Incorporating User Preference into Optimal Vehicle Routing Problem of Integrated Sharing Transport System

Satomi AIKO a*, Phathinan THAITHATKUL b, Yasuo ASAKURA c

a School of Environment and Society, Tokyo Institute of Technology, Tokyo, 152-8552, Japan; E-mail: s.aiko@plan.cv.titech.ac.jp
b Center for Spatial Information Science, the University of Tokyo, Chiba, 277-8568, Japan; E-mail: t.phathinan@csis.u-tokyo.ac.jp
c Same as the first author; E-mail: asakura@plan.cv.titech.ac.jp

Abstract: To increase the utilization of existing resources, vehicle- and ride-sharing systems have been introduced as an efficient door-to-door service. To leverage the sharing concept, these systems have been combined as an integrated sharing transport system (ISTS) such that existing vehicles and services in the transport system are highly utilized. To operate ISTS efficiently, this study aims to introduce and formulate the optimal vehicle routing problem, which can simultaneously support vehicle- and ride-sharing features, and to provide the optimal solution that satisfies all users’ activity patterns. As ISTS may degrade users’ satisfaction because of discomfort, user preference is incorporated into the optimization model. With the developed model, the importance of considered factors, such as user preference, can be adjusted according to specified policies. The optimal solutions of several policies are compared and discussed using numerical experiments. Moreover, the equality operation policy, which equally considers user preference and system efficiency, is presented.

Keywords: Ride-Sharing System, Car-Sharing System, Shared Autonomous Vehicle, Optimization Problem, Vehicle Routing Problem, User Preference

1. INTRODUCTION

In an era of high energy consumption, maximizing the utilization of resources has been emphasized in every business segment because of limited resources. A sharing economy is one of the key concepts for increasing the utilization of existing assets and services by sharing with others (Botsman and Roger, 2010). In term of transport, a public/private-owned vehicle (asset) and a ride (service) can be shared with other travelers; this is referred to as vehicle sharing (e.g., car sharing, bike sharing) and ride sharing (e.g., taxi sharing, carpooling), respectively. These sharing systems enable travelers to travel door-to-door with higher utilization of existing resources compared with that of traveling individually by car, and these sharing systems are more society friendly in terms of environmental and congestion issues.

Recently, the vehicle-sharing system, which provides shared vehicles and a reservation service, has been widely developed on a commercial scale, including Asian countries (Barth et al., 2015). Regarding the ride-sharing system, which usually refers to a system that provides a matching service among potential travelers for sharing a door-to-door journey (Ghoseiri et al., 2011), it has already been adopted and systematically operated in some countries. For instance, in the United States, UberPOOL, where a trip in an UberPOOL vehicle can be automatically arranged for sharing with potential travelers, has been adopted. However, in Asian countries, the currently adopted ride-sharing systems only provide a service that gathers potential travelers and assigns travel requests to them, similar to a ride-sharing system.
travelers and lets them find a partner by themselves (Ainoriya, 2017; Noritomo, 2017). One of the reasons could be the difficulty of providing matching that can satisfy travelers’ preferences. This is because travelers may feel uncomfortable when they have to share their private space with people with whom they are unacquainted (Amey et al., 2011). User preference regarding travel partners, such as same gender and smoking behavior, is therefore important to be considered in a ride-sharing system in order to provide matching that satisfies users’ personal preferences and avoids the abandonment of the system because of user’s dissatisfaction with matching. For instance, a female traveler may feel more comfortable sharing a ride with another female traveler, and a nonsmoking traveler may prefer to be matched with another nonsmoking traveler. In recent decades, such user preference consideration has been facilitated by the development of internet-enabled devices and social networking systems.

Additionally, vehicle-sharing and ride-sharing concepts have been further combined as an integrated sharing transport system (ISTS) for a future transport system. ISTS refers to a system where all transport assets and services are shared with everyone in the society. The unique feature of the ISTS is the integrated sharing feature; for example, the integrated sharing feature of car- and ride-sharing is where a ride in a shared car is allowed to be shared with other travelers. With the recent development of autonomous vehicle technologies, it can be expected that typical passenger cars (i.e., where a human driver is required) will be replaced by autonomous vehicles. In such a reformation, if the sharing concept is well realized and widely adopted by people, no one needs to own a private vehicle, as using the public-owned shared autonomous vehicles costs less than owning a vehicle. Then, the features of the ISTS for using passenger cars will be simplified to an integration of shared autonomous vehicles and ride-sharing systems (Fagnant and Kockelman, 2015). This ISTS enhances the benefits of sharing concepts. In addition, it also enables travelers who cannot drive (e.g., children, elders, disabled people) to travel independently, such that this system would be applicable to Asian countries, as they have been confronting the aging society problem (Bloom et al., 2010). In order to operate the vehicles efficiently, it is essential to introduce the optimal vehicle routing problem, particularly for the ISTS. In addition, in order to assign ride-matching appropriately among travelers such that they continue adopting the ISTS because they are satisfied with the assigned matching, it is necessary to incorporate user preference into the ISTS’s optimal vehicle routing problem.

Therefore, this study aims to formulate an optimal vehicle routing problem, incorporating user preference, that satisfies all users’ activity patterns in the ISTS. The problem is formulated as a time-space network-based optimization problem using mixed-integer quadratic programming. Even though considering individual preference is expected to reduce the abandonment of sharing trips in practice, it is also expected to increase the system’s total travel distance, as travelers may prefer traveling alone. In the developed model, the importance of user preference consideration can be adjusted, as well as other related factors such as the total travel time of vehicles. This means that the developed model can be utilized for operating the ISTS according to the specified policy. To present the characteristics of the formulated model as well as the effects of user preference consideration on the optimal vehicle routing schedule, numerical experiments are conducted on a simple transport network and users’ activity patterns by varying the importance of user preference consideration. The optimal vehicle routing schedules for the extreme policies (i.e., a policy neglecting user preference and a policy fully considering user preference) are discussed through numerical experiments. Additionally, numerical experiments are conducted to introduce the desirable operation policy that can appropriately consider user preference.

This paper is organized as follows. The literature on the modeling of the matching problem in ride-sharing systems and the ISTS is reviewed and discussed in section 2. The

model for the ISTS is developed and described in section 3, which covers the ISTS concept and the model formulation in sections 3.1 and 3.2, respectively. The numerical experiments on the formulated model are in section 4. Then, the possible application of the formulated model to the practical situation is discussed in section 5, followed by a conclusion in section 6.

2. LITERATURE REVIEW

The driver-rider(s) matching problem has been extensively studied for ride-sharing systems. In order to operate the ride-sharing system efficiently, the matching problem has been mostly formulated as an optimization problem similar to the dial-a-ride problem (Cordeau and Laporte, 2007) with different specific aims and objectives such as maximization of the number of users (Agatz et al., 2012). For instance, Herbawi and Weber (2012) have formulated the optimization problem for driver-rider(s) matching in dynamic ride-sharing systems where riders are not allowed to transfer between vehicles. The objective of their optimization model is to minimize total vehicle travel distance and time, to minimize the total time of a ride-sharing trip, and to maximize the number of ride matches where the total travel distance and time of each trip for a driver must satisfy acceptable detouring that the driver defines. Besides that, they proposed a solving algorithm; namely, the generational genetic algorithm. Di Febbraro et al. (2013) have also formulated an optimization model for driver-rider(s) matching, but their objective is to minimize the difference between desired and real departure and arrival times. This means that their model determines the optimal departure and arrival times of users. By allowing riders to transfer between vehicles, Masoud and Jayakrishnan (2015) formulated the ride-matching problem between riders and drivers as vehicle routing problem based on a time-space network to maximize the number of matches while minimizing the number of transfers. They also proposed a solving algorithm for the optimization problem; namely, a decomposition algorithm, which divides the problem into subproblems that are solved iteratively. Moreover, the approaches for solving the time-space network-based optimization problem were also discussed in their study. As travelers who can drive and own a car can play either driver or rider roles in ride-sharing systems, Agatz et al. (2011) formulated the maximum weight bipartite matching optimization problem for assigning driver and rider roles that maximize the system’s travel distance saving. These optimization-based studies have mostly formulated the driver-rider(s) matching problem with drivers and riders assigned to travel corresponding to a system/socially optimal matching solution. The user’s personal preference regarding ride-sharing partners, which has been noted as an important factor in ride-sharing systems, has not been explicitly considered in previous formulations of the optimization problem.

On the other hand, to obtain a matching solution that satisfies individual preference regarding ride-sharing partners—such as same gender, similar age, similar interests, smoking behavior—the matching problem has also been formulated as an agent-based model. For instance, the matching problem has been formulated based on an auction approach (Nourinejad and Roorda, 2015; Kleiner et al., 2011). In these models, a user can be matched with a partner who provides her/him with the minimum cost among potential partners under some restrictions of the auction process. For example, a rider selects a preferable driver among the list of potential drivers, then a driver selects a preferable rider among the list of riders who selected that driver. Additionally, some researchers have formulated the matching problem based on matching theory to obtain a stable matching solution. In the stable matching solution, all users are satisfied with their partner, and they cannot increase their satisfaction by changing their partner. Wang (2013) and Yotsutsuji et al. (2016) have formulated the driver-rider matching problem based on the stable marriage problem, which is one of the well-known problems in matching theory that finds stable matching between two different groups of men and women.
(Gale and Shapley, 1962). On the other hand, the rider-rider matching problem has also been formulated based on another problem in matching theory; namely, the stable roommates problem, by Thaithatkul et al. (2015a). Moreover, the day-to-day dynamics of the formulated rider-rider matching problem have been further investigated in Thaithatkul et al. (2016, 2015b).

In these agent-based models, even though user preference has been considered, the matching solutions are not socially optimal. A matching problem that is socially optimized and satisfies user preference has not been studied.

The matching problem has recently been studied under the ISTS concept (Levin et al., 2016; Fagnant and Kockelman, 2015). The matching problems in previous studies were specifically for a shared autonomous vehicle with a ride-sharing service and modeled based on an agent-based framework. In these models, users will use the service of the system only if their trips satisfy some specified constraints, and the assigned vehicle routes and sharing trips are not necessarily optimal. User preference on the use of shared autonomous vehicles in the ISTS framework has been separately studied using an online stated choice survey in Australia by Krueger et al. (2016). However, studies for the ISTS are still limited. Similar to the studies on ride-sharing systems, a matching problem that can comprehensively consider both system aspects (i.e., system optimization) and user aspects (i.e., user satisfaction) has not been studied.

Even though a matching problem that simultaneously considers user preference and social optimum is necessary for sustainably and efficiently executing the ISTS as well as ride-sharing systems, it has not been formulated. Therefore, this study aims to develop a comprehensive matching model for the ISTS. We formulate the ride-matching problem by incorporating user preference into an optimal vehicle routing problem, with the objective of minimizing user discomfort together with other operation costs, and satisfying all users’ activity patterns. The concept of a time-space network is applied to development of a model similar to that of Masoud and Jayakrishnan (2015) because of its advantage of handling both a physical transport network and a time dimension.

3. MODEL DEVELOPMENT

In this section, a model for the optimal vehicle routing problem incorporating individual preference is developed for the ISTS. First, the general concept of the ISTS is introduced in section 3.1. Then, the model is formulated in section 3.2.

3.1 General Concept of ISTS

In a future transport system, all surface transport systems including train, bus, taxi, and bike, as well as all facilities and infrastructures, will be combined into a single system and will use the same fare system. As well as sharing transport systems, the vehicle- and ride-sharing systems are integrated into one single system—namely, the ISTS—such that users can use any sharing transport including shared bike, shared car, and shared ride through ISTS. Moreover, both vehicles and services can be shared simultaneously such that an occupied shared vehicle can be further shared with other travelers if there are available seats. Therefore, the assets and services in the ISTS are operated efficiently with higher utilization.
According to the abovementioned concept, a user of ISTS can be any user from any sharing transport system, as shown in Figure 1. Each type of user plays a different role in the ISTS, such as vehicle supply, ride supply, vehicle demand, and ride demand. If the supply from supply-side users is not sufficient for the demand from demand-side users, external supply from the system might be required as another input of the ISTS. On the other hand, if supply from supply-side users meets the demand from demand-side users, the ISTS can be continuously executed without external supply. Note that when autonomous vehicles are commercialized and prevalent in society, some types of potential users (i.e., private vehicle drivers and owners) are expected to disappear from the ISTS. Additionally, when the sharing economy concept is well accepted by travelers, the number of private vehicle owners is expected to decrease and even to reach zero, as owning a vehicle will become more expensive than using the ISTS. To use the ISTS, users are required to provide their information including their role, activity pattern (if one exists), and constraints via any internet-enabled device/application. Smartphone applications will be a typical example of such communication instruments.

With the information provided by potential users, the ISTS provides users with potential matching that will satisfy their requirements together with trip information. The possible matching includes all types of simple matching and integration. As previously mentioned, the integration of simple matching is a feature of ISTS; for example, driver-rider(s)-vehicle matching in car- and ride-sharing systems, and rider(s)-autonomous vehicle matching with
shared autonomous vehicles in ride-sharing systems. Trip information includes optimal vehicle routing, scheduling, and benefits.

With this ISTS, the on-demand service can be used cost-effectively and safely by everyone in the society, especially travelers who do not have a driving license, children, elders, and disabled people, through one single system, the ISTS.

3.2 Model Formulation

In this study, the framework of the formulated model in the ISTS is shown by the dashed boxes in Figure 1. The ride-matching of interest is a matching between rider(s) and vehicle(s), where the vehicles have neither trip preferences nor time constraints, such as autonomous vehicles and taxis. In addition, this consideration can be realized in a society where public-owned shared autonomous vehicles are prevalent and the sharing economy concept is well accepted by travelers. Within this framework, we formulate the ride-matching model as an optimal vehicle routing problem. With the formulated model, the optimal route is assigned to vehicles in a desirable way, where one vehicle may be assigned to many users for different periods (i.e., a car-sharing feature) or may be assigned to carry several users at the same time (i.e., a ride-sharing feature). The model is developed based on the assumptions explained in section 3.2.1. The formulation of a vehicle routing problem incorporating individual preferences is presented and explained in section 3.2.3.

3.2.1 Assumptions

With respect to the aforementioned area of interest in the ISTS, the vehicle routing problem is formulated based on assumptions that are summarized as follows.

1. A user’s activity pattern is given to the system and must be satisfied.
2. Users’ preferences are evaluated as discomfort and given to the system.
3. A user must travel between nodes by riding in a vehicle and may transfer between vehicles at any node.
4. The capacities of all vehicles are given and are always sufficient.
5. A vehicle must begin and finish a working trip at a designated base.
6. A time-space network is considered where time is discrete.
7. The travel time between nodes is given and fixed.

For the first assumption, regarding the users in the system, “users” refers to travelers who are willing to travel by using the ISTS. In order to use the service, a user is required to provide her/his activity pattern to the system. Based on the provided activity patterns, trip information including origin, destination, earliest departure time, and latest arrival time can be obtained, as shown in Figure 2. In order to travel feasibly, the period between the given earliest departure time and the latest arrival must not be less than the minimum required travel time between the specified origin and destination. To avoid dissatisfaction with this ISTS, all users’ activity patterns must be satisfied.

As ride-sharing requires a user to share her/his private space with other users, a user may feel uncomfortable when s/he rides in a vehicle with a stranger. Therefore, user preference in this study is evaluated as discomfort when riding in a vehicle with other travelers, as per the second assumption. The discomfort when a user shares a ride depends on her/his partner and increases corresponding to the travel time of the shared trip. This means that when a user shares a ride with more than one user, her/his discomfort during that ride could be increased, and a discomfort matrix, which represents the discomfort of users when they share a ride with other users, can be asymmetric. Note that the discomfort of an individual user when s/he ride-shares
with a particular user can also be different depending on other factors such as individual trip purpose and time constraints. In order to determine precisely the cost function of such discomfort, another study is required such as a stated preference survey. To maintain the simplicity of the model for investigating the effects of user preference consideration on the system’s efficiency, such discomfort of a user ride-sharing with another user is assumed to be constant and given to the system.

Regarding the third assumption, because this study focuses on sharing transport, a user can only move by riding in a vehicle. A user is allowed to transfer between vehicles at any node on her/his route to the destination. To make a transfer, a user may wait at any node until an available vehicle arrives at that node.

Concerning the assumptions regarding the vehicles, the capacities of all vehicles may be different and are provided to the system, as per the fourth assumption. In order to satisfy all users’ activity patterns, the total capacities must be sufficient to service all users. This means that the total number of vehicles is also known. The fifth assumption represents the system’s own vehicles, where the origin and destination of all vehicles are at a specified base with no scheduling constraints. The vehicles with these characteristics can be, for example, shared autonomous vehicles or taxis, where they need to be on standby at a stand or station.

The sixth and seventh assumptions concern the adopted transport network. In order to consider time and space aspects simultaneously and conveniently, a time-space network (Kliwer et al., 2006) is adopted. The time-space network has three dimensions, which consist of the two dimensions of the physical transport network and one dimension of discrete time. Moreover, for simplicity, a network with no congestion is considered such that travel time between nodes is assumed to be fixed and given to the system.

![Diagram](image)

Figure 2. Obtaining trip information from users’ activity patterns

### 3.2.2 Notation

The parameters and sets used in the model formulation are listed as follows.

- \( k \) : vehicle.
- \( K \) : set of vehicles, where \( k \in K \).
The decision variables are the routes of a vehicle and a user in the time-space network, and they are presented respectively as shown below.

\[ x_{ijkt}^k = \begin{cases} 1 & \text{if vehicle } k \text{ travels between node } i \text{ and node } j \text{ from time step } t \text{ to time step } t', \text{ and } 0 \text{ otherwise, where } t' = t + c_{ij}. \\ \end{cases} \]

\[ y_{ijrt}^r = \begin{cases} 1 & \text{if user } r \text{ travels between node } i \text{ and node } j \text{ from time step } t \text{ to time step } t', \text{ and } 0 \text{ otherwise, where } t' = t + c_{ij}. \end{cases} \]

### 3.2.3 Formulation

The model is formulated as a mixed integer quadratic programming problem. As aforementioned, this study aims to consider user preference; therefore, the formulated vehicle routing problem incorporates user preference. The objective of the developed model is to minimize the total cost of users’ discomfort, the total travel cost of users and vehicles, and the total cost of having one vehicle operating, which can be expressed as follows.
Minimize
\[
\alpha_1 \sum_{u \in R} \sum_{r \in R} \sum_{t \neq i,j \in G} \sum_{i \in G} c_{ij} w_{ru} y_{ijtt'}^r y_{ijtt'}^u + \alpha_2 \sum_{r \in R} \sum_{t \neq i,j \in G} \sum_{i \in G} y_1 c_{ij} y_{ijtt'}^r + \beta_1 \sum_{k \in K} \sum_{t \neq i,j \in G} \sum_{i \in G} y_2 c_{ij} x_{ijtt'}^k + \beta_2 \sum_{k \in K} \sum_{t \neq i,j \in G} \sum_{i \in G} y_2 c_{ii} x_{ijtt'}^k + \beta_3 \sum_{k \in K} \sum_{t \neq i,j \in G} \sum_{i \in G} y_3 x_{ijtt'}^k \]

The first term represents the cost of discomfort that all users experience when they share their trip with other users, where \( y_{ijtt'}^r \) and \( y_{ijtt'}^u \) are equal to one. The discomfort when user \( r \) ride-shares with user \( u \) is denoted as \( w_{ru} \), where \( w_{ru} \) is a positive value. If user \( r \) rides in a vehicle alone, this discomfort does not occur (i.e., \( w_{rr} = 0 \) for \( \forall r \in R \)). Note that \( w_{ru} \) can also represent the positive preference of user \( r \) ride-sharing with user \( u \)—for example, user \( r \) has the advantage of socializing with user \( u \) during a ride-sharing trip—by determining \( w_{ru} \) as a negative value. The second term represents the travel cost of all users. This travel cost is only considered when users are moving between nodes. The third term represents the travel cost of all vehicles for moving between nodes that are not the base. The fourth term represents the cost of having the vehicles work in the system. These five terms can be considered differently by adjusting the priority parameters \( \alpha_1, \alpha_2, \beta_1, \beta_2, \) and \( \beta_3 \). In a case where \( \alpha_1 \) is equal to zero, users’ discomfort is neglected.

This optimal routing model is subject to the following constraints.

\[
\sum_{j \in G} x_{b_{jtt'}}^k = 1 \quad t = 0, \forall k \in K, \quad (2)
\]

\[
\sum_{i \neq b \in G} \sum_{j \in G} x_{ijtt'}^k = 0 \quad t = 0, \forall k \in K, \quad (3)
\]

\[
\sum_{j \neq b \in G} \sum_{t \neq i} x_{b_{jtt'}}^k \leq 1 \quad \forall k \in K, \quad (4)
\]

\[
\sum_{i \neq b \in G} \sum_{t \neq i} x_{b_{tt'}}^k \leq 1 \quad \forall k \in K, \quad (5)
\]

\[
\sum_{i \in G} \sum_{j \neq b \in G} x_{ijtt'}^k = 0 \quad t' = t_e, \forall k \in K, \quad (6)
\]

\[
\sum_{i \in G} x_{b_{tt'}}^k = 1 \quad t' = t_e, \forall k \in K, \quad (7)
\]

\[
\sum_{i \in G} x_{h_{tt'}}^k = \sum_{j \in G} x_{h_{b_{jtt'}}}^k \quad \forall h \in G, \forall t' \in T (\text{where } t' \neq 0, t_e), \forall k \in K, \quad (8)
\]

\[
\sum_{j \in G} y_{ijtt'}^r = 1 \quad i = s_d^r, t = t_d^r, \forall r \in R, \quad (9)
\]
Constraints (2)–(8) are related to vehicles, based on a conservation law. At time step zero, all vehicles must either depart from, or stay at, the base node, as per constraint (2). Constraint (3) ensures that no vehicle departs from any other node besides the base node at time zero. Constraints (4) and (5) allow each vehicle to depart from, and come back to, the base not more than one time in order to avoid a back-and-forth travel pattern by the vehicle. Additionally, constraints (6) and (7) ensure that all vehicles finally come back to the base. Lastly, constraint (8) ensures that no vehicle suddenly disappears from, or appears in, the system.

In the same way as for vehicles, the constraints related to users are determined corresponding to a conservation law. Constraints (9)–(12) ensure that users begin their trips only from their departure node at their earliest departure time and that users finish their trips only by arriving at their arrival node by their latest arrival time. Additionally, constraint (13) ensures that no user suddenly disappears from, or appears in, the system between her/his earliest departure time and latest arrival time.

In order to satisfy all users’ activity patterns, constraint (14) ensures that the total capacity of all vehicles is sufficient. This means that all users can travel between nodes by riding in a vehicle. Finally, the decision variables are set to be binary in constraints (15) and (16), where $x_{ijtt'}^k$ or $y_{ijtt'}^r$ is equal to one if the vehicle or user moves between nodes $i$ and $j$ during time steps $t$ and $t'$.

4. NUMERICAL EXPERIMENT

As the formulated model can be used for operating the vehicles in a desirable way or according to a specified policy, the optimal vehicle routing schedule can be changed corresponding to a policy of user preference consideration. Therefore, the objectives of conducting the numerical experiments are to present the characteristics of the formulated model, to investigate the effects of a user preference consideration policy on the optimal vehicle routing schedule, and to introduce a potentially appropriate policy for user preference consideration.

The numerical experiments are conducted on a simple transport network and users’ possible moving period, as explained in section 4.1. The optimal vehicle routing schedules under extreme policies, which are policies neglecting user preference and giving equal precedence to user preference and system efficiency, are presented and explained in sections 4.2.1 and 4.2.2, respectively. By neglecting user preference, the optimal routing solution is expected to be the most efficient vehicle operation, where vehicles are assigned to pick up users
as much as possible. By making user preference and system efficiency equally important, the optimal vehicle routing solution may result in an increased number of one-traveler trips to reduce user discomfort, requiring an increased number of working vehicles. To introduce an appropriate policy, the results of optimal vehicle routing schedules under policies that consider user preference at different levels are compared and explained in section 4.2.3. Lastly, the characteristics of the formulated model as well as the results of all introduced policies are discussed in section 4.3.

Note that the exact solutions of the developed model are obtained by a branch and bound algorithm using a math programming solver; namely, Gurobi Optimizer (Gurobi, 2017).

4.1 Numerical Experiment Setting

In the numerical experiments, the following simple transport network is considered. The network consists of one base node (i.e., node 0) for vehicles and another four nodes (i.e., nodes 1, 2, 3, 4) for users to travel between. The nodes are connected by links with given travel times, as illustrated in Figure 3(a). All nodes can be accessed from the base with 1 time step such that the trips from/to the base are minimally considered, as such trips do not carry any users.

In the numerical experiments, there are six users (|R| = 6) with the given users’ possible moving periods, which can be obtained from the users’ activity patterns, as follows. To simplify the numerical experiments while maintaining the ability to present the features of the developed model, all users have the same origin at node 1 (s_i = 1, for ∀r ∈ R) but different destinations, where two users travel to node 2, three users travel to node 3, and one user travels to node 4, as shown in Figure 3(b). Additionally, users’ earliest departure time and latest arrival time are given differently. With the given users’ possible moving periods, it is possible for all users to share a ride in the shared vehicle.

The means of transport is considered to be an autonomous vehicle such that no driver is required, and all users can travel freely. The number of vehicles is given as six vehicles (|K| = 6) with the same capacity of four seats per vehicle (q_k = 4, for ∀k ∈ K) such that the total capacity is sufficient to service all users’ demands even for a situation when no one shares a ride or a vehicle.

As previously mentioned, user preference is evaluated in terms of discomfort measured in monetary units, and in the numerical experiments, the cost of discomfort when a user shares a ride with other users for one time step is given as equal to the cost of traveling alone for one unit of time. For the same period of travel, the cost of discomfort when a user shares a ride with any two users is twice the cost of discomfort when sharing a ride with only one user. On the other hand, such discomfort does not occur when a user rides in a vehicle alone (w_{rr} = 0, for ∀r ∈ R). By making the cost of traveling for one unit of time equal to one (γ_1 = 1) for all users, the cost of discomfort for sharing a ride with one user for one unit of time is also equal to one for all users (w_{ru} = 1, for ∀r, u ∈ R where r ≠ u). The other parameters are given as follows. The cost of a vehicle traveling for one unit of time is equal to one (γ_2 = 1). The cost of having one vehicle working in the network is also equal to one (γ_3 = 1).

Regarding the priority parameters, in order to study the effect of incorporating user discomfort in the formulated vehicle routing problem, the parameter representing the priority of user discomfort α_1 is varied from 0 to 50. To reduce the complexity of the result’s implication, the other priority parameters are fixed throughout the experiments as follows: α_2 = 0.1, β_1 = 50, β_2 = 0.1, and β_3 = 0.1. Therefore, only the costs of users’ discomfort and total vehicle travel time are significantly considered.

The results obtained from the formulated optimal vehicle routing problem are presented using a two-dimensional figure, where the x-axis represents nodes, and the y-axis represents...
time. A simple example of the computed result is shown in Figure 4. In this example, there are two vehicles whose working routes are represented by solid lines. The dashed lines represent the movements of users, where the upright triangle ▲ shows a user’s earliest departure time, and the inverted triangle ▼ shows the user’s latest arrival time. A ride in a vehicle is represented by parallel solid and dashed lines. If there is more than one dashed line aligned parallel with one solid line, it represents a ride-sharing trip. On the other hand, if the dashed lines are separately aligned along the same solid line, it represents a car-sharing situation, where more than one user uses the same car during different periods.

Figure 3. Given transport network (a) and users’ possible moving period (b) for the numerical experiments

Figure 4. Example of the result’s representation

4.2 Results

The extreme cases where user preference is neglected (i.e., \( \alpha_1 = 0 \)), and given equal precedence with system efficiency (i.e., total travel time of vehicles) in the formulated optimal vehicle routing problem (i.e., \( \alpha_1 = \beta_1 = 50 \)) are presented in sections 4.2.1 and 4.2.2, respectively. The cases where the priority of user preference is varied are presented in section 4.2.3 in order to find a preferable priority ratio between user preference and system efficiency in the developed model (\( \alpha_1 : \beta_1 \)).
4.2.1 Result neglecting user preference

By considering only system efficiency (i.e., $\alpha_1 = 0$ and $\beta_1 = 50$), the optimal solution is that all users share a ride, as presented in Figure 5. In this solution, all users are organized to share their rides as much as possible to minimize the total moving time of working vehicles, as follows. Two users who have the same destination at node 2 share their whole ride from node 1. The other four users share their ride on another vehicle from node 1 to node 3; then three users alight, as node 3 is their destination, and another user continues riding in that vehicle alone from node 3 to her/his destination at node 4.

This result shows the most efficient vehicle routing solution for the given users’ possible moving periods. Additionally, it results in the minimum required number of working vehicles (two), where one of them is operated at its maximum capacity.

![Figure 5. Optimal vehicle routing solution for the following priority parameters: $\alpha_1 = 0$, $\alpha_2 = 0.1$, $\beta_1 = 50$, $\beta_2 = 0.1$, and $\beta_3 = 0.1$](image)

![Figure 6. Optimal vehicle routing solution for the following priority parameters: $\alpha_1 = 50$, $\alpha_2 = 0.1$, $\beta_1 = 50$, $\beta_2 = 0.1$, and $\beta_3 = 0.1$](image)
4.2.2 Result giving same priority to user preference and system efficiency

Giving the same priority to user preference and system efficiency (i.e., $\alpha_1 = 50$ and $\beta_1 = 50$) in the developed model, results in all users traveling alone such that all six vehicles are used, as shown in Figure 6. This result indicates that for a case where two users share their ride, the total cost of discomfort for both users is greater than the cost reduction from reducing one working vehicle, as both users feel uncomfortable, while one vehicle is reduced. Therefore, the formulated optimization problem tries to minimize the total cost of discomfort because the discomfort cost dominates in this scenario. This solution satisfies the preference of all users, as no discomfort occurs; however, it is not an efficient scenario for vehicle operation.

4.2.3 Results varying the priority of user preference consideration

By making the priority of user preference $\alpha_1$ equal to 10, 20, 30, and 40, the optimal vehicle routing solutions are obtained, as shown in Figure 7. These results confirm that increasing the priority of user preference results in the decreasing of vehicle utilization such that the required number of vehicles is increased.

For $\alpha_1$ equal to 10 in Figure 7(a), the optimal result shows that three vehicles are required for the operation. From node 1 to node 2, each vehicle carries two users. Once two users arrive at their destination (node 2), one vehicle returns to the base. From node 2 to node 3, three users who have the same destination share their ride, while one user who has a different destination rides alone to her/his destination (node 4). This is to reduce the cost of discomfort when a user shares a ride with more than one user. In the same way, for $\alpha_1$ equal to 20 in Figure 7(b), the number of required vehicles is four, and only two of them perform the ride-sharing trip. For $\alpha_1$ equal to 30 and 40 in Figures 7(c) and (d), respectively, the results are equivalent to that with $\alpha_1$ equal to 50 in Figure 6, where six vehicles are required, and no one shares a ride. This means that considering user preference and efficiency at ratio of 30:50 already results in the neglecting of efficiency.

Furthermore, the total time during which all users experienced discomfort (discomfort time) is compared with the total moving time of vehicles, corresponding to the increasing of user preference consideration, as shown in Figure 8. As previously explained, the total discomfort time (red solid line) is more sensitive to the user preference consideration ($\alpha_1$) than the total moving time of vehicles (blue solid line), as it can be clearly seen that the total discomfort time decreases faster than the increase in the total moving time of vehicles. The results also show the border priority parameter of user preference ($\alpha_1^*$) that divides the dominant consideration of the optimal vehicle routing results between system efficiency (i.e., the left-hand side of $\alpha_1^*$ or $\alpha_1 < \alpha_1^*$) and user preference (i.e., the right-hand side of $\alpha_1^*$ or $\alpha_1 > \alpha_1^*$), while both considerations are equally dominant at the border priority parameter of user preference (i.e., $\alpha_1 = \alpha_1^*$).
Figure 7. Optimal vehicle routing solution for the following priority parameters: (a) $\alpha_1 = 10$, (b) $\alpha_1 = 20$, (c) $\alpha_1 = 30$, and (d) $\alpha_1 = 40$ where $\alpha_2 = 0.1$, $\beta_1 = 50$, $\beta_2 = 0.1$, and $\beta_3 = 0.1$. 
4.3 Discussion

In the developed model, the importance of user preference can be taken into account for the optimal vehicle routing assignment by adjusting the priority parameter of user preference $\alpha_1$. By neglecting user preference (section 4.2.1), the optimal vehicle routing schedule of this model shows the integrated feature of shared autonomous vehicles with ride-sharing. On the other hand, by giving equal priority to user preference and system efficiency in the formulated model (section 4.2.2), the optimal vehicle routing schedule of this model is equivalent to that of a shared autonomous vehicle system where no ride-sharing trip occurs. These results show the ability of the developed model to provide the possible matching solutions shown in Figure 1.

In order to increase the utilization of existing resources and to sustain the adoption of the ISTS, it is necessary to introduce an appropriate priority parameter, which can be done by conducting numerical experiments varying the priority parameter of user preference (section 4.2.3). Through these numerical experiments, the results show the higher sensitivity of user preference compared with system efficiency (Figure 8). The turning point of the priority parameter of user preference, which changes the dominant consideration of the optimal solution from system efficiency to user preference, is introduced as $\alpha_1^*$. In addition, at point $\alpha_1^*$, the optimal vehicle routing solution follows the equality concept, where the optimal vehicle routing schedule has the same effect (same total travel time) on both the system side and the user side, which could be introduced as a possible operation policy for the ISTS.

5. Model Application

As aforementioned, the sharing system of passenger cars in the ISTS could be simplified to an integration of shared autonomous vehicles and ride-sharing systems if all typical passenger cars were replaced by public-owned autonomous vehicles and sharing systems were broadly utilized. The optimal vehicle routing model developed in this study can be directly applied to such a situation. Even though the travelers in such a society have to use the ISTS for their door-to-door
journey, the resulting discomfort and stress while sharing private space with others cannot be overlooked. In order to introduce a user-friendly ISTS, the relevant authorities can use the developed model to operate such a system where the importance of user discomfort can be freely adjusted.

However, before reaching the abovementioned situation where all vehicles are owned by the society, some travelers may still own a private vehicle. In this situation, travelers have an alternative of using their own private vehicle to travel instead of using the ISTS. If the travelers are not satisfied with the ISTS, they may shift their travel mode from the ISTS to a private vehicle without sharing. This incident could cause the increasing of traffic congestion as well as resource consumption, and even the abandonment of the ISTS. To avoid such an undesirable phenomenon, the developed model can also be applied. The importance of user discomfort in this case could be given higher priority than the above situation in order to convince travelers to adopt the ISTS.

The developed model can be used to find an appropriate policy by conducting numerical analysis. For instance, a policy that can consider user and system aspects equally for the specified society can be introduced by investigating the ratio of priority parameters that results in the same total travel time for both the system and the users. In addition, the optimal policy, where the cost of users’ discomfort and the cost of system operation are equivalent, can be further determined using this formulated model if there is a proper method of evaluating users’ discomfort, which requires another study. In the case of Asian countries, this ISTS can be successfully operated if the preference of users in that society regarding trip sharing is known and the appropriate operation policy is determined using the formulated model.

6. CONCLUSION

In this study, the ISTS of vehicle- and ride-sharing systems is focused on, as it leverages the advantages of the sharing economy concept. The contribution of this study is the model development of the optimal vehicle routing problem for the ISTS. As user preference has been denoted as one of the influential factors for the successful adoption of any sharing system—especially a ride-sharing system—user preference, which is considered as discomfort when sharing a ride, measured in monetary units, is incorporated into the optimal vehicle routing problem. Therefore, the model is formulated to minimize users’ discomfort together with other related operation costs. In the objective function, the priority of the consideration of users’ discomfort among other related costs can be adjusted such that the administrator is able to operate the system in any desirable way. Moreover, the optimal vehicle routing schedule of the formulated model always satisfies all users’ activity patterns in order to eliminate possible dissatisfaction caused by delay. Additionally, the numerical experiments are conducted using a simple transport network and users’ activity patterns to understand the model’s characteristics and the effects of user preference consideration on system operation. In the numerical experiments, the discomfort of sharing a ride with another traveler for one unit of time is assumed to cost as much as traveling alone for one unit of time. Note that to represent the real-world context, such discomfort should be carefully determined; however, that is not the objective of this study. The results show the concept of a priority ratio between user preference and system efficiency that can consider both user and system aspects in an equal way for the given users’ activity patterns.

The developed model can be used by the relevant authority to operate the ISTS efficiently. Moreover, it is expected to be applicable to Asian countries, as user preference is taken into consideration. However, the developed model still has some limitations. For instance, the number of transfers for one rider is neglected in this model, which can be considered by simply
adding to the objective function of a link-based model or modeling this problem using a path-based approach to obtain a more practical solution. The ability to identify which user rides in which vehicle is not yet available, which can be extended for an easier interpretation of results. The model can be further extended to cover all aspects of the ISTS framework comprehensively, as well as other public transport systems such as bus and/or rail systems, which could be considered as an application of Mobility as a Service (MaaS). Besides the model formulation aspects, the evaluation of user discomfort as well as the investigation of an appropriate policy for considering user preference and social optimum should be studied in order to make it applicable to more general cases in the real world. In addition, a solution algorithm that can handle large-scale calculations needs to be further studied, as the exact solution method employed in this study is only appropriate for small-scale networks.

ACKNOWLEDGEMENTS

This work was supported by KAKENHI Grant-in-Aid for Challenging Exploratory Research (15K14045).

REFERENCES


