{w \in P} H_{0w}^j \tag{C6.3}$$

$$R_{uw}^j \leq t_{uw}^r M, \quad \forall j \in \eta, \forall u, w \in N \tag{C6.5}$$

$$\sum_{u \in P} X_{u,w}^v \leq \sum_{j \in \eta} \sum_{u \in P} H_{u,w}^j, \forall v \in V, \forall w \in \tilde{P}_P^- \tag{C6.6}$$

$$\sum_{w \in P} X_{u,w}^v \leq \sum_{j \in \eta} \sum_{w \in P} H_{u,w}^j, \forall v \in V, \forall u \in \underset{\sim}{P}_P^+ \tag{C6.7}$$

A.6 Constraints for Calculating Parking Time Rewritten for Implementation

$$\tau_u^a - (T_w - T_u - t_{uw}) \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u \leq k_w \tag{C1.10a.1a}$$

$$\tau_u^a - (T_w - T_u - t_{uw}) \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u \leq k_w \tag{C1.10a.1b}$$

$$\tau_w^b \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u \leq k_w \tag{C1.10a.2a}$$

$$\tau_w^b \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u \leq k_w \tag{C1.10a.2b}$$

$$\tau_u^a \leq (1-\sum_{v\in V} X_{uw}^v)\cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u > k_w \tag{C1.10b.1a}$$

$$\tau_u^a \geq (\sum_{v\in V} X_{uw}^v - 1)\cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u > k_w \tag{C1.10b.1b}$$

$$\tau_w^b - (T_w - T_u - t_{uw}) \leq (1-\sum_{v\in V} X_{uw}^v)\cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u > k_w \tag{C1.10a.2a}$$

$$\tau_w^b - (T_w - T_u - t_{uw}) \geq (\sum_{v\in V} X_{uw}^v - 1)\cdot M, \forall u \in P^+, \forall w \in P^-, t_{wu} > 0, k_u > k_w \tag{C1.10a.2b}$$

$$\tau_w^b - (T_w - T_u - t_{uw}) \leq (1-\sum_{v\in V} X_{uw}^v)\cdot M, \forall u \in P^+, \forall w \in P^+, t_{wu} > 0 \tag{C1.10b.3a}$$

$$\tau_w^b - (T_w - T_u - t_{uw}) \geq (\sum_{v\in V} X_{uw}^v - 1)\cdot M, \forall u \in P^+, \forall w \in P^+, t_{wu} > 0 \tag{C1.10b.3b}$$

$$\tau_u^a \leq (1-\sum_{v\in V} X_{uw}^v)\cdot M, \forall u \in P^+, \forall w \in P^+, t_{wu} > 0 \tag{C1.10b.4a}$$

$$\tau_u^a \geq (\sum_{v\in V} X_{uw}^v - 1)\cdot M, \forall u \in P^+, \forall w \in P^+, t_{wu} > 0 \tag{C1.10b.4b}$$

$$\tau_u^a \leq (1-\sum_{v\in V} X_{uw}^v)\cdot M, \forall u \in P^-, \forall w \in P^+, t_{wu} > 0, k_u \leq k_w \tag{C1.11a.1a}$$

$$\tau_u^a \geq (\sum_{v\in V} X_{uw}^v - 1)\cdot M, \forall u \in P^-, \forall w \in P^+, t_{wu} > 0, k_u \leq k_w \tag{C1.11a.1b}$$

$$\tau_w^b - (T_w - T_u - t_{uw}) \leq (1-\sum_{v\in V} X_{uw}^v)\cdot M, \forall u \in P^-, \forall w \in P^+, k_u \leq k_w \tag{C1.11a.2a}$$

$$\tau_w^b - (T_w - T_u - t_{uw}) \geq (\sum_{v\in V} X_{uw}^v - 1)\cdot M, \forall u \in P^-, \forall w \in P^+, t_{wu} > 0, k_u \leq k_w \tag{C1.11a.2b}$$

$$\tau_u^a - (T_w - T_u - t_{uw}) \leq (1-\sum_{v\in V} X_{uw}^v)\cdot M, \forall u \in P^-, \forall w \in P^+, t_{wu} > 0, k_u > k_w \tag{C1.11b.3a}$$

$$\tau_u^a - (T_w - T_u - t_{uw}) \geq (\sum_{v\in V} X_{uw}^v - 1)\cdot M, \forall u \in P^-, \forall w \in P^+, t_{wu} > 0, k_u > k_w \tag{C1.11b.3b}$$

$$\tau_w^b \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^-, \forall w \in P^+, t_{wu} > 0, k_u > k_w \tag{C1.11b.4a}$$

$$\tau_w^b \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^-, \forall w \in P^+, t_{wu} > 0, k_u > k_w \tag{C1.11b.4b}$$

$$\tau_u^a - (T_w - T_u - t_{uw}) \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^-, \forall w \in P^-, t_{wu} > 0 \tag{C1.11b.4a}$$

$$\tau_u^a - (T_w - T_u - t_{uw}) \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^-, \forall w \in P^-, t_{wu} > 0 \tag{C1.11b.4b}$$

$$\tau_w^b \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^-, \forall w \in P^-, t_{wu} > 0 \tag{C1.11b.4b}$$

$$\tau_w^b \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^-, \forall w \in P^-, t_{wu} > 0 \tag{C1.11b.4b}$$

$$\tau_u^a \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^+, \forall w \in N, t_{wu} = 0 \tag{C1.12a.1a}$$

$$\tau_u^a \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^+, \forall w \in N, t_{wu} = 0 \tag{C1.12a.1b}$$

$$\tau_w^b - (T_w - T_u) \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^+, \forall w \in N, t_{wu} = 0 \tag{C1.12a.2a}$$

$$\tau_w^b - (T_w - T_u) \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^+, \forall w \in N, t_{wu} = 0 \tag{C1.12a.2b}$$

$$\tau_u^a - (T_w - T_u) \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^-, \forall w \in N, t_{wu} = 0 \tag{C1.12a.3a}$$

$$\tau_u^a - (T_w - T_u) \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^-, \forall w \in N, t_{wu} = 0 \tag{C1.12a.3b}$$

$$\tau_w^b \leq (1 - \sum_{v \in V} X_{uw}^v) \cdot M, \forall u \in P^-, \forall w \in N, t_{wu} = 0 \tag{C1.12a.4a}$$

$$\tau_w^b \geq (\sum_{v \in V} X_{uw}^v - 1) \cdot M, \forall u \in P^-, \forall w \in N, t_{wu} = 0 \tag{C1.12a.4b}$$

$$\tau_u^a \leq (\sum_{v \in V} \sum_{w \in P} X_{uw}^v) \cdot M, \forall u \in P \tag{C1.13a}$$

$$\tau_w^b \leq (\sum_{v \in V} \sum_{u \in P} X_{uw}^v) \cdot M, \forall w \in P \tag{C1.13b}$$

A.7 Abbreviations

Table A.5: Abbreviations

ABA	Activity-based approach
ABM	Activity-based model
AV	Autonomous vehicle
CPM	Computational process model
CV	Conventional vehicle
LSP	Location selection problem
MaaS	Mobility as a Service
MDSAM	Multi-dimensional alignment method
MILP	Mixed integer linear problem
NDP	Network design problem
PAV	Private autonomous vehicle
PDP	Pick-up and delivery problem
PDPTW	Pick-up and delivery problem with time window constraints
PT	Public transit
SAV	Shared autonomous vehicle
VMT	Vehicle mile traveled
ZOT	Zero occupancy trip

Table A.6: Abbreviations for ABMs

ADAPTS	Agent-based Dynamic Activity Planning and Travel Scheduling
ALBATROSS	A Learning-based Transportation Oriented Simulation System
AMOS	Activity-Mobility Simulator
CARLA	Combinatorial Algorithm for Rescheduling Lists if Activities
CEMDAP	Comprehensive Econometric Micro-simulator for Daily Activity-travel Patterns
DEBNetS	Dynamic Event-Based Network Simulator
FAMOS	Florida Activity Mobility Simulator
HAPP	Household Activity Pattern Problem
HAPP	Household Activity Pattern Problem with Autonomous Vehicles
mHAPP	multimodal Household Activity Pattern Problem
mHAPPAV	multimodal Household Activity Pattern Problem with Autonomous Vehicles
PCATS	Prism-Constrained Activity-Travel Simulator
PESASP	Program Evaluating the Set of Alternative Sample Paths
SimAGENT	Simulator of Activities, Greenhouse Emissions, Networks, and Travel
SMASH	Simulation Model of Activity Scheduling Heuristics
STARCHILD	Simulation of Travel/Activity Responses to Complex Household Interactive Logistic Decisions
TASHA	Travel Activity Scheduler for Household Agents
SHAPP	Stochastic Household Activity Pattern Problem