Experimental Examination and Simulation Analysis of Standing-type Personal Mobility Device Sharing

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***Abstract*—This study considers sharing of standing-type personal mobility devices. Such devices offer various advantages as a means of transportation, but they have been used only slightly for this purpose to date. Their cost makes sharing such devices more attractive than owning them. Sharing personal mobility devices is expected to introduce beneficial social influences such as a modal shift. For this study, we conducted small-scale experiments to assess their feasibility. Then we considered larger cases in simulations. The experiments employ four sharing stations and four personal mobility devices by more than 60 registered users. Larger scale simulations are based on a multi-agent model, presenting results for its usage compared with other means of transportation. Such a simulation is expected to provide a basis for future demand prediction and planning of personal mobility sharing.**

I. INTRODUCTION

Urban traffic presents numerous problems including traffic congestion and traffic accidents, which are especially severe for elderly people. Furthermore, considering the weight ratio with humans, current transportation means such as private automobiles are inefficient. Using personal mobility devices is a promising approach. We consider standing-type personal mobility devices such as Segways [1], AIST Micro-Mobility Devices [2], and Toyota Winglets [3]. Their main usage has remained rather limited to date: touring for sightseeing or patrolling purposes. However, other applications of personal mobility devices as a means of transportation are quite attractive. Their advantages for urban use are their efficiency and environmental friendliness. Moreover, their low speed mitigates the probability and severity of accidents. Furthermore, they are well suited to the recently advocated concept of compact cities [4], [5]. In this report, we simply refer to such standing-type, self-balancing personal mobility devices as PMs.

For introduction of such PMs in the community, sharing is more probable than owning because sharing costs are usually much lower for both purchasing and maintenance. If PMs are introduced into a town, then the human flow is changed and new behaviors are expected to emerge. PM sharing systems, however, have not yet been studied sufficiently.

This study was conducted to examine the expected change in human behavior, especially a modal shift, by introducing a PM sharing system into society using outdoor experiments and a multi-agent simulation. Regarding the sharing of mobility devices, bicycle sharing has been studied [6], [7], [8] and has become popular recently in large cities. Vélib' in Paris [9], Santander Cycle in London [10], and Capital Bikeshare in Washington, D.C. [11] are examples of successful systems. In these cities, bicycles are rented at sharing stations. They can be returned to any station among many in the city. A PM and its sharing system differ from bicycle sharing in the following ways.

1) Seamless PM riding between indoor and outdoor environments is possible. This feature can sometimes be useful for visiting shopping malls, museums, and other destinations.
2) PMs can be carried easily in other transportation modes such as trains and cars. Such usage expands the PM range of operation.
3) Because PMs are equipped with information processing capability, assistance by an IT infrastructure is expected to be easy.
4) Charging time is required. When the mobility device is returned to a sharing station, depending on the riding distance or time of the previous user, some charging time is necessary before it is rented to another user.

In addition, the efficiency of usage is crucially important to the operation cost because providing PMs usually costs more than providing bicycles. Sharing of other mobility devices has been examined in other studies [12], [13].

For this study, we consider PM sharing by experiments for basic feasibility and by simulation for large-scale investigation. The experiments employ four sharing stations and four personal mobility devices with more than 60 registered users. Larger scale simulation is based on a multi-agent model, showing some results of PM usage, particularly addressing biased usage and connection with trains, compared with other transportation means.

II. PERSONAL MOBILITY SHARING EXPERIMENTS

We have conducted sharing experiments since September 2014 in Tsukuba, Japan [14]. In general, riding such mobile devices is prohibited in Japan. Our experiments were conducted in the Tsukuba Mobility Robot Experimental Zone, a specially designated zone where experiments of mobile robots are permitted under some regulations.

A. Tsukuba Mobility Robot Experimental Zone

Tsukuba City was designated as a Mobility Robot Experimental Zone by the Cabinet Office in 2013 [15]. It was intended for advanced experiments using mobile robots. (Mobility Robot Experimental Zones have now been abolished,

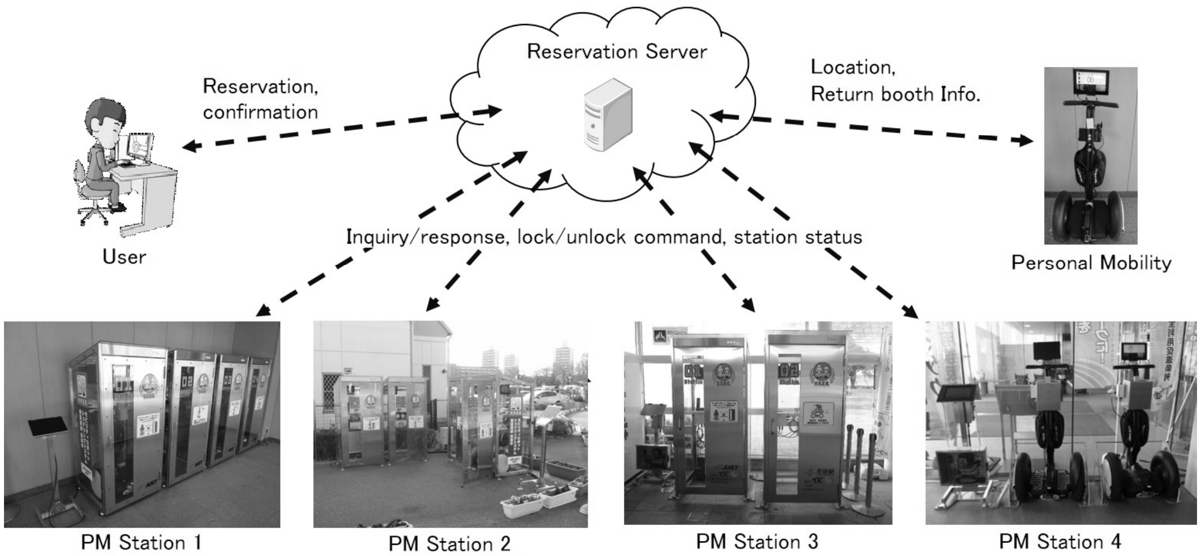


Fig. 1. PM sharing system overview

with expansion to the entirety of Japan with appropriate permission.)

The area encompasses two train stations: Tsukuba Station and Kenkyugakuen Station. The permitted regions include a sidewalk, a paved area, or a pedestrian area with 3 m or greater width within the area. Current regulations hold that a person must accompany the rider to monitor the mobility robot safety.

B. System overview

Our sharing system is one-way reservation type. Each user makes a reservation in advance. Then the user can return the device to any sharing station after use. Our sharing system consists mainly of three components, as described in detail below:

1) Four sharing stations (PM stations) with 20 booths in all,
2) Four PMs,
3) Reservation server on the Internet.

An overview of the system is presented in Fig. 1.

C. System components

1) PM stations: We built four PM stations in the Tsukuba Mobility Robot Experimental Zone as in Table I. Their appearance is shown in Fig. 1. PM station 4, which is intended for indoor use, has a simple structure, but other stations have box-type booths. Each location is presented in Fig. 2.

Each station is equipped with a Tablet computer (Xperia Tablet Z; Sony Corp.) as a user interface. A registered user can unlock a door and take out a PM by entering a valid reservation code. The intended use of Stations 1 and 2 is the transportation of AIST employees between AIST and Tsukuba Station. The distance is about 3.8 km. Riding PMs takes about 20 min, which is comparable to taking a bus (AIST shuttle bus or public bus).

TABLE I. PM STATIONS

Number	Location	Area	# Booth
1	AIST	Tsukuba	4
2	Tsukuba Station	Tsukuba	4
3	Kenkyugakuen Station	Kenkyugakuen	2
4	City Hall	Kenkyugakuen	2

Stations 3 and 4 are intended mainly for transport of City Hall employees between City Hall and Kenkyugakuen Station. The distance is about 0.5 km.

Doors of the PM stations are usually locked electromagnetically. They are unlocked when 1) a user enters a valid reservation code and a successful response is returned from the reservation server, and 2) a PM to be returned arrives to its destination PM station.

2) Personal mobility: We modified a Segway for sharing experiments, as shown in Fig. 3. A tablet computer (Xperia Tablet Z; Sony Corp.) is attached to provide sharing information to the user and to store various driving data including GPS, movies ahead, acceleration, and gyro information. Using the GPS data, various location-based information can be presented such as the distance to the destination and possible deviation from the intended route. Acceleration and gyro data are used to raise an alert of sudden stop [16]. In addition to these sensors, a sensor node has been developed to collect data of various kinds in a uniform manner [14].

When a PM is in use, its location is transmitted to the server by a mobile router (ULTRA WiFi 007Z for Biz; SoftBank) so that an administrator can track its location in real time. Additionally, microcomputer (Mega ADK; Arduino) is attached to communicate with the booths and the onboard tablet computer. This cable connection between a PM and a booth is important to confirm the return of the PM unit to the booth.

3) Reservation server: A reservation server is deployed on the Internet. The server handles reservation requests from registered users as described below. Furthermore, the server

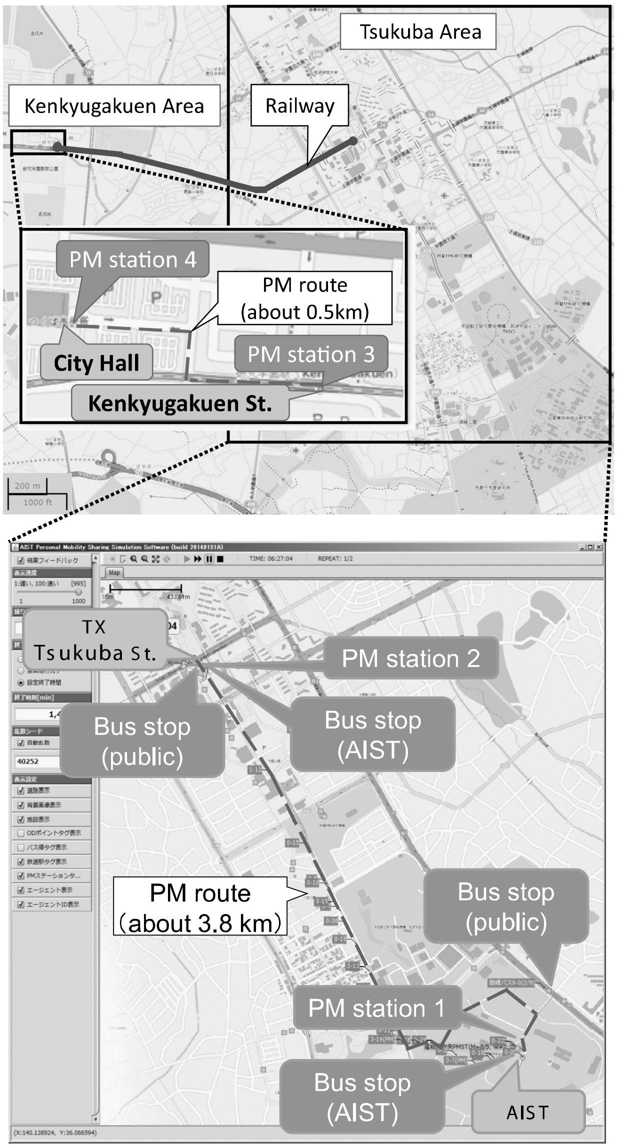


Fig. 2. Experimental areas (upper) and OD points, the locations of PM stations and bus stops in a simulator snapshot (lower)

communicates with sharing stations and PMs to update current status information and to command them, e.g., locking/unlocking.

A user makes a reservation using the server. After logging onto the site, the user makes a reservation by specifying the date, time, and OD (origin/destination) stations.

Ascertaining availability for accepting requests is not simple because one-way and unmanned operation is presumed. For these experiments, we adopted a heuristic method according to the following simplification.

- The base time slot is 15 min and each reservation is a multiple of the slots.
- A request made earlier has priority.
- If a request is not realizable or breaks its later reservation, then it is reserved as tentative.

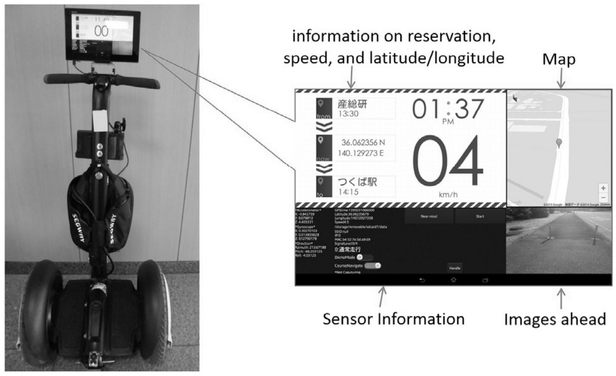


Fig. 3. Segway for sharing

- A tentative reservation might become valid by receiving another reservation.

A typical scenario of the last case is the following: user A makes a reservation request R to ride from station S to station T at 13:00, but there is no available PM in S and the request R is tentative. Then, another user B requests a ride from station T to station S at 11:00, which makes request R valid.

A reservation code is issued to each valid reservation. The user can rent a PM using the code at a reservation time.

D. Usage results

Stations 1 and 2 (Tsukuba Area) have been in operation from September 2013. In April 2014, Stations 3 and 4 (Kenkyugakuen Area) were added. The total number of registered users, total usage, and total riding distance until the end of 2015 are presented in Table II.

TABLE II. USAGE RESULTS

	# Registered users	Total usage	Total distance
Tsukuba Area	55	152	830 km
Kenkyugakuen Area	about 10	25	12.5 km

We evaluated safety and acceptability. No important accident or incident has occurred. The system is safe to date, and has been accepted without problems.

III. PERSONAL MOBILITY SHARING SIMULATOR

Based on the hardware experiments, we conduct a simulation for larger scale situations. The simulation scenario is similar. We consider four stations located with the same locations in the Tsukuba Mobility Robot Experimental Zone. In the simulation, we consider non-reservation type sharing. We mainly consider transportation between AIST and Tsukuba Station and investigate the share of PMs with other transportation means. Hereinafter, we introduce the personal mobility sharing simulator in [17], [18].

A. Simulator overview

The developed simulator is based on a multi-agent model with potential flexibility in its configuration for individual agents with different characteristics of walking speed, riding speed, and mobility preference attributed by age, gender, etc.

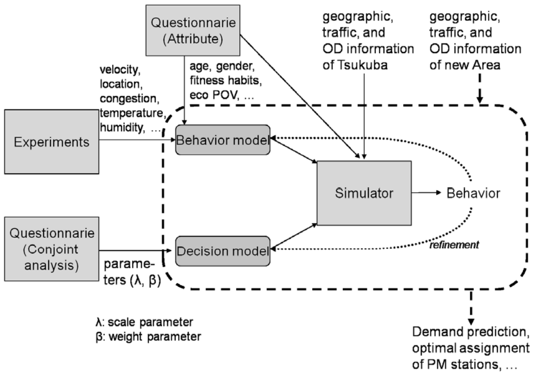


Fig. 4. Simulator diagram

Moreover, various behavioral phenomena arise attributable to the limited number of PMs and capacity of PM stations. Their effects on renting and returning were naturally treated. A schematic of the overall framework, including behavior and decision models, is presented in Fig. 4.

The parameters of the behavior and decision models for the simulator were decided by experiments in the Tsukuba Mobility Robot Experimental Zone, and by a questionnaire. The simulations were conducted using these obtained values. Through feedback of such information, the behavior and decision models can be refined. Once a simulator with these models is thoroughly developed with the geographic, traffic, and OD information of Tsukuba, presumably, the same approach can be applied to other cities by providing the relevant local information. Then, simulation can be conducted for demand prediction or planning of the optimal assignment of PM stations.

In the following, we describe the decision model and behavior model. These are applied to agents when they move within the Tsukuba and Kenkyugakuen Areas. We assume that each agent uses trains for transportation between two areas, which is treated in IV.C Experiment 2.

B. Decision model

To model the user behavior, we needed to build some sort of decision model. We adopted the nested logit model [19], [20]. For this model, we assumed that the possible mobility candidates were PMs and buses of two types. Each candidate was assigned a choice probability. Depending on the probability, one of them was chosen stochastically as follows.

For each choice of mobility device, its representative utility was calculated. It was defined by several aspects. As in the conducted experiment, we assumed only one type of agent with the same representative utility. We assumed a category of mobility device $C = \{c_{\text{bus}}, c_{\text{PM}}\}$. Each category represented $c_{\text{bus}} = \{m_{\text{AIST}}, m_{\text{public}}\}, c_{\text{PM}} = \{m_{\text{PM}}\}$. The utility function $V_{m|c}$ for mobility m in category c was assumed to be a weighted sum of factors such as distance, estimated required time, estimated delay time, and preference of main transportation mode as

$$V_{m|c} = \beta_1 x_{m|c,1} + \beta_2 x_{m|c,2} + \cdots + \beta_N x_{m|c,N}.$$

Depending on the representative utility, the choice probability $P_{m,c}$ of mobility m in category c was defined as the product of the probability that category c was chosen. The conditional probability that m was chosen in category c as

$$\begin{aligned} P_{m,c} &= P_{m|c} \cdot P_c \\ &= \frac{\exp(V_{m|c})}{\sum_{m' \in c} \exp(V_{m'|c})} \cdot \frac{\exp(\lambda I_c)}{\sum_{c' \in C} \exp(\lambda I_{c'})}, \end{aligned}$$

where

$$I_c = \ln \sum_{m \in c} \exp(V_{m|c}).$$

The actual parameters, λ and β_i, for this model were obtained through conjoint analysis based on responses to a questionnaire.

C. Behavior model

We adopted a simple behavior model. In the simulator, each agent is generated at some designated time with origin and destination. Then each agent stochastically chooses its behavior using the decision model. If the agent chooses a bus, for instance, it walks to the nearest bus stop, waits and gets on a bus, gets off the bus at the bus stop close to its destination, and walks to the destination. The free-flow speeds for walking and riding PMs are given. However, the actual speeds in the simulation decrease depending on the ratio decided by the attributes of the agent and the density of pedestrians on the same road segment. Buses are assumed to arrive on time. Only the expected maximum delay time is used in the decision model.

IV. Simulation Scenario and Results

We conduct simulations to show some PM usage, particularly addressing biased usage and connection with trains, compared with other transportation means.

A. Simulation scenario

The presumed scenario for simulation here specifically examines the travel behavior of employees of our institute (AIST) on a business trip, traveling between AIST and the nearest train station. The road network is given as a shapefile. We assumed buses of two types: the AIST shuttle bus and a public bus, with respective capacities of 20 and 50 passengers. The actual fare (260 yen) of the public bus was also used. In the simulation, we used actual timetables of buses (the 34 and 59 routes, respectively, for the AIST and public buses during the simulation period) and actual locations of bus stops.

We used the parameters in [18]. In the decision model, two buses were in a single nest. The values for β_i are presented in Table III and $\lambda = 0.785$. Here, the parameters from β_1 to β_4 and from β_9 to β_{15} were used for the corresponding cases.

B. Simulation parameters

The main parameters of the behavior model are explained below. The free-flow speed of walking was 4 km/h. Getting on/off the PMs took no time. Moreover, we used a fixed time (15 min) for charging before a returned PM was rented to another user.

TABLE III. WEIGHT PARAMETERS

Parameter	Item	Value
β_1	preference to AIST bus	-0.144
β_2	preference to public bus	-1.053
β_3	preference to PM	0
β_4	preference to walk	(-20)
β_5	moving distance (km)	-1.053
β_6	boarding time (min)	-0.131
β_7	walk and wait time (min)	-0.143
β_8	maximum delay time (min)	-0.07
β_9	fare (yen)	-0.015
β_{10}	crowdedness level1 (AIST bus)	0.613
β_{11}	crowdedness level2 (AIST bus)	0.352
β_{12}	crowdedness level3 (AIST bus)	-1.109
β_{13}	crowdedness level1 (public bus)	0.057
β_{14}	crowdedness level2 (public bus)	0.08
β_{15}	crowdedness level3 (public bus)	-1.19

When no PMs were available, users must wait for a PM to be returned. If no PM is returned for a fixed amount of time (called the *maximum wait time*), then users gave up using PMs and chose another mobility mode (walking, in this case). The wait time actually affected the utility of PMs, but estimating it in advance was difficult. Therefore, we conducted simulations several times (10, in this case) in one simulation run, with feedback of the resulting PM wait times. The following results are the average of 10 simulation runs. In this simulation, the following parameters were fixed: the AIST bus fare was 0 yen (as is), the expected delay of both buses was 10 min, the maximum wait time for PMs in Tsukuba Area and buses was 20 min. The speed of a PM was 10 km/h. For this study, we investigated the share of PMs and the success rate of renting considering biased demands.

C. Simulation experiments

Given the settings presented above, we conducted two experiments.

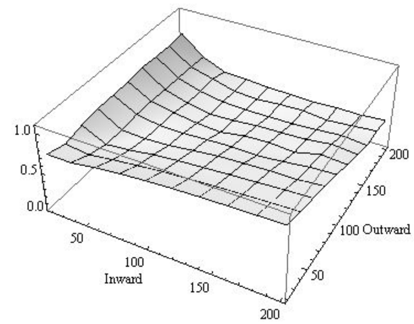
Experiment 1: Moving between AIST and Tsukuba Station. Agents are generated randomly at a constant rate at AIST and Tsukuba Station. Each user chooses its transportation mode according to the decision model described above.

Experiment 2: Moving between AIST and City Hall. In this case, the agents are generated at AIST and City Hall. They take the train to move between Tsukuba Area and Kenkyugakuen Area. The arrival rate of users from City Hall to Tsukuba Station is not uniform because of the train timetable. In Kenkyugakuen Area, PMs are available.

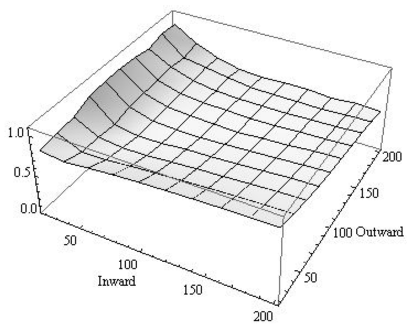
In both cases, simulations were conducted from 9:00 to 17:00 by changing the number of generated agents. The number of agents per hour was 20 to 200 (step 20) in one-way travel. Hereinafter, movement from AIST to Tsukuba station is designated as *outward*. The opposite direction is *inward*. The number of PMs assigned initially to each PM station was changed from 5, 10, 25, and 50 (10, 20, 50, and 100 in total). Agents were generated randomly at the specified ratio in each simulation run. We assumed that the PM stations were sufficiently large that PMs could be returned to any station at any time.

D. Simulation results

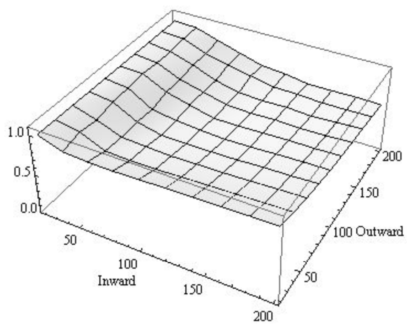
Fig. 5 presents the success rate of renting for Experiment 1. This is the average of both directions. Because the number



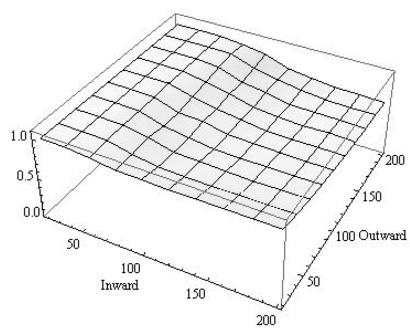
(a) Success rate of rent: 10 PMs



(b) Success rate of rent: 20 PMs

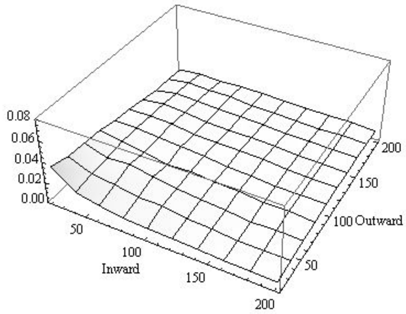


(c) Success rate of rent: 50 PMs

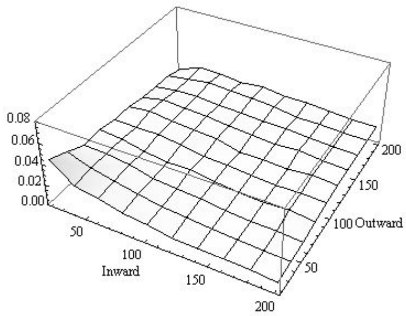


(d) Success rate of rent: 100 PMs

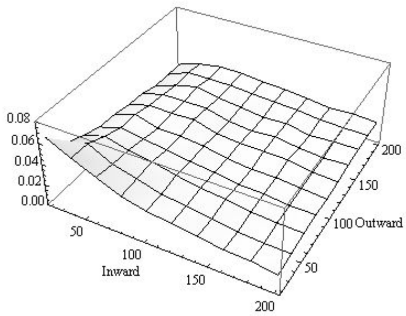
Fig. 5. Success rate of renting in Experiment 1



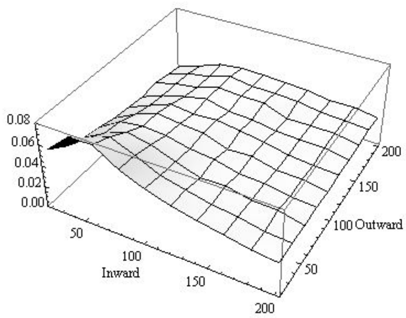
(a) Share of PMs: 10 PMs



(b) Share of PMs: 20 PMs

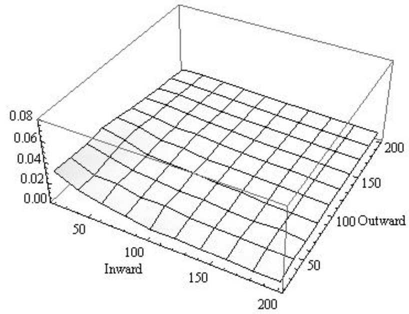


(c) Share of PMs: 50 PMs

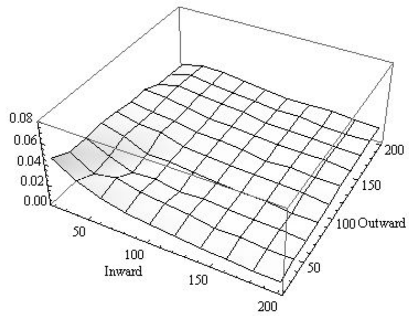


(d) Share of PMs: 100 PMs

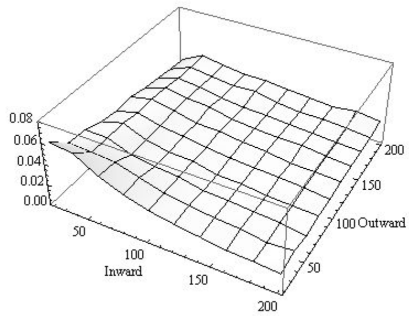
Fig. 6. Share of PMs in Experiment 1



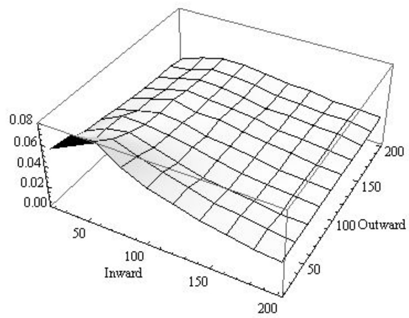
(a) Share of PMs: 10 PMs



(b) Share of PMs: 20 PMs

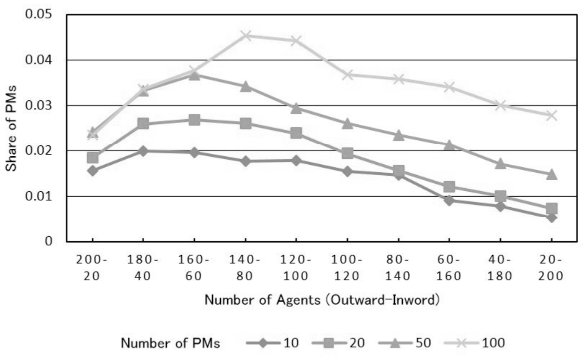


(c) Share of PMs: 50 PMs

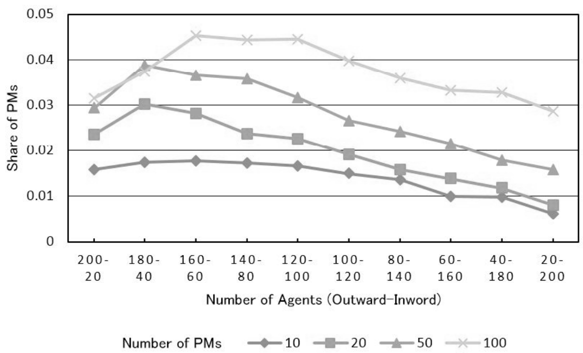


(d) Share of PMs: 100 PMs

Fig. 7. Share of PMs in Experiment 2



(a) Share of PMs in Experiment 1



(b) Share of PMs in Experiment 2

Fig. 8. Share of PMs for the same total number of agents

of available PMs increases, the success rate is improved. In this setting, the number of inward agents influences the success rate. When the number is insufficient, success rate is decreased by unbalanced usage, especially in (a) and (b).

The share of PMs is shown in Fig. 6. As the number of available PMs increases, the share also increases, but the increase is not so large. The maximum share was 0.075 at Inward=60, Outward=20 with 100 PMs in total.

As a result of Experiment 2, the share of PMs is shown in Fig. 7. These graphs are similar to Fig. 6. The graphs show that the nonuniform arrival rate does not have a strong effect on the PM share in this setting. Resulting shares extracted for the total number of 120 agents are shown respectively in Figs. 8(a) and 8(b) for Experiment 1 and 2. As these graphs show, the peak is shifted larger given fewer available PMs and fewer inward agents.

V. Discussion and Conclusions

We considered personal mobility sharing through results of experiments and simulation. Experiments showed that PMs are safe, with no related problems to date. In addition, simulation study revealed that more than 8% potential users might use PMs if there are a sufficient number of PMs. Unbalanced usage decreases its share depending on the total number of agents. Connection usage with trains did not strongly affect the share. Further study with varying scenarios and conditions will be necessary.

For unbalanced usage, manual relocation is necessary for usability. Some relocation methods have been studied [21], [22]. If we were able to introduce an autonomous driving capability without humans, then such problems can be expected to decrease.

Many avenues remain for future work. First, we are planning to increase users to gather participants for experiments with different kinds of data. Additionally, the simulation accuracy remains unclear. Moreover, the calibration of the results should be considered. Based on the calibration, refinements in both the decision and behavior models as well as in parameter values are expected to improve the results. In this case, we must introduce other mobility device candidates in the simulation such as bicycles and private cars.

Large-scale simulations are expected to provide a basis for the future demand prediction and planning of sharing stations for a large-scale introduction of PMs into society: The demands of PM devices can be evaluated based on more realistic assumptions, suggesting optimal planning of a PM sharing system.

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