A Framework for Evaluating the Validity of Autonomous Vehicles in Multimodal Transportation Systems

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1 Introduction

The realization of autonomous vehicles (AVs) and their potential use in Mobility as a Service (MaaS) systems has been heralded as dramatically transforming our daily lives and the automobile market. As AV technologies become marketable, the decisions of households to consider replacing their conventional vehicles (CVs) with AVs will likely depend on a comparison between the economic benefits of CVs and those of AVs; i.e. an examination of how much the AV reduces travel-activity participation costs compared to those of a CV. For this examination, not only the prices and operational costs of the respective vehicles, but also the household's travel-activity pattern, matter. However, the complexity of the household's travel-activity pattern cannot be illustrated by conventional trip-based models. In this sense, projecting the impacts of AVs on the society requires analyses based on the needs and preferences of households to participate in activities that are dispersed in both time and spaceso-called activity-based paradigms of travel.

Among a number of activity-based models (ABMs), which purportedly more accurately capture the nature of travel behavior, the household activity pattern problem (HAPP) framework due to Recker (1995) [3] mathematically describes the travel-activity pattern generation process as a mixed integer programming problem. The solution of HAPP simultaneously gives optimal solutions to the travel-activity pattern scheduling and vehicle routing problems based on utility maximization principles. Since this problem is formulated as a variant of the well-known pick up-and-delivery problem with time window constraints (PDPTW) originally proposed by Solomon and Desrosiers (1988) [4], it has the operational capability of specifying multiple temporal-spatial constraints as well as of the decision process of a travel-activity pattern. The research presented here uses a modified version of HAPP as an activity-based framework that can be used to systematically evaluate a household's AV adoption based on a utility comparison between CV and AVvis-a-vis its daily travel-activity pattern - that also can be used to evaluate so-called mobility-as-a-service (MaaS) systems.

2 mHAPPAV

2.1 General Formulation

We present here the reformulation of HAPP as multimodal HAPP with AV (mHAPPAV). Although the reformulation is quite extensive, it follows that of the original HAPP in that it posits 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. Expressed as a MILP, the general mathematical form of mHAPPAV for household i during a certain time period is:

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

subject to

$$\boldsymbol{AX} \le \boldsymbol{c}$$

where

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

$\boldsymbol{b}$ 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.
- R^j_{uw}: Binary decision variable equal to unity if household member j travels from activity u to activity w on rideshare, 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 which 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 are regarded as the most desirable paths through time and space for a household to complete its prescribed activity agenda.

We do not discuss specific terms for the objective function and constraints that are summarized by Yamada (2019) [5]. We note some of the assumptions employed by Recker (1995) [3]. The original formulation assumes the case of CVs; each vehicle is constrained to travel along with its driver and remain parked until an activity in which the driver participates ends. 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.

In order to represent the possible travel-activity patterns that may be realized by AVs, we revise the HAPP formulation by dividing each activity into 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). This revision enables the model to illustrate trips to and from an activity separately. So, for example, 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 opt to not stay until its passenger ends an activity and, instead, may wander around to pick up and deliver other passengers, or park at a different location, while the activity is being executed. Furthermore, by utilizing AVs, a member can be delivered and picked up by different vehicles. Accordingly, an AV may access an activity location twice, or different vehicles may access the same activity.

2.2 Incorporation of Public Transit Alternatives into the mHAPPAV framework

This subsection introduces how the mHAPPAV platform incorporates transportation modes other than those used for personal travel (e.g., CVs and AVs) that: (1) do not provide door-to-door service, (2) have fixed schedules, and (3) require access modes. Chief among such services are traditional public transit (PT) systems. With higher capacities coming on line, PT can be expected to still play an important role in urban transportation systems of metropolitan cities even after AVs become available - perhaps being aided by AVs in its "last mile" problem. 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 consequently requires travelers to use complementary modes for access/egress in order to complete their trips. 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 HAPP reformulation 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 become excessively large 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 sections, 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/he is using a PT mode. These separate nodes are accordingly thought to be stations or stops of PT, and the duration of the activity is viewed as the 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 1. 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.

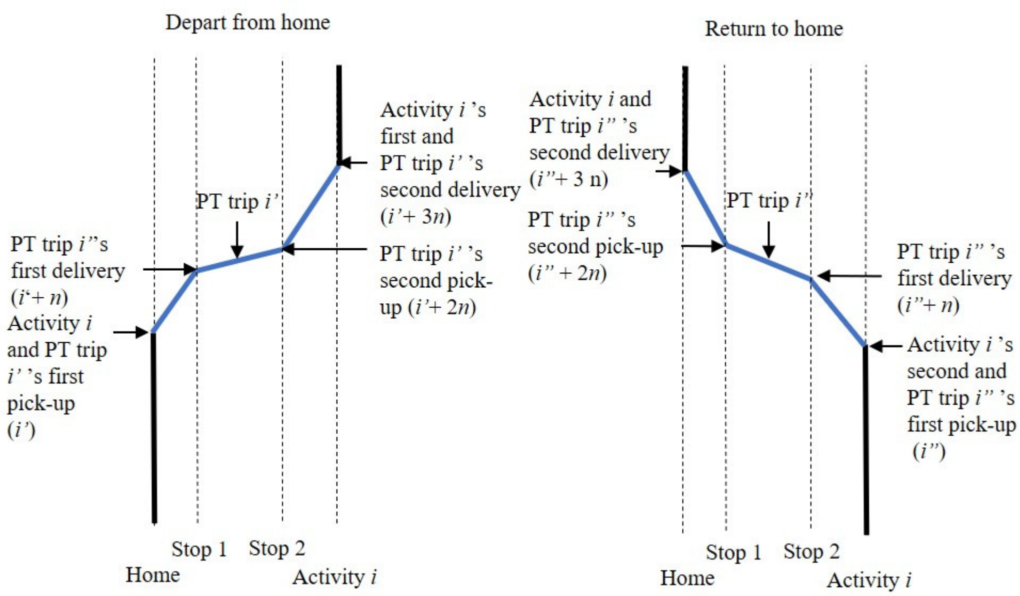

Figure 1: Illustration of the PT Trip Representation in HAPP

3 Examples

This section presents a series of applications of mHAPPAV model to evaluate the viability of AVs in different environments. These examples contrasts the optimal travel-activity patterns of a household of two members with the option of owning either two CVs or one AV, and with three out-of-home activity locations ($i = 1, 2, 3$). The examples moreover illustrates the incorporation of walking, rideshare or taxi, and PT as well as private modes such as bikes into the mHAPPAV framework. To illustrate multimodal trips with mHAPPAV, let us suppose the setting including the schedule for PT shown in Figure 2. The public transit is operated under a fixed schedule, and its fare is three dollars per ride. The household members are able to walk between home and stop 1, stop 2 and activity 1, and home and activity 2. They can use as many as two CVs and an AV as well as in Case a, 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, parking cost for vehicle at stop 1 is ten dollars per day. Below are the parameters specified for the following cases.

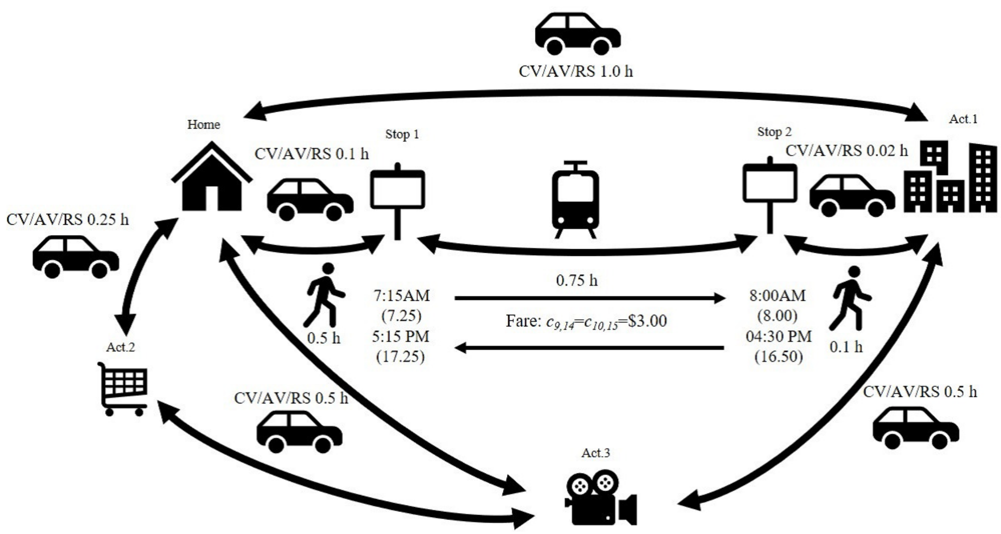

Figure 2: Setting for Case 1 and 2

Travel time and cost for vehicles between activity locations

Table 2: Travel Time for Vehicles (in hours)

t^v_{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 3: Travel Cost for CVs (in dollars)

c^v_{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

$$\Omega^1_\nu = \{1, 3\}, \Omega^2_\nu = \{2\}$$
$$\Omega^1_H = \{1\}, \Omega^2_H = \{2, 3\}$$

3.1 Case 1: A Simple Example involving multi-modal choice

The decision between ownership of CVs vs. AVs will depend on factors beyond simple comparisons of factors associated with travel time - ownership and operating costs can be expected to play a significant role in the decision. To assess this situation in a realistic fashion we specify the objective function for the purpose of viability analysis as follows:

$$\begin{aligned}
\min Z = &\sum_{v\in V_C}\sum_{u\in N}\sum_{w\in N} c_C^v v_{\text{ave}} t_{uw}^v X_{uw}^v + \sum_{v\in V_A}\sum_{u\in N}\sum_{w\in N} c_A v_{\text{ave}} t_{uw} X_{uw}^v + \sum_{v\in V_A}\sum_{w\in P^+} K_A X_{0,w}^v \\
&+ \sum_{v\in V_C}\sum_{w\in P^+} K_C^v X_{0,w}^v + \sum_{j\in\eta}\sum_{u\in N}\sum_{w\in N} c_{uw}^R R_{uw}^j + \sum_{j\in\eta}\sum_{u\in\tilde{P}_D^-} c_{u,u+n}^P H_{u,u+n}^j \\
&+ \beta\sum_{j\in\eta}(\bar{T}_{4n+1}^j - \bar{T}_0^j)
\end{aligned} \tag{O2}$$

where c_C and c_A are the costs per mile for CV and AV, respectively, and v_{ave} is the average vehicle speed. In addition, $c_{u,u+n}^P$ represents a fare for using PT between u and $u+n$,K_C is the ownership cost of a CV, and K_A is that of an AV.

Realistic 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) [2]

Figure 3 displays five possible optimal patterns, say (a) - (e), realized depending on two parameters: the value of time of the household (β) and the price of AVs (K_A). In patterns (c) and (e), the household members do not use the PT service. If the service were not available, the household would only consider adopting an AV based on the comparison of these two patterns. 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, we carry 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 4 identifies the regimes of optimal patterns associated with combined values of time and cost ratios. Each regime in Figure 4 corresponds to the pattern with the same index in Figure 3. 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. 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 1.79 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.

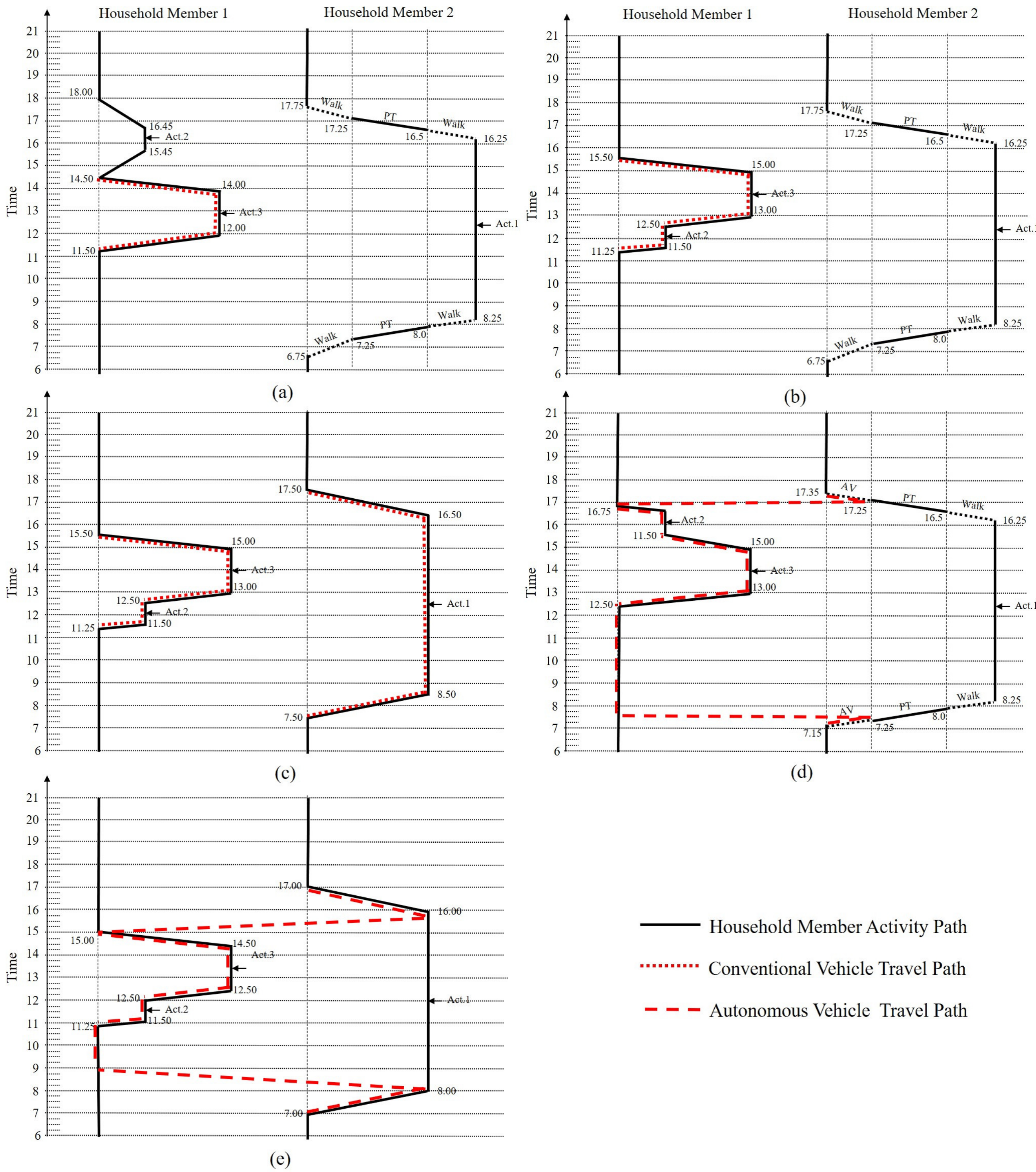

Figure 3: Possible Travel-Activity Patterns for Case 1

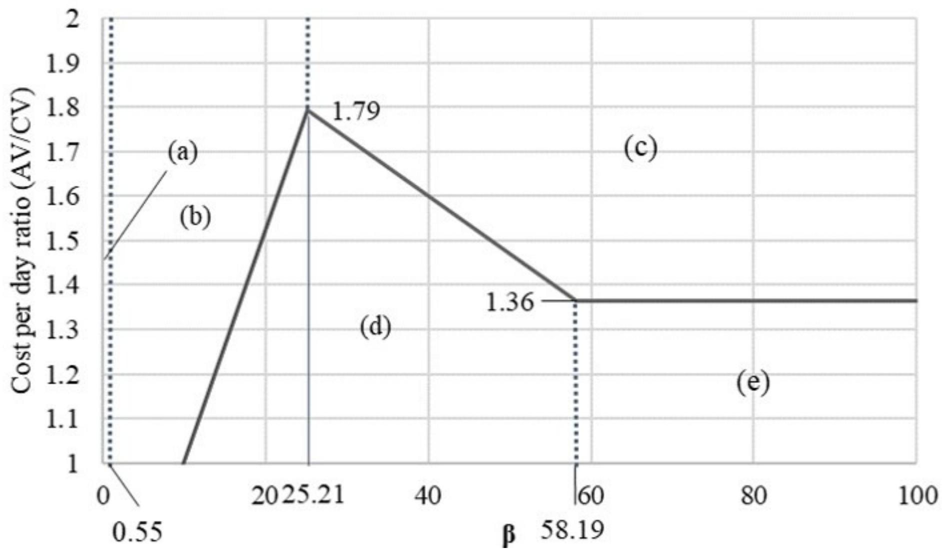

Figure 4: Travel-Activity Pattern Analysis Regarding AV Ownership Cost and Time-value Parameter for Case 1

3.2 Case 2: AVs Competing with Rideshares

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 1 except that ridershare is available between 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 4.

Table 4: Fares for Rideshare (in dollars)

c_{uw}^R ($)	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

In addition to the five patterns in Figure 3, there are two more travel-activity patterns with rideshare. They are shown in Figure 5 and denoted (f) and (g). In both of these, 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.

The household members choose one of the seven patterns, based on the price of AV and the household's value of time parameter as in Case 2. Figure 6 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 may 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 nonetheless unnecessary for the household desiring less travel time to own two CVs, thanks to the rideshare and PT services.

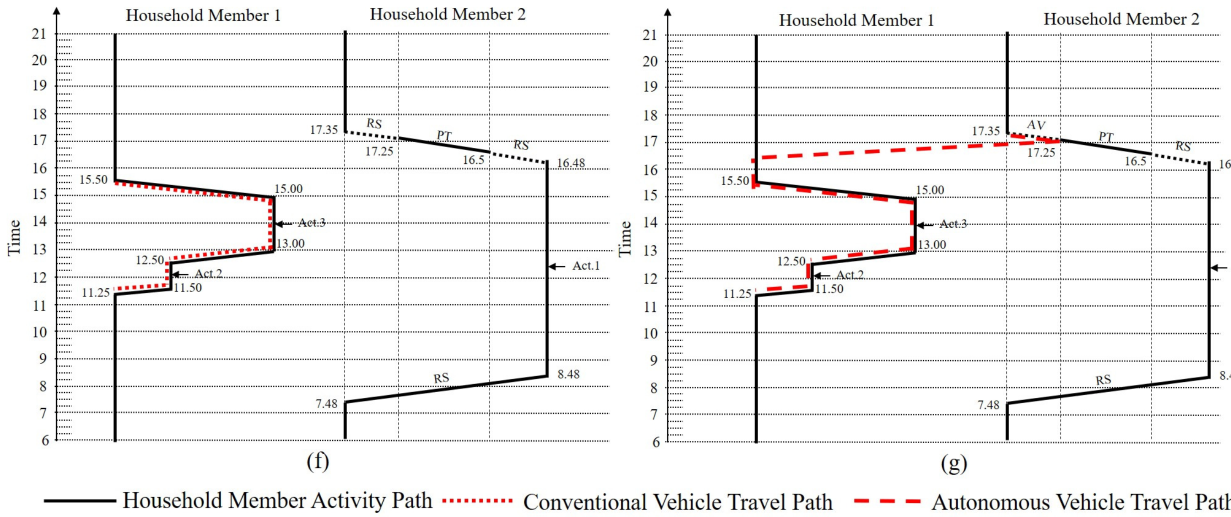

Figure 5: Additional Possible Travel-Activity Patterns in Case 2

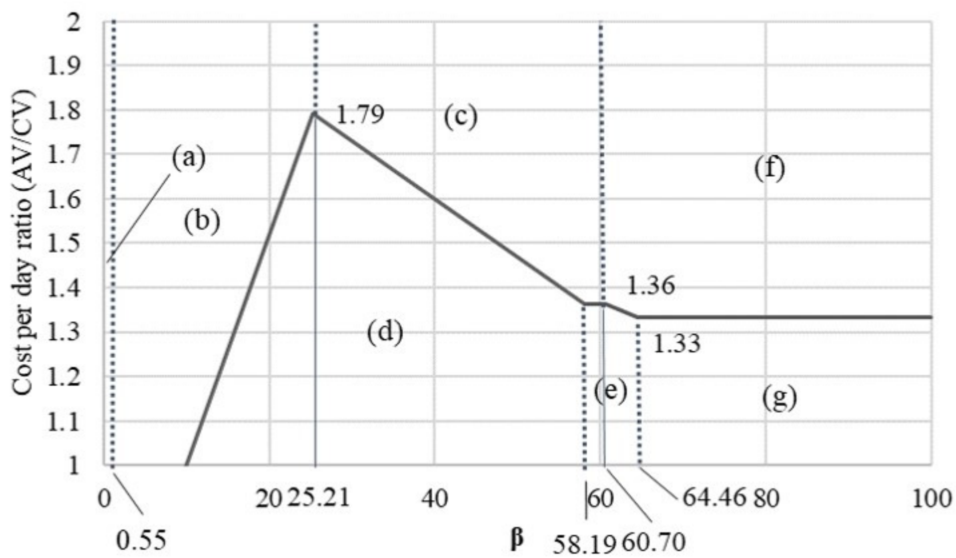

Figure 6: Travel-Activity Pattern Analysis Regarding AV Ownership Cost and Time-value Parameter for Case 2

4 Conclusions

This research focuses on evaluating the viability of AVs in the existence of multiple transportation modes based on the mHAPPAV framework. 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. Without insights to the comprehensive impacts of AVs, we cannot establish an effective strategy for AV operation. In this context, this research proposes a basic framework that explicitly depicts travel-activity patterns would make it desirable for a household to purchase an AV as such a new mobility option. The model can be used to forecast travel behavior after private AVs become available in a well-developed urban transportation system. A household's decision of whether to purchase AVs or still rely on CVs can be guided by the framework presented in this research because it illustrates a specific context where AVs are useful for the household in terms of its ownership costs. Even though this analysis is based on hypothetical arrangements, a similar kind of investigation could be considered when managing futuristic MaaS, in which AVs are a significant option among multiple transportation modes.

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