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DAY-TO-DAY DYNAMICS OF PASSENGER MATCHING PROBLEM IN SMART RIDESHARING SYSTEMS

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ABSTRACT

With the development in technologies, matching applications by considering user preference on smart devices have already appeared and adopted day-to-day in ridesharing market. Unfortunately, the service providers have less intention to analyze and understand their dynamic ridesharing system (DRS), e.g., feasibility, equilibrium stability of DRS. Therefore, this study is aimed to understand DRS's feasibility and investigate the DRS's day-to-day equilibria (i.e., existence, uniqueness, and stability) by analyzing day-to-day dynamics of DRS through a formulated model of one-on-one passenger matching problem by considering user preference for DRS. User preference is referred to a travel utility consisting of travel cost reduction and waiting time in this study. Based on the formulated model, the numerical analysis was conducted to achieve the aims. Moreover, the existence of stable equilibrium was also revealed through the numerical analysis.

Keywords: Smart Ridesharing Systems, Dynamic Ridesharing Systems, Day-to-day Dynamics, Passenger Matching Problem

1. INTRODUCTION

Ridesharing systems have been introduced as a solution to simultaneously respond to a requirement on demand responsive transit (DRT) and consideration of environmental issue along with traffic congestion. A fundamental idea of ridesharing is to share a ride to other travelers with similar itineraries and schedules (Gidofalvi and Pedersen, 2007; Chan and Shaheen, 2012). Therefore, assigning appropriate matches between travelers is essential for minimizing total travel costs and dissatisfactions. Numerous researchers have modelled the ridesharing system as Dial-A-Ride Problem (DARP) to achieve these objectives (Lin *et al.*, 2012; Hosni *et al.*, 2014).

Ridesharing systems have been further developed as real-time demand responsive systems, namely 'dynamic ridesharing systems (DRS)'. By performing DRS day-to-day, travelers usually make decisions on their travel mode and choose their ridesharing partner based on their previous experience in ridesharing. For DRS management, it is essential to understand a feasibility of operating DRS and investigate its day-to-day equilibria. With a good understanding on the day-to-day dynamics of DRS, DRS service providers can develop a better DRS. Unfortunately, a study on the day-to-day dynamics of DRS has not received much attention.

User preference was stated as an important challenge to make travelers travel with an offered ridesharing partner in practice (Agatz *et al.*, 2010; Kleiner *et al.*, 2011). Recently, ridesharing systems have been integrated with information and communication technologies (known as smart ridesharing systems, SRS). The matching problems by considering user preference have been enabled through the features of smart devices. The models for one driver and one passenger matching problem based on stable marriage problem and parallel auction were proposed by Wang (2013) and Kleiner *et al.* (2011), respectively. A static model for one-on-one passenger matching problem based on stable roommates problem was proposed by Thaithatkul *et al.* (2015).

As smart devices have enabled SRS to satisfy user preference in term of eliminating discomfort of sharing private space by sharing to preferable travelers, we therefore considered the simplest case of passenger matching problem as one-on-one passenger matching problem in SRS. In order to focus on passenger matching problem, driver in this problem is considered as professional driver (e.g., taxi driver). This study is aimed to understand DRS's feasibility and investigate the DRS's day-to-day equilibria (i.e., existence, uniqueness, and stability) based on the formulated DRS model of one-on-one passenger matching problem by considering user preference in SRS. The modified stable roommates problem is employed to represent the one-on-one passenger matching by considering user preference (Irving, 1985; Thaithatkul *et al.*, 2015). User preference in this study is considered as travel utility consisting of travel cost reduction and waiting time. Day-to-day equilibria are investigated by conducting the numerical experiments based on formulated DRS model.

The remainder of the paper is structured as follows. The model formulation and assumptions are explained in section 2 which is divided into 2 subsections, i.e., within day model in subsection 2.1, and day-to-day model in subsection 2.2. Based on the formulated model, day-to-day equilibria of DRS were numerically investigated in section 3. This study is concluded in the last section.

2. MODEL FORMULATION

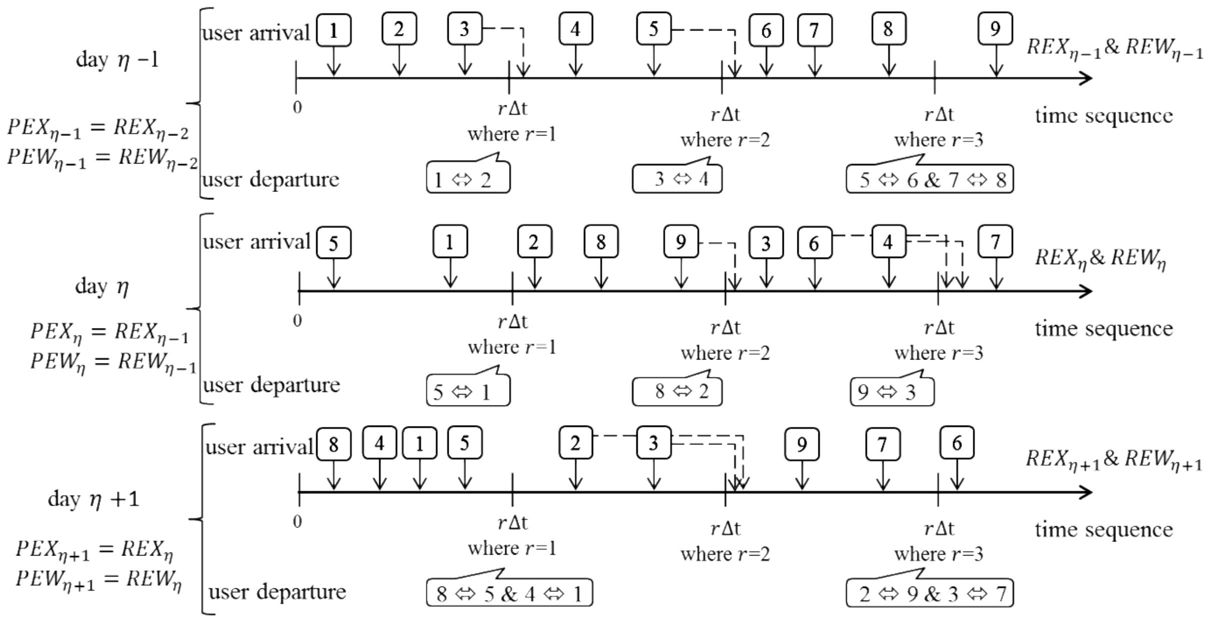


Figure 1. Matching on one day time horizon in dynamic ridesharing system

In this study, DRS model was formulated by considering that DRS is performed based on one day time horizon and adopted day-to-day as illustrated in Figure 1. Each time sequence represents that DRS is repeatedly performed at every Δt throughout a day. The process for within day DRS model is explained in subsection 2.1. As DRS is considered to be adopted day-to-day, DRS users (passengers) are expected to continuously participate DRS with different arrival sequence and experience different outcome from participating different day. Users can make decisions (i.e., travel mode, ridesharing partner) based on their previous experience. The further explanation on day-to-day DRS model is given in subsection 2.2. The DRS model was formulated based on the following assumptions.

(a) There are two choices of travel mode; riding alone and ridesharing.
(b) Maximum number of available passenger seats for ridesharing is two.
(c) Vehicle supplies are always sufficient.
(d) All users have same origin but different destination.
(e) Users travel in one dimension.
(f) User's delay cost function is linear over time.

(g) Travel time is given and fixed as there is no traffic congestion.
(h) Users' arrival sequence, S, has an exponential distribution with parameter λ_S.

In order to focus on ridesharing mode, the available choices of travel mode are limited to either riding alone or ridesharing. Riding alone implies to a mode that passengers travel alone by hiring a vehicle driven by professional driver (e.g., taxi driver). The available passenger seats are assumed to be at a maximum of two seats to consider the simplest matching case of one-on-one passenger matching. The third assumption is set to enable passengers to immediately travel once they find a preferable partner. All passengers have same origin is set to assume a situation where passengers are waiting for a ride at the same location but without queue (e.g., taxi stand) in the fourth assumption. Moreover, the fifth assumption is set to assume that passengers' travel cost of ridesharing will never cost more than traveling alone, and to simplify a computation of sharing cost. However, this assumption may be possible to further relax in order to practically reflect the real world problems. User's delay cost function, which is caused by waiting time for being matched with a preferable ridesharing partner, is assumed to be linear over time for a simple computation in the sixth assumption. In order to maximize users' travel utility, which is further explained in the next subsection, users should be able to wait until their preferable partner is found when participate in DRS. With the seventh assumption, direct travel time and direct travel cost are constant throughout the matching algorithm. To consider this model as a dynamic case, users' arrival sequence S is set as an exponential distribution to describe the arrival time of individual user that randomly appears in the DRS.

2.1 Within Day Model

As we considered a matching on one day time horizon, a within day DRS model is developed and described in this subsection.

2.1.1 Travel Utility

User preference was formulated as a travel utility. The travel utility consists of travel cost reduction and waiting time as shown in equation (1) as they were revealed as the first consideration in positive and negative perceptions in DRS, respectively (Nielsen *et al.*, 2015). This travel utility was used to evaluate a utility of traveling alone and sharing a ride with one another.

$$u_{ij}(\tau_i) = \alpha_1 x_{ij} c_i + \alpha_2 \tau_i \qquad \text{for } i, j \in S \tag{1}$$

$$x_{ij} = \begin{cases} 0 & \text{for } i, j \in S, i = j \\ c_j/2c_i & \text{for } i, j \in S, i \neq j, c_i > c_j \\ 1/2 & \text{for } i, j \in S, i \neq j, c_i \leq c_j \end{cases} \tag{2}$$

where,
$\mu_{ij}(\tau_i)$: travel utility of riding alone for $i = j$, and travel utility of ridesharing for $i \neq j$,
τ_i : waiting time of user i,
c_i : travel cost (i.e., fare) of user i,
x_{ij} : percentage of cost reduction for user i traveling with user j,
α_1 : marginal utility for saving one unit of money, $\alpha_1 > 0$,
α_2 : marginal disutility for waiting one unit of time, $\alpha_2 < 0$.

In equation (1), travel utility of ridesharing for user i to user j is denoted as $u_{ij}(\tau_i)$ for $i \neq j$ where i and j are members of users' arrival sequence S with exponential distribution. The first term in equation (1) represents utility of travel cost reduction when user i rideshares with user j. As driver is assumed to be a professional driver in this study, travel cost refers to a fare. The travel cost reduction is used to represent travel utility instead of travel time due to the fifth assumption that users travel in one dimension, meaning that travel cost of ridesharing can only be decreased or equal to travel cost of riding alone, while travel time will never be changed when rideshares. For ridesharing case, since user i will only leave the system when being matched with a preferable ridesharing partner, user j; the second term therefore represents a disutility of waiting time for being matched when ridesharing is expected to be worth than riding alone. Moreover, the travel utility matrix is asymmetric where $u_{ij} \neq u_{ji}$, unless travel cost and arrival time of user i and user j are equal. Equation (1) when $i = j$ represents the travel utility of riding alone denoted as $u_{ii}(\tau_i)$. The second term in equation (1) represents a disutility of waiting time until user i decides to travel alone which must be equal to zero in order to maximize the travel utility when riding alone is expected to be worth than ridesharing. This means that if ridesharing is initially expected to be worth than riding alone, riding alone will never be worth than ridesharing as waiting time is linearly increased over time for both transport modes. The travel cost reduction in the first term of equations (1) is written in a form of percentage of travel cost reduction when traveling with user j which can be calculated as shown in equation (2). As riding alone cannot reduce any travel cost, percentage of travel cost reduction is equal to 0 for $i = j$ in equation (2). Hence, the first term in equation (1) for $i = j$ can be eliminated for $i = j$. According to our fourth and fifth assumptions, percentage of travel cost reduction for user i when ridesharing with user j whose travel cost is smaller; travel cost of user i can be shared by user j only for a common path, percentage of cost reduction is therefore equal to $c_j/2c_i$ for $i \neq j$ and $c_i > c_j$, which is a value between $(0, 1/2]$. In case of user i traveling with user j whose travel cost is larger than or equal to user i's travel cost; user i can save the travel cost at the maximum of 50%.

2.1.2 Matching Process Setting

The within day model, DRS is set to be repeatedly performed at every $\Delta\mathrm{t}$ to involve both existing and new passengers in each matching as shown in Figure 1. The existing passengers refer to users who appear and cannot find a preferable partner in the previous matching, while new passengers refer to users who recently appear in the system within current interval. The matching at $r\Delta\mathrm{t}$ is called a matching round r. Users who are matched with their preferable partner will leave the system (i.e., user 1 and user 2 for r = 1 in day $\eta - 1$ of Figure 1), while users who cannot be matched with their preferable partner (i.e., user 3 for r = 1 in day $\eta - 1$ of Figure 1) will be involved in the next matching round with new users (i.e., user 4 and user 5 for r = 2 in day $\eta - 1$ of Figure 1). This process of DRS is repeatedly performed throughout the day. As our matching is performed on one day time horizon, round r is restarted at the beginning of each day.

The individual expected travel utility of ridesharing for user i can be written based on equation (1) as shown in equation (3). The individual expected travel utility of ridesharing is denoted as $EU_i^{RS}(\tau_i|S, \mathcal{A})$, a function of individual waiting time until user i is matched to a preferable ridesharing partner which is dependent on S and $\mathcal{A}$. The individual expected percentage of cost reduction (EX_i) and individual expected waiting time ($EW_i(\tau_i)$) are dependent on S and $\mathcal{A}$ as well.

$$EU_i^{RS}(\tau_i|S, \mathcal{A}) = \alpha_1 EX_i c_i + \alpha_2 EW_i(\tau_i) \tag{3}$$

The process of each matching round is illustrated in Figure 2. Firstly, individual user will choose ridesharing only if traveling by ridesharing is expected to provide better travel utility than traveling alone. The expected travel utility of traveling alone for user i is denoted as $EU_i^A(\tau_i)$, a function of individual waiting time until user i decides to travel alone which is independent of S and $\mathcal{A}$. However, participating in ridesharing system requires at least $\Delta\mathrm{t}$ time for being matched with a preferable partner; thus, equation (4) must be satisfied to choose ridesharing as a travel mode. In case that equation (4) is not satisfied, user must immediately leave the system by riding alone as riding alone is expected to be worth than ridesharing and receive travel utility for riding alone at zero. As both $EU_i^{RS}(\tau_i|S, \mathcal{A})$ and $EU_i^A(\tau_i)$ can be linearly reduced time by time, if ridesharing is initially worth than traveling alone, traveling alone will never be worth than ridesharing at any time.

$$EU_i^{RS}(\tau_i|S, \mathcal{A}) + \alpha_2 \Delta\mathrm{t} > EU_i^A(\tau_i) \tag{4}$$

For each matching round r, matching will be performed based on users who satisfy equation (4) (i.e.,

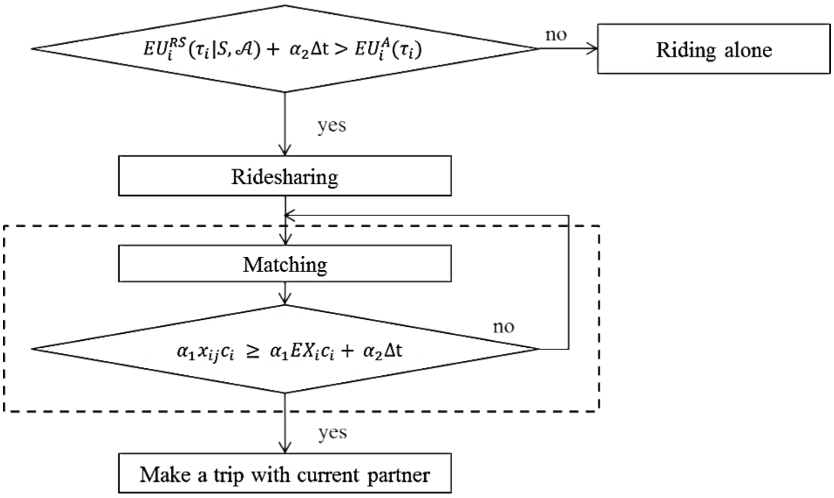


Figure 2. Matching process in dynamic ridesharing system.

users who choose ridesharing as their travel mode) within $r\Delta t$. After the matching of each round r, users will be notified whether they are matched with a preferable partner. Since expected waiting time can only affect to the travel mode choice in equation (4), a preferable partner refers to a user j who provides user i a higher cost reduction comparing to the individual expected cost reduction in the next matching round. Thus, users can only leave the system and travel with user j only if equation (5) is satisfied. If travel cost reduction when sharing a ride with user j is not greater than or equal to the expected travel cost reduction in the next matching round, users do not need to travel with the offered user j and can wait until a preferable partner is found as there is no time window constraint.

$$\alpha_1 x_{ij} c_i \geq \alpha_1 EX_i c_i + \alpha_2 \Delta t \tag{5}$$

The one-on-one passengers matching problem (Thaithatkul et al., 2015) was employed for each matching round. This matching algorithm was modified from the stable roommates problem proposed by Irving (1985). This matching provides stable matching pairs among a current set of users where no one prefers another than their current partner. An output of stable matching pair can result in two different ways; matching pair (i,i) and matching pair (i,j) where $i \neq j$. Stable matching pair (i,i) implies that user i travels alone. Stable matching pair (i,j) implies that user i shares a ride with user j.

Based on this within day matching process, users with high individual travel cost tend to choose ridesharing as their travel mode. Once they choose ridesharing and participate in DRS, users with high individual travel cost become more difficult to find a preferable partner when matching is performed on heterogeneity group of users in term of individual travel cost. Thus, this formulated model is efficient (i.e., all ridesharing users can find their preferable ridesharing partner) when matching is performed on homogeneous group of users.

2.2 Day-to-day Model

By adopting DRS day-to-day, DRS users are expected to continuously participate in DRS; however, users' arrival sequence may be different among different day which can result in different outcome (i.e., travel mode, departure time, ridesharing partner) as shown in Figure 1. For each day, users can make decisions on their travel mode and ridesharing partner based on their previous experience. In this study, we considered a simple updating method as follows. For day η, individual user is assumed to have expected DRS performance (i.e., perceived expected percentage of cost reduction (PEX_η) and perceived expected waiting time (PEW_η)) as same as previous day DRS performance (i.e., revealed expected percentage of cost reduction ($REX_{\eta-1}$) and revealed expected waiting time ($REW_{\eta-1}$)) as shown in equations (6) and (7). This means that all users perceive the same DRS performance (i.e.,

PEX_η and PEW_η) throughout day η. Since individual user has different c_i, the individual perceived expected travel utility for ridesharing (PEU_i^{RS}) is thus different among users as shown in equation (8).

$$PEX_\eta \;=\; REX_{\eta-1} \tag{6}$$

$$PEW_\eta \;=\; REW_{\eta-1} \tag{7}$$

$$PEU_i^{RS} = \alpha_1 PEX_\eta c_i + \alpha_2 PEW_\eta \qquad \text{for } i \in S_\eta \tag{8}$$

At the end of day η, DRS performance (i.e., REX_η and REW_η) can be revealed as shown in equations (9) and (10) which will be used as the perceived expectation for the following day. The REX_η and REW_η can be calculated by averaging x_{ij} and τ_i, respectively, for all users in day η. The x_{ij} and τ_i are dependent to $PEX_\eta, PEW_\eta, S_\eta$, and $\mathcal{A}$. This process is repeated when DRS is adopted day-to-day.

$$REX_\eta = \textstyle\sum_i x_{ij}(PEX_\eta, PEW_\eta, S_\eta, \mathcal{A})/|S_\eta| \quad \text{for } \forall i \in S_\eta \tag{9}$$

$$REW_\eta = \textstyle\sum_i \tau_i\,(PEX_\eta, PEW_\eta, S_\eta, \mathcal{A})/|S_\eta| \quad \text{for } \forall i \in S_\eta \tag{10}$$

Based on this assumption, the DRS's day-to-day equilibria (i.e., existence, uniqueness, and stability) can be investigated. DRS's day-to-day equilibria are when DRS performance is revealed to be equal to a perceived DRS performance, i.e., $REX_\eta = PEX_\eta, REW_\eta = PEW_\eta$ as illustrated in Figure 3. A stable equilibrium in day-to-day DRS is an equilibrium that revealed DRS performance from any initial perceived DRS performance always converges to. On the other hand, a fixed point which revealed DRS performance always diverges from is called unstable equilibrium in day-to-day DRS.

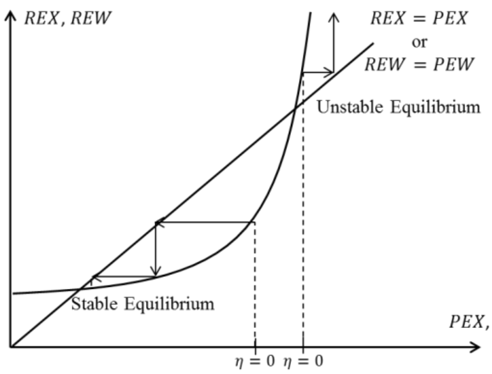


Figure 3. Dynamic ridesharing system's day-to-day equilibria

3. NUMERICAL ANALYSIS

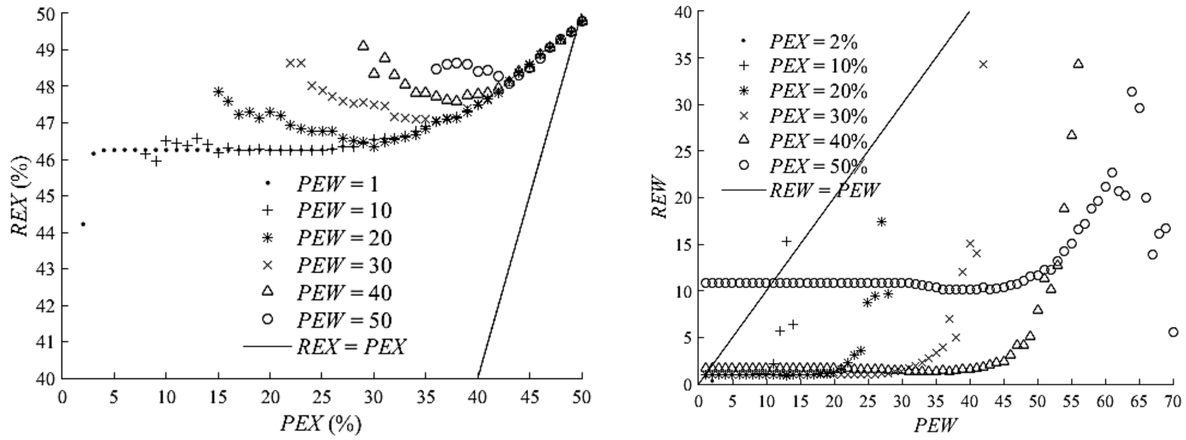
As investigating DRS's day-to-day equilibria (i.e., existence, uniqueness, and stability) is essential but difficult to be analytically analyzed, we therefore conducted a numerical analysis in this section.

3.1 Numerical Analysis Setting

In order to investigate the DRS's day-to-day equilibria, we conducted the numerical experiments with all possible pairs of PEX and PEW to obtain the revealed performance. The PEX was given as an integer value between 0 to 50%, while PEW was given as an integer value between 0 to 100 minutes. The rest setting and parameters are given as follows. Individual travel cost was given as a random number from truncated normal distribution which is always greater than zero as $c_i \sim N(\mu, \sigma^2)$ with parameters μ and σ given at 100 and 16.67, respectively. The parameters α_1 and α_2 were given equal to 1 and -1, respectively. The matching was set to be performed at every 1 minute, $\Delta t = 1$. Users' arrival sequence, S, has an exponential distribution with parameter λ_S equal to 1 user/minute.

3.2 Results of Numerical Analysis

The following results were obtained during 51st round to 150th round from the total of 200 rounds to represent the results during the day.



(a) (b)

Figure 4. Relationship between (a) PEX and REX, and (b) PEW and REW of formulated day-to-day DRS, where α_1= 1, α_2 = −1, Δt = 1, μ = 100, and σ = 16.67.

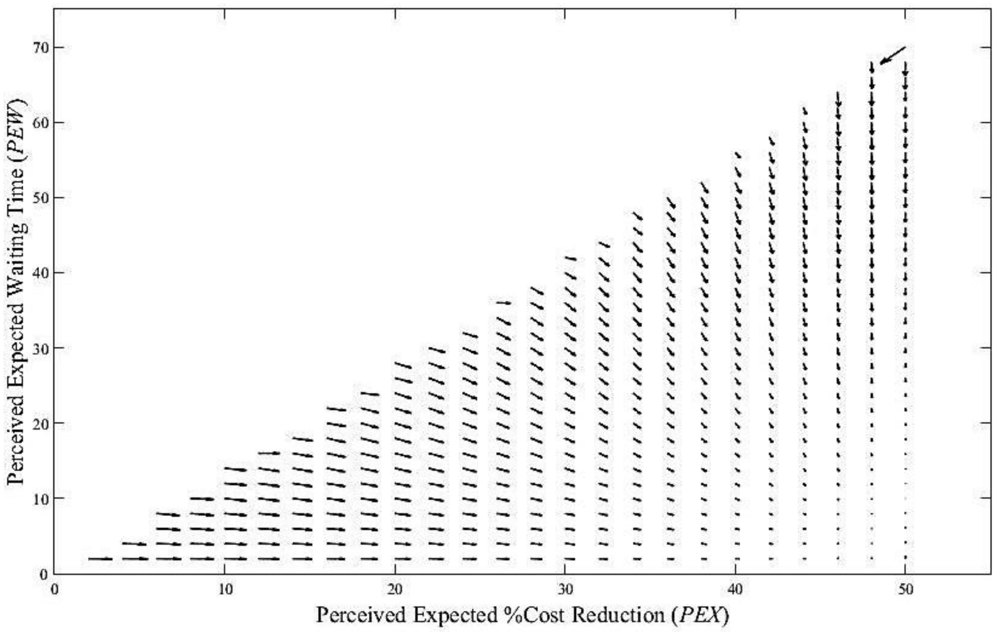


Figure 5. Dynamics of formulated day-to-day DRS, where α_1= 1, α_2 = −1, Δt = 1, μ = 100, and σ = 16.67.

Figure 4 (a) illustrates the relationship between PEX and REX for a given PEW of DRS. For any given PEW, REX will rapidly converge to its stable equilibrium with almost 50% of cost reduction. Even if users expected the maximum possible percentage of cost reduction at 50%, users will still obtain almost as much as their expectation. This implies that the formulated model of DRS can provide a very good performance in term of percentage of cost reduction when DRS is performed day-to-day. In term of waiting time, REW will also rapidly converge to its stable equilibrium for any PEX when DRS is performed day-to-day as shown in Figure 4 (b). However, a stable equilibrium for REW is revealed to be longer when users perceive PEX at 50% as it is required longer time to find a preferable partner that satisfies equation (5). As REW for some PEX terminates by dropping down due to a reduction in number of users who rideshare; if we assume that all users choose ridesharing, REW will finally rise up and reach its unstable equilibrium where REW is equal to PEW. Once unstable equilibrium of REW is revealed; if PEW is perceived higher than REW's unstable equilibrium, all users' travel choice will tend to be riding alone. On the other hand, if PEW is perceived lower than REW's unstable equilibrium, all users' travel choice will tend to be ridesharing.

Based on these results, the dynamics of formulated day-to-day DRS can be represented by vector as shown in Figure 5. For those PEX and PEW without arrow (outside triangle) imply that users choose to ride alone instead of ridesharing (i.e., riding alone is expected to be worth than ridesharing), while PEX and PEW with arrow (inside triangle) imply that users choose ridesharing (i.e., ridesharing is expected to be worth than riding alone). The arrows show a direction to REX and REW for a feasible pair of PEX and PEW. A length of each arrow represents how fast it can converge to a stable equilibrium. Therefore, Figure 5 shows that REX and REW will finally converge to the stable equilibrium (i.e., almost bottom right corner of triangle) for any feasible pair of PEX and PEW.

4. CONCLUSION

This study aimed to analyze the day-to-day dynamics of dynamic ridesharing systems (DRS) based on the formulated model of one-on-one passengers matching problem by considering user preference in smart ridesharing systems to understand a feasibility of operating DRS, and investigate its day-to-day equilibria. The modified stable roommates problem was employed to represent this matching problem. User preference referred to a travel utility consisting of travel cost reduction and waiting time. The day-to-day dynamics of DRS was realized by conducting numerical experiments. The existence of stable equilibrium in day-to-day dynamics was revealed through the numerical experiments.

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REFERENCES

Agatz, N., Erera, A., Savelsbergh, M. and Wang, X. (2010) Sustainable Passenger Transportation : Dynamic Ride-Sharing. *ERIM Report Series Research in Management*,.

Chan, N.D. and Shaheen, S.A. (2012) Ridesharing in North America: Past, Present, and Future. *Transport Reviews: A Transnational Transdisciplinary Journal*, 32, pp. 93–112.

Gidofalvi, G. and Pedersen, T. (2007) Cab-sharing: An effective, door-to-door, on-demand transportation service. *Transport Systems and Services*, pp. 1–8.

Hosni, H., Naoum-Sawaya, J. and Artail, H. (2014) The shared-taxi problem: Formulation and solution methods. *Transportation Research Part B: Methodological*, 70, pp. 303–318.

Irving, R.W. (1985) An efficient algorithm for the "stable roommates" problem. *Journal of Algorithms*, 6, pp. 577–595.

Kleiner, A., Nebel, B. and Ziparo, V.A. (2011) A Mechanism for Dynamic Ride Sharing Based on Parallel Auctions. *Proceedings of the Twenty-Second International Joint Conference on Artificial Intelligence*, 1, pp. 266–272.

Lin, Y., Li, W., Qiu, F. and Xu, H. (2012) Research on Optimization of Vehicle Routing Problem for Ride-sharing Taxi. *Procedia - Social and Behavioral Sciences*, 43, pp. 494–502.

Nielsen, J.R., Hovmøller, H., Blyth, P.-L. and Sovacool, B.K. (2015) Of "white crows" and "cash savers:" A qualitative study of travel behavior and perceptions of ridesharing in Denmark. *Transportation Research Part A: Policy and Practice*, 78, pp. 113–123.

Thaithatkul, P., Seo, T., Kusakabe, T. and Asakura, Y. (2015) A Passengers Matching Problem in Ridesharing Systems by Considering User Preference. *Proceedings of the Eastern Asia Society for Transportation Studies*,.

Wang, X. (2013) Optimizing Ride Matches for Dynamic Ride-Sharing Systems. Georgia Institute of Technology.