Sustainable Market Design for Short-trip Rideshares: Simulation Based on Bipartite Matching

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Abstract: In this paper, we focused on a short-trip rideshare system supported by other-regarding preferences of drivers and passengers in a village community, with non-monetary rewards included. The study objective was to develop a methodology for simulating various mechanism designs of the short-trip rideshare system. We studied, through numerical simulation, ways to improve system sustainability by giving informational guidance. As a result, we showed that by messages that can shape expectations of driver candidates about the success of ridesharing, a higher number of rideshare pairs can be sustained. From our numerical example, we concluded that the informational guidance in which a system operator conveys the messages roughly three times of ten, which induce each of driver candidates to take action toward delayed matching in place of failure, is reasonable for promoting system sustainability from the viewpoint of both the number of rideshare pairs and the welfare level of all participants.

Keywords: Low-density Small Community, Public Transport Substitute, Short-trip Rideshare, System Sustainability, Informational Guidance Mechanism, Bipartite Matching

1. INTRODUCTION

1.1 Background

In village communities in Japan, there are households with no access to bus and taxi services. In such households, when someone uses the household’s car, if there is one, the other household members have no transportation to facilities or daily necessities beyond a distance, which obviously limits external activities. One proposed method to assist people who have no transportation is establishing a support service for getting a ride from other households in the village community (Sasaki et al., 2013; Yotsutsuji et al., 2013).

There are various types of systems for facilitating ridesharing. In this paper, we focus on a type in which drivers give rides to people who need transportation assistance, picking the people up for non-monetary rewards, on the way from the drivers’ origin to the drivers’ destination in a short trip. We refer to such a trip as a short-trip rideshare (ST-RS). In addition, we focus on a system in which a system operator provides a short-trip rideshare service by using incentives to promote participation and matching, in pairs, between members who have been separately registered as driver candidates and passenger candidates with an
understanding of the non-monetary reward conditions. We refer to the overall system as an ST-RS system.

Sasaki et al. (2013) and Yotsutsuji et al. (2013) showed some requirements for an ST-RS system to be effective in a village community. One of the described requirements was that the trip frequencies and head counts of driver candidates can be higher than the corresponding numbers for passenger candidates. Under such a requirement, when the ST-RS system is operated on the basis of bipartite matching between drivers and passengers, we consider that mechanisms for system sustainability are an important issue.

1.2 Issues

For long trips, one motive for drivers to accept passengers is to split travel costs with the passengers. However, for short trips, travel costs are typically far less than the amount shouldered by a paying passenger. In such cases, the system operator may need to provide a non-monetary motive for drivers if the system is to be sustainable. Our research focuses on altruism by drivers toward particular passenger candidates as the motive.

If the trip frequencies and head counts of driver candidates are the same as those of passenger candidates, then bipartite matching will work fine in the ST-RS system. However, when there is a discrepancy between drivers and passengers as far as trip frequencies and head counts, members who have had repeated experiences in which there was nobody to share a ride with may well decide to not participate in the ST-RS system. As a mechanism for maintaining the number of matched pairs, our research focuses on the role of information in setting driver candidates’ expectations that ridesharing will be feasible and doing so in a system by which the operator gives driver candidates information about whether the ridesharing will be feasible.

1.3 Purpose

Authors’ previous studies (Sasaki et al., 2013; Yotsutsuji et al., 2013) were feasibility studies which made the issues of the rideshare system obvious through a demonstration experiment in reality. It turned out that, the system has been feasible but a mechanism design will help make the system sustainable. However, by means of demonstrations in reality without advance verifications on the desk, it seemed to be difficult to validate the effects of a lot of various mechanism designs. A methodology for predicting the effects in advance was needed.

The objectives of this study are to develop a methodology for simulating various mechanism designs of the rideshare system on the desk, and to simulate a scenario of the impact of an information guidance mechanism on the system sustainability. Additional contribution of this study as compared to the previous studies is to prepare simulation models necessary to confirm the system feasibility by use of real world data for validation.

In this study, assuming an ST-RS system supported by other-regarding preferences of driver and passenger candidates with no monetary reward, we analyzes the sustainability of the ST-RS system through numerical simulation. This study makes the following assumptions for simulation.

1) Driver candidates are focused on immediate goals and passenger candidates are focused on ultimate goals. Driver candidates make near-term-focused decisions with a myopic policy about whether to make a detour necessary to serve a passenger candidate or travel directly toward their destination. In contrast, passenger candidates make long-term-focused decisions with a far-sighted policy about whether to go out or postpone going out (stay home) on the basis of the
expectation of a rideshare.

2) The operator searches for a stable matching set in each period. As a method for finding a bipartite matching between driver and passenger candidates in each matching stage, the operator adopts the deferred acceptance (DA) algorithm (Gale and Shapley, 1962; Roth, 2008), which can realize stable matched pairs.

3) The rideshare agreement can be executed as planned in every period. No-shows, last-minute cancellations, and delays do not occur.

4) No return trip: Although passenger candidates may decide not to go out without a guarantee that a rideshare for the return trip can be ensured, only one-way trips are considered in this paper.

5) Preferences in each period are determined by certain externalities. Preferences of the candidates are allowed to vary in each period, even though the candidate shares a ride with the stable matched partner in each period, because of the effect of externalities on preference formation.

The purpose of this paper is twofold. One purpose is to simulate a phenomenon in which the number of participants and the number of matched pairs decreases when the operator does not introduce any additional mechanisms, such as informational guidance, into the ST-RS system. The other is to study whether sustainability of the ST-RS system can be improved through the introduction of an informational guidance mechanism.

2. RELATED RESEARCH

Rideshare systems may succeed, even those not based on indirect reciprocity, which, in this context, exists when drivers expect to become passengers in the future. We consider it possible that drivers will participate in a rideshare system even when they have no opportunity to be a passenger. Rideshare systems supported by other-regarding preferences and altruism have been investigated previously, such as in Sasaki et al. (2013) and Yotsutsuji et al. (2013); these studies investigated, through a questionnaire survey, how a rideshare system with two-sided matching between drivers and passengers would be feasible among transportation-poor people in a village community. The results showed that drivers have no hesitation in giving a ride to an acquaintance, but passengers have hesitation about traveling free of charge. Those studies focused on this hesitation as a system sustainability issue.

There are various approaches to model the other-regarding preferences, also known as social preferences. Schmidt (2011) classified the approaches into three types of approach: intention-based, type-based, and outcome-based. In intention-based approaches, each player incorporates partner intention, considering why the partner engaged in a specific behavior when choosing own behavior. Therefore, players will choose kind behavior when their partner is kind and hostile behavior when their partner is hostile. In type-based approaches, players incorporate their partner’s type into their own behavior. Therefore, players choose kind behavior when the partner is seen as good and hostile behavior when the partner is seen as bad. Game theory is used to analyze the behaviors in both approaches. In outcome-based approaches, players incorporate the outcome of their partner’s behavior into their own behavior. This is a conventional approach, described in various contexts as the pure altruism model, “warm glow” model, inequality aversion model, and so on. In the Japan Society of Civil Engineers (JSCE), behavior models that consider social preference employ the outcome-based approach. Kobayashi et al. (1996) proposed a random utility model that incorporates partner utility, distinguishing “kiss-and-ride” systems, which assume paternalistic motives, from altruism-based rideshare systems. Morikawa et al.
(1997) proposed a random utility model based on shared log-sum variables representing differences in utility between system users. In this paper, we propose a model that considers hesitation by passenger candidates, applying the outcome-based approach used in Fehr and Schmidt (1999).

The rideshare system is considered as a transportation market for matching demand for short trips with the supply of rides. Matsushima and Kobayashi (2005) explained that such transportation systems experience market failures in four areas: congestion externality, trading externality, scale economy, and strategic complementarity in mode choice. Here, the externalities with the most influence on are the trading externality (also known as the thin-market externality) and the strategic complementarity in mode choice. The trading externality is the possibility that when the number of participants has decreased in each of the previous periods, decline in the number of participants can accelerate among both driver and passenger candidates. Strategic complementarity in mode choice occurs because passenger candidates who plan a trip must consider the travel mode for the return trip. In this paper, we focus on the trading externality in particular and do not consider the influence of externalities on the return trip.

It is important for the rideshare systems to incorporate dynamic information. Agatz et al. (2011, 2012) analyzed a framework for a dynamic rideshare system (DRS). A DRS resembles an in-city taxi service, allowing rides at arbitrary times, rather than a carpooling service, in which users must travel at a fixed time. The analysis focused on maximizing the number of participants and minimizing average trip cost. Kleiner et al. (2011) proposed a DRS system that relies on a strategy-proof auction mechanism in which passengers bid for drivers. For this study, the objective was to minimize average travel distance and maximize the number of rideshare pairs. Chan and Shaheen (2012) investigated the history of DRSs in North America. They showed that rideshare users in North America were mainly motivated by reduce high-occupancy vehicle tolls or parking fees at the destination. Furuhata et al. (2013) classified DRSs into four types according to the type of route matching: identical, inclusive, partial, and detour. Siddiqi and Buliung (2013) investigated the history of systems operations for DRSs that use information and communication technology.

The above-mentioned research into DRS systems has focused on the case of high-density residential areas where driver candidates are frequently traveling and on ensuring that when a passenger candidate asks for an appointment with the rideshare service, the operator can immediately arrange a match by searching among driver candidates in the area. The case considered here is different; we focus on low-density village communities.

3. FRAMEWORK

3.1 Matching and Ridesharing

In the proposed ST-RS system, we assume a timeline consisting of many periods on a discrete time axis. We divide each period into two stages, the matching stage and the ridesharing stage. The ridesharing stage in one period overlaps with the matching stage in the next. Because of this overlap, matching and ridesharing take place simultaneously.

We assume that the total time to be considered is constant (e.g., one week) and does not depend on periods. The preferences each driver and passenger candidate (collectively, “members”) must be declared by the end of the matching stage to participate in the subsequent ridesharing stage. For each matching stage, the operator decides matches on the basis of ordered preferences at the end of the matching stage and then announces the matches.
Members then share rides with their matched partners by the end of the ridesharing stage; during this time, the operator is preparing the next matches.

We assume that the trip frequencies and head counts of the driver candidates are higher than those of the passenger candidates in the village community. To model this assumption in a simple way, we assume that each driver candidate must go out in every period, but passenger candidates sometimes stay at home. Additionally, driver candidates may share a ride even if it requires a detour from the quickest route, but passenger candidates must have both origin and destination on the (possibly detoured) route of the driver candidate.

3.2 State and Behavior

Each member is assigned a state according to the failure or success of the rideshare. After each rideshare, the members can share the utility of ridesharing with their matched partner; members gain no utility when they do not rideshare in the period. On the basis of their experiences and the uncertainty of the future state for the ridesharing stage, each member makes decisions about specific partners in the matching stage. After this, each member ranks their preferences for all partners.

The action taken by each member depends on the state of the period, not the period itself. Passenger candidates may choose to go out or stay home (i.e., seek a rideshare or not); driver candidates may choose to detour to accept a passenger or to travel the quickest route to their destination. We assume that driver candidates have a short-term focus, considering only the current trip with non-monetary reward; in contrast, passenger candidates are assumed to have a longer-term focus because they may choose to stay home instead of participating in a rideshare.

3.3 Mechanism

To achieve system sustainability, the operator can design different mechanisms, which can include both information and incentives. Information mechanisms update expectations on the basis of messages. Incentives influence decision-making in actors by offering rewards for desired behavior. In this paper, we focus on information mechanisms.

We consider an information guidance mechanism and analyze it by applying the framework described in Kamenica and Gentzkow (2011) for persuasive communication. The information conveyed by the informational guidance mechanism is in the form of messages that the operator provides to driver candidates (but not passenger candidates) according to the system state. As the objective, the operator chooses a rule for providing messages intended to maximize the probability that driver candidates will accept a detour. The operator chooses a strategy under which driver candidates provide the message to passenger candidates that “you can rideshare” in cases where the rideshare-matching succeeded in the prior period and, in cases where the rideshare-matching failed, provide a message of “you cannot rideshare” or “you can probably rideshare” with a probability. We refer to the method of deciding the stated probability as the informational guidance rule. For driver candidates, a Bayesian learning strategy is used to decide the probability of each state according to the given message.

4. MODELS

4.1 Scheduling
Let $D$ and $S$ be a set of passenger candidates (rideshare demanders) and a set of driver candidates (rideshare suppliers), respectively, with $D$ and $S$ mutually disjoint. Let $N$ be the set of all members in the ST-RS system, that is, $N = D \cup S$, where $|D| \geq 2$, $|S| \geq 2$, and $|S| > |D|$. Each $d \in D$ has an ordered preference for members of $S$; likewise, each $s \in S$ has an ordered preference for members of $D$. Let $\succ_k$ be a binary relation on $N$ that reflects the preferences of member $k \in N$. Then, $\succ_k$ is assumed to induce a strict weak ordering.

We assume that the operator and the members operate according to the scheduling system shown in Figure 1. The initial value of time is zero, and the initial period is period 1 in Figure 1. In each period $\tau$, the end of the period-$\tau$ matching stage and the beginning of the period-$\tau$ ridesharing stage both occur at time $\tau$. Decision-making for members in period $\tau$ occurs at the end of the matching stage, and the state of the ridesharing stage is uncertain at time $\tau$.

![Figure 1. Schedule of matching and ridesharing in the ST-RS system](image)

### 4.2 Matchings

By reference to Gusfield and Irving (1989) and Roth and Sotomayor (1990, 1992), we define a process of two-sided matching between the driver and passenger candidates. We refer to $\mu(k)$ with $k \in N$ and $\mu : N \to N$ as the partner for member $k$. We specify that $\mu(k) = k$ indicates that $k$ was not matched with a partner. Here, any function $\mu$ that satisfies the following relations is termed a matching.

$$
\mu(d) \in S \cup \{ d \}, \quad \mu(s) \in D \cup \{ s \} \quad \text{for } \forall d \in D, \forall s \in S
$$

(1)

When a matching $\mu$ satisfies $\mu(k) \succ_k k$ for each $k$, meaning that $k$ has an ordered preference for partners that $k$ prefers to being unmatched, the matching $\mu$ is termed individually rational. We here describe a pair of $d \in D$ and $s \in S$ as the tuple $(d,s)$. When a tuple $(d,s)$ satisfies $d \succ s, \mu(s)$ and $s \succ d, \mu(d)$, namely, $s$ prefers $d$ to the matched partner $\mu(s)$ and $d$ prefers $s$ to the matched partner $\mu(d)$, then the matching $\mu$ can be improved with respect to $(d,s)$. When an individually rational matching $\mu$ cannot be improved with respect to any pair of members, it is called stable. Let $\mu^*$ be a stable matching. We refer to a set of partners from $\mu^*$ as a stable matching set, which is represented as a pair $\{\mu^*(s), \mu^*(d)\}$. Any pair of members who belong to the same stable matching set in period $\tau$ cannot "run off" with any other members. However, if the preference orders of the pair vary in period $\tau + 1$, then the stable matching sets may be different in period $\tau + 1$.

In this paper we assume that the ordered preference of member $k$ in the matching stage in period $\tau$ is faithfully reflected in the values that $k$ has assigned to all partners encountered up to time $\tau$. The member chooses the best action with respect to each
prospective partner at time $\tau$ in the matching stage of period $\tau$, including consideration of both whether the prospective was a partner in the ridesharing stage of period $\tau - 1$ and whether the prospective partner is someone with whom the member would be able to share a ride in the ridesharing stage of period $\tau$. If the member is unwilling to share a ride with a prospective partner, the member grades that partner lower than every novel partner.

4.3 Ridesharing

Following Agatz et al. (2011, 2012), we assume the relation between detour trips and ridesharing that is illustrated in Figure 2. Let $l_{ij}$ be the distance of a link from node $i$ to node $j$. Let $O_k$ and $D_k$ be the origin and destination, respectively, of a trip planned by member $k$. Let $l_d$ and $l_s$ be the respective distances of routes between the origin and destination of a trip planned by passenger candidate $d$ and by driver candidate $s$. In this paper, for the sake of simplicity, we assume that each member’s origin and destination pair is fixed and constant across all periods. In Figure 2, we can set $l_d = l_{O_d,D_d}$ and $l_s = l_{O_s,D_s} + l_{O_s,D_d} + l_{D_d,D_s}$ under this assumption.

We assume that the utility of ridesharing is directly proportional to the distance of the route on which a pair $(d,s)$ has shared a ride; specifically, it is proportional to $l_d$ in Figure 2. There are two components in the utility of ridesharing. One depends on the distance of detour that the driver took on behalf of the passenger. The other depends on the distance of the route on which the driver and passenger shared a ride. Let $r^D_d$ be the passenger $d$’s utility from ridesharing with driver $s$, and analogously for $r^S_s$, where the top-right suffix of $r$ is the utility subject. Here, we define $r^D_d$ and $r^S_s$ as the following equations, where $\xi^D$ and $\xi^S$ are strictly positive parameters.

$$
 r^D_d = \xi^D l_d \frac{l_s}{l_d + l_s}, \quad r^S_s = \xi^S l_d \frac{l_d}{l_d + l_s}.
$$

(2)

![Figure 2. Detour trips and ridesharing](image)

4.4 The Trading Externality

We consider a trading externality as follows. The greater the number of passengers ($N^D$) who participate in the system in period $\tau$, the lower the probability for each individual passenger of being matched with a driver. Moreover, when the number of driver candidates ($N^S$) exceeds the number of passenger candidates in period $\tau$, the probability for each passenger of being matched with a driver is high. Let $\Delta^D$ be the ratio obtained by dividing the number of passengers who participated in period $\tau - 1$ by the number that participated in the period $\tau$; when the denominator is 0, we take the ratio as 1. By definition, $\Delta^D > 1$ indicates a decrease in participating passengers in period $\tau$. As an externality affecting a passenger $d$’s preference, the trading externality means that $d$ is positively influenced if $(N^S - N^D)\Delta^D$ is
positive when the number of participating drivers is greater than the number of participating passengers. In addition, the influence of this positive externality on a passenger $d$ will reduce the preference for a partner $s$ as the number of matches between the two increases. The same externality applies to on driver candidate preferences.

Let $m_{d,s}$ be the number of matches between $d$ and $s$ up to period $\tau$. Let $\eta_d^D$ and $\eta_s^S$ be the respective effects of the trading externality on the preferences of $s$ and $d$ for each other in period $\tau$. We define $\eta_d^D$ and $\eta_s^S$ by the following equations, where $\xi^D$, $\xi^S$, $\kappa^D$, and $\kappa^S$ are parameters satisfying $0 < \xi^D, \xi^S \leq 1$ and $\kappa^D, \kappa^S \geq 0$.

$$
\eta_d^D = \xi^D (N^S - N^D) \Delta^D - \kappa^D \log m_{d,s},
\eta_s^S = \xi^S (N^D - N^S) \Delta^S - \kappa^S \log m_{d,s}.
$$  (3)

4.5 Passenger Hesitation

Following Fehr and Schmidt (1999), we formulate each passenger candidate’s hesitation about ridesharing according to the driver candidates offered. Fehr and Schmidt proposed that own utility decreases due to inequality aversion when own utility is lower than others’ utilities. We assume, in contrast, that the utility of a passenger candidate $d$ for a driver candidate $s$ in period $\tau$ will decrease due to $d$’s hesitation when $d$’s utility, $r_d^D$, is higher than $s$’s utility in period $\tau - 1$.

Let $h_d^D$ be passenger candidate $d$’s hesitation in period $\tau$. Here, we define $h_d^D$ as follows, where $h_d^D \leq 0$ and $\beta^D$ is a parameter with $\beta^D \geq 1$.

$$
h_d^D = -\beta^D \max \{0, r_d^D - r_s^S\}.
$$  (4)

4.6 Decision-making

Let $C$ be a set of possible states for $d, s \in N$, and let $A$ and $B$ be action sets of $s$ and $d$, respectively. After observing $c \in C$ and evaluating $\mu(s)$ and $\mu(d)$ in the ridesharing stage in period $\tau - 1$, members $s$ and $d$ choose an $a \in A$ and $b \in B$, respectively, such that the choice maximizes $s$’s utility and $d$’s utility for $\mu(s)$ and $\mu(d)$, respectively, in period $\tau$.

A driver $s$ must detour to share a ride with passenger $d$, but the driver cannot always share the ride. We refer to an action by a driver traveling directly toward the destination as without detour and its complement as with detour. For the passenger, passenger $d$ must go out to share a ride with driver $s$, even though the passenger cannot always share the ride. We refer to staying home (postponing the trip) as without going out and its complement as with going out. Symbolically, we define the state possibilities $C$, $A$, and $B$ as follows.

$$
C = \{\text{rideshare failure, rideshare success}\} = \{c_0, c_1\},
A = \{\text{without detour, with detour}\} = \{a_0, a_1\},
B = \{\text{without going out, with going out}\} = \{b_0, b_1\}.
$$  (5)

An outcome $c' \in C$ in the ridesharing stage of period $\tau$ depends on the state’s transition probabilities, as determined by a time-homogeneous Markov decision process on the basis of both the outcomes in the ridesharing stage of period $\tau - 1$ and $a \in A$ and $b \in B$ in the matching stage of period $\tau$. Let $p_a^{c'} = P(c'|c,a)$ and $p_b^{c'} = P(c'|c,b)$ be the states’ transition probabilities. We define the state’s transition probability matrices, $P^a$ and $P^b$, as follows.
Here, we formulize the decision-making of a driver candidate \( s \in S \). Let \( v^s_{a}(c, a) \) be the value of \( s \) taking action \( a \) with respect to \( d \) in state \( c \). We assumed that \( s \)'s behavior is near-term focused. Therefore, choosing \( a_0 \in A \) in period \( \tau \), driver \( s \) decides \( v^s_{a}(c, a_0) \) without considering the state of the ridesharing stage in period \( \tau \). We can formulize the choice of the best action for \( s \), which we denote \( a^* \), as follows, where \( V^s_{a}(c, a) \) represents a value function.

\[
a^* = \arg \max_{a \in A} \{ V^s_{a}(c, a) \} \quad \text{for } c \in C. \tag{7}
\]

The value function, \( V^s_{a}(c, a) \), is described by the following equation, where \( \delta \) is a discount factor with \( 0 \leq \delta < 1 \) applied to the expected utility of the ridesharing stage.

\[
V^s_{a}(c, a) = v^s_{a}(c, a) + \delta \sum_{c' \in C} p^s_{a,c'}v^s_{a}(c', a). \tag{8}
\]

Here,

\[
v^s_{a}(c_0, a) = \begin{cases} 0 & \text{if } a = a_0, \\ \eta^s_{a} & \text{if } a = a_i, \end{cases} \quad v^s_{a}(c, a) = \begin{cases} r^s_{a} & \text{if } a = a_0, \\ r^s_{a} + \eta^s_{a} & \text{if } a = a_i. \end{cases}
\]

Now, we formulize the decision-making of passenger candidate \( d \in D \). Let \( v^p_{b}(c, b) \) be the value of \( d \) taking action \( b \) with respect to \( s \) under state \( c \), and let \( V^p_{b}(c, b) \) be a value function. We assume that \( d \)'s behavior is long-term focused. Therefore, in period \( \tau \), \( d \) will chooses the action that maximizes the discounted present value of total expected utility over an indefinite period. Then, we can write \( V^p_{b}(c, b) \) as the following equation.

\[
V^p_{b}(c, b) = \mathbb{E} \left[ \sum_{r=0}^{\infty} \delta^r v^p_{b}(X^r, b) \left| X^0 = c \right. \right], \tag{9}
\]

where \( \mathbb{E} \) is the expectation function.

However, because we assumed that \( d \) is permitted to not go out, we must consider the utility of staying at home in equation (9). Let \( \alpha \) be the rate at which \( d \) stays home, with \( 0 < \alpha \leq 1 \), and let \( Z \) be the utility of staying home, which is assumed to be equal to the opportunity cost of going out without ridesharing. We can formulize the choice of the best action for \( d \), which we denote \( b^* \), as follows.

\[
Z, b^* = \arg \max \{ Z, \ V^p_{b}(c, b_0), \ V^p_{b}(c, b_1) \} \quad \text{for } c \in C. \tag{10}
\]

The value function, \( V^p_{b}(c, b) \), is described by the following equation. We note that the hesitation \( h^p_{b} \) is included in \( v^p_{b}(c, b) \).

\[
V^p_{b}(c, b) = v^p_{b}(c, b) + \delta \left( (1 - \alpha) \left( p^p_{0,c}Z + p^p_{0,b}V^p_{b}(c_1, b) \right) + \alpha Z \right). \tag{11}
\]
\[ v^D_s(c_0, b) = \begin{cases} 0 & \text{if } b = b_0, \\ \eta^D & \text{if } b = b_1, \\ \rho^D + \eta^D + h^D & \text{if } b = b_1. \end{cases} \]

4.7 Evaluation Criteria

We set the number of participants \((N^S \text{ and } N^D)\), the number of rideshare pairs, and the level of welfare \((W)\) as criteria for evaluating the period \(\tau\) with respect to the sustainability of the ST-RS system.

We express \(W\) as the sum of the Nash products of the values given by all participants \(N = D \cup S\) including rideshare pairs, that is, as the sum of the product of each \(V^S_d(c_i, a_i)\) and the corresponding \(V^D_s(c_i, b_i)\):

\[
W = \sum_{(d, r) \in N} V^S_d(c_i, a_i) \cdot V^D_s(c_i, b_i). \tag{12}
\]

5. MECHANISM DESIGN

5.1 Deferred Acceptance Mechanism

The system operator is searching for stable matching sets in each period by following the DA algorithm (Gale and Shapley, 1962; Roth, 2008). The set of stable matching sets searched by the DA algorithm becomes efficient through the algorithm, meaning that all stably matched members have no incentive to improve on the stable matching \(\mu^*\), and so they ultimately form the core of a cooperative game. Since any set of stable matching sets induced by a stable matching is a subset of the core, it satisfies Pareto efficiency and individual rationality.

One issue that emerges when the operator adopts the DA algorithm for the matching process of the ST-RS system is that the operator cannot prevent strategic false revelation of preferences by members. In the DA algorithm, in general, each member offers a match to the most preferred partner, and the potential partner then holds the offer. Because of this, the system is vulnerable to being affected by the potential partner revealing a strategic preference order; a system not vulnerable to this is called strategy-proof.

In the ST-RS system, we set the driver candidates as the offered side (potential partners) and the passenger candidates as the offering side for the DA algorithm. This is because we assume that driver candidates will not reveal false preferences for wanting to share a ride with particular passenger candidates.

5.2 Informational Guidance Mechanism

By applying the analytical framework of Kamenica and Gentzkow (2011), we formulate an informational guidance mechanism to be introduced in the ST-RS system. In the proposed system, the operator provides a message to each driver candidate \(s \in S\) according to the informational guidance rule \(\varepsilon\) during the matching stage of period \(\tau\) after observing the state \(c \in C\) from the ridesharing stage of period \(\tau - 1\). Let \(G^s\) be a set of messages determined according to the informational guidance rule \(\varepsilon\). We here define \(G^s\) to be the following.

\[
G^s = \{ \text{You cannot rideshare, You can probably rideshare} \} = \{ g_0, g_1 \}. \tag{13}
\]
Now, we describe the strategy of the operator. The informational guidance rule can be explained as an action by which the operator makes recommendations to driver candidates. The operator wishes to induce detour behavior in the driver candidates no matter which state is observed. Let $\pi^e(g \mid c)$ be a probability distribution of the message $g \in G^e$ conditioned on the state $c \in C$. We define $\pi^e(g \mid c)$ as follows.

$$
\begin{align*}
\pi^e(g_0 \mid c_0) &= 1 - \epsilon, \quad \pi^e(g_1 \mid c_0) = \epsilon, \\
\pi^e(g_0 \mid c_1) &= 0, \quad \pi^e(g_1 \mid c_1) = 1.
\end{align*}
$$

Here, we formulate the decision-making of a driver candidate $s \in S$ under the informational guidance mechanism. The driver candidate $s$ applies a Bayesian learning strategy concerning occurrence probability of state $c \in C$ by examining the message $g \in G^e$. Let $\overline{p}(c)$ and $p(c \mid g)$ be the prior probability and posterior probability, respectively, for state $c$. We here define $\overline{p}(c)$ as the following equation, where $\theta$ is a parameter satisfying $0 < \theta < 1$:

$$
\overline{p}(c_0) = 1 - \theta, \quad \overline{p}(c_1) = \theta.
$$

Now, we define $p(c \mid g)$ according to the Bayesian rule, obtaining the following equations:

$$
\begin{align*}
p(c_0 \mid g_0) &= \frac{(1 - \epsilon)(1 - \theta)}{(1 - \epsilon)(1 - \theta)} = 1, \quad p(c_1 \mid g_0) = \frac{0}{(1 - \epsilon)(1 - \theta)} = 0, \\
p(c_0 \mid g_1) &= \frac{\epsilon(1 - \theta)}{\epsilon(1 - \theta) + \theta}, \quad p(c_1 \mid g_1) = \frac{\theta}{\epsilon(1 - \theta) + \theta}.
\end{align*}
$$

Then, $s$ will choose action $a$, predicting state $c$ on the basis of the message $g$ (Figure 3). If $c$ satisfies $c_0 = a_0$ and $c_1 = a_1$, then $s$ has increased utility from the message. We here define the value of message, $u(c, a)$, as the following equations, where $\overline{u}$ is a strictly positive parameter:

$$
\begin{align*}
u(c, a) &= \begin{cases} 
\overline{u} & \text{if } c_0 = a_0, c_1 = a_1, \\
0 & \text{if } c_0 = a_1, c_1 = a_0.
\end{cases}
\end{align*}
$$

The value function $V_d^s(c, a)$ of $s$ is given by

$$
V_d^s(c, a \mid g) = v_0^d(c, a) + u(c, a) + \delta \sum_{c' \in C} p(c' \mid g) v_0^d(c', a) \quad \text{for } \exists g \in G^e.
$$

When message $g_1$ is observed, $s$ chooses action $a_1$ if $V_d^s(c, a_1 \mid g_1) \geq V_d^s(c, a_0 \mid g_1)$, otherwise action $a_0$. When $g_0$ is observed, $s$ always chooses $a_0$. 

![Figure 3. Information guidance mechanism](image-url)
6. A NUMERICAL EXAMPLE

We simulate two scenarios about the trading externality, using a simple road network illustrated in Figure 4. We use the following setup for numerical simulation. We set $|D| = 5$ and $|S| = 10$, which meets the condition that $|S| > |D|$. For equation (3), we took the parameter values $\xi^D = \xi^S = 0.01$ and prepared two cases for parameters $\kappa^D$ and $\kappa^S$. In one (Case 1), $\kappa^D = 0.2$ and $\kappa^S = 0.15$ so that the effect of negative trading externalities was high for repeated matching with the same partner; in the other (Case 2), $\kappa^D = 0.01$ and $\kappa^S = 0.01$ so that the effect was small. For equation (4), we set $\beta^D = 1$. For equation (6), we used normally distributed random numbers with mean 0.5 and variance 0.05 as the parameter values for $p_{00}^0$, $p_{11}^0$, $p_{00}^1$ and $p_{11}^1$ in each period. The stay-at-home rate, $\alpha$, was chosen uniformly randomly from between zero and one in each period. The discount factor, $\delta$, was given as $\delta = 0.95$. The prior probability in the Bayesian learning strategy, $\theta$, was given as $\theta = 0.5$.

To discuss the results of this numerical example, we will show the changes in the number of participants and the effect of the trading externality (Figure 5), changes in the number of rideshare pairs and the effect of informational guidance (Figure 6), and changes in the level of welfare and the effect of informational guidance (Figure 7). Note that the simulation results which were described in Figures 5 to 7 are affected by the randomness of $p_{00}^0$, $p_{11}^0$, $p_{00}^1$, $p_{11}^1$ and $\alpha$.

![Figure 4. Road network](image_url)

![Figure 5. Time series of the number of participants and the effects of the trading externality](image_url)
7. DISCUSSIONS

As illustrated in the right panel of Figure 5, Case 1 shows that the number of participating driver candidates decreases in the early period, compared with Case 2, in which the moving average is relatively stable. In Case 1, a driver candidate making near-term-focused decisions quickly rescinds a detour for a repeated-matching partner in the early period, because negative trading externalities are high. Once his preference to detour for the repeated-matching partner ranks lower than one to travel directly toward the destination, he subsequently tends not to detour for such partner. In Case 2, in contrast, he tends to keep detouring for such partner because negative externalities are low, even though his decisions are near-term-forced in the same way as Case 1. Accordingly, one of the measures to maintain his participation is to minimize disutility of repeated matching with the same partner, for example, by means of giving rides to acquaintances.

To focus on system sustainability, we further consider only Case 1. As illustrated in the left panel of Figure 5, at least two passenger candidates are engaged in seeking for more than 30 periods. As illustrated in the left panel of Figure 6, in the absence of information, stretches of more than 30 periods in which there are no rideshare pairs emerge. Accordingly, at least two passenger candidates go out without ridesharing for more than 30
periods. In contrast, when the informational guidance mechanism is used, there is a decline in the number of rideshare pairs, with information resulting in a low level depending on the informational guidance rule $\varepsilon$ (right panel of Figure 6). When $\varepsilon$ is nearly equal to 0.5 (i.e., the guidance is somewhat ambiguous), then we can prolong the existence of a higher number of rideshare pairs. As illustrated in Figure 7, when $\varepsilon$ is nearly equal to zero (i.e., information is unambiguous), the welfare level of rideshare pairs is high. Accordingly, $\varepsilon$ represents a trade-off problem, where the number of rideshare pairs is balanced against the welfare level of the pairs.

As illustrated in the case that $\varepsilon$ is equal to zero in both Figure 6 and 7, the number of rideshare pairs decreases in the early period, as the welfare level of the pairs shows a periodicity and a trend that the moving average is almost stable. The reason why such trend of the welfare level is observed for no rideshare pairs is because the welfare was defined as the sum of the products of the values given by all participants including unmatched member. When a driver candidate cannot rideshare by virtue of a message that he cannot rideshare, he can gain utility from the message. The reason why there is the periodicity is because repeated matching with the same partner has causes the welfare level of the pairs to decrease sharply until each of the pairs matches the different partner, even if the number of the pairs is small.

From among the alternatives for $\varepsilon$ in our numerical example, we suggest $\varepsilon = 0.3$ as a reasonable setting for system sustainability from the viewpoint of both the number of rideshare pairs and the welfare level of those pairs. An $\varepsilon$ of 0.3 means that there is a 30% chance a driver will still be able to obtain a ride even if a first matching fails. Our suggestion is that a system operator using information and communication technology conveys the messages to driver candidates roughly three times of ten, which induce each of the driver candidates to take action toward delayed matching in place of failure.

8. CONCLUSION

In this paper, we focused on an ST-RS system supported by other-regarding preferences of driver and passenger candidates with non-monetary rewards in a village community. The study objective was to develop a methodology for simulating mechanism designs of the ST-RS system. Through numerical simulation, we studied improvements to the system sustainability from an informational guidance mechanism. We showed that, through messages that can induce driver candidates’ expectation about the likely success of ridesharing, the number of rideshare pairs can be sustained. From our numerical example, we concluded that the informational guidance in which a system operator conveys the messages roughly three times of ten, which induce each of the driver candidates to take action toward delayed matching in place of failure, is reasonable for promoting system sustainability from the viewpoint of both the number of rideshare pairs and the welfare level of all participants.

We mention application of this system to developing countries in the eastern Asia briefly here. In suburban cities in which the number of households’ cars is increasing and the level-of-service of public transport is low, ensuring the mobility of people with low income will enhance the quality of life of them. In addition to that, in the area where people are friendly and strongly connected in the suburban cities, a shared mobility such as vanpooling and hitchhiking with strangers is occurring. We think that, if the sharing can be systemized, the mobility of people will be improved in the area. The framework and methodology that we proposed here will be useful for systemizing the shared mobility and validating application of the system by use of real world data.

The following issues remain. For further improvement of the sustainability, we intend to
study incentive mechanism, such as loyalty card services, for changing the behavior of members. For the case where driver candidates are allowed to select the partner, rather than accepting requests from passengers, the DA algorithm will need to be modified. For the case where passenger candidates can require a return trip as a condition of ridesharing, a matching algorithm that considers strategic complementarity in mode choice must be adopted.

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