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Research Article

Shared Autonomous Taxi System and Utilization of Collected Travel-Time Information

Zhiguang Liu [ID],[1] **Tomio Miwa** [ID],[2] **Weiliang Zeng** [ID],[3]
Michael G. H. Bell,[4] **and Takayuki Morikawa**[5]

[1]*Department of Civil Engineering, Nagoya University, Nagoya 464-8603, Japan*
[2]*Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya 464-8603, Japan*
[3]*School of Automation, Guangdong University of Technology, Guangzhou, Guangdong 510006, China*
[4]*Institute of Transport and Logistics Studies, Business School, The University of Sydney, Sydney, NSW, Australia*
[5]*Institute of Innovation for Future Society, Nagoya University, Nagoya 464-8603, Japan*

Correspondence should be addressed to Weiliang Zeng; weiliangzeng@gdut.edu.cn

Shared autonomous taxi systems (SATS) are being regarded as a promising means of improving travel flexibility. Each shared autonomous taxi (SAT) requires very precise traffic information to independently and accurately select its route. In this study, taxis were replaced with ride-sharing autonomous vehicles, and the potential benefits of utilizing collected travel-time information for path finding in the new taxi system examined. Specifically, four categories of available SATs for every taxi request were considered: currently empty, expected-empty, currently sharable, and expected-sharable. Two simulation scenarios—one based on historical traffic information and the other based on real-time traffic information—were developed to examine the performance of information use in a SATS. Interestingly, in the historical traffic information-based scenario, the mean travel time for taxi requests and private vehicle users decreased significantly in the first several simulation days and then remained stable as the number of simulation days increased. Conversely, in the real-time information-based scenario, the mean travel time was constant. As the SAT fleet size increased, the total travel time for taxi requests significantly decreased, and convergence occurred earlier in the historical information-based scenario. The results demonstrate that historical traffic information is better than real-time traffic information for path finding in SATS.

1. Introduction

Autonomous vehicles (AVs) have undergone rapid development in recent years. Many automobile manufacturers and IT companies around the world, including Google, Uber, Tesla, and Toyota, are testing their AV products on real road networks [1]. In some countries, AVs are allowed to enter select areas, but not the entire public road network. A Singaporean technology company called "nuTonomy" uses AVs as taxis within an area of 2.5 square miles [2]. On December 2, 2017, four self-driving buses were tested on public roads in Shenzhen, China, which is believed to be the first live test of autonomous buses in the world [3]. There is considerable evidence to indicate that the use of AVs will become more widespread in the near future.

AVs can be designed to connect with each other and can exchange traffic information related to the road network [4]. The AVs start when orders are transmitted to the controller inside the vehicles, and they drive automatically based on the instructions from the controller. Owing to these advantages, AVs are expected to make transportation more efficient and comfortable and reduce cost, environmental impact, and congestion [5].

In a traditional taxi operation system, a driver can serve only a single customer or a group of customers in a point-to-point journey. For example, the average occupancy rate of a taxi in New York City is only 1.2 passengers per trip [6]. Empty taxis usually cruise along urban roads looking for customers. This is economically burdensome because they increase the traffic volume, which may lead to traffic congestion on the

urban road network. Overall, the operational efficiency is relatively low. The main reason why customers decide to hire taxis is that they have limited time, but heavy traffic prevents customers from reaching their destinations on time [7]. Meanwhile, the current system is unable to match the entire taxi demand during peak hours. Measures to solve such problems are urgently needed.

Accordingly, this study was conducted with the objective of developing a shared autonomous taxi system (SATS) and investigating the efficiency of the system through simulation experiments. In the studied system, customers are assumed to be willing to share a taxi with other customers and can request a taxi through a smartphone. Shared autonomous taxis (SATs) remain parked when unoccupied to reduce the road burden. A taxi is automatically assigned by the SATS to pick a customer up after considering both unoccupied and occupied taxis. By taking advantage of unoccupied seats, the SATS can reduce the total number of taxis required on the road network.

AVs are equipped with superior technological sensors [8], which are used to accurately perceive the surrounding environment, and collect traffic information. In this study, as probe vehicles, SATs were deemed capable of collecting valuable traffic information, including data pertaining to the vehicle location and link travel time. The collected traffic information can be used for path finding and categorized as historical and real-time information. The effectiveness of using the two types of information was investigated in this study.

The remainder of this paper is organized as follows. In Section 2, the literature on taxi sharing and the performance of shared AVs is reviewed. The SATS considered in this study is explained in Section 3. Section 4 presents the traffic information used for path finding in the SATS. The simulation design and results are described in Section 5. Finally, conclusions and a discussion of future work are presented in Section 6.

2. Literature Review

Autonomous taxi systems were proposed prior to the year 2000, e.g., the autonomous dial-a-ride taxi system [9], even though the technology for navigation and positioning was not sufficiently advanced at that time. With the development of AVs, a customer can request an SAT and ride it to his/her destination. The sharable taxis can be assigned to a single person or shared with other customers. The deployment of shared AVs (SAVs) can lead to a reduction in the total number of private cars on urban road networks. Fagnant and Kockelman [10] designed an agent-based model for SAV operations in which four strategies are used to relocate AVs with the aim of minimizing waiting times for future travelers. A 5-min interval is chosen as the iteration period. At the beginning of every 5-min interval, the travel demand in every zone is predetermined. A parameter called "block balance" is proposed, which represents the difference between the expected demand and supply for SAVs in the upcoming 5 min. By comparing the average number of trips served by an SAV with that by a private car, they concluded that one SAV can replace approximately 11 conventional cars. Fagnant et al. [11] provided more details with regard to link-level travel times. Their proposed model comprises four submodules: SAV location and trip assignment, SAV fleet generation, SAV movement, and SAV relocation. An SAV is assigned first to the traveler who has been waiting for the longest time. Fagnant and Kockelman [12] developed SAV simulations for clients with different origins and destinations by considering dynamic ride sharing (DRS). Five conditions are considered to judge whether a ride could be shared: the total travel time and the increase in the remaining journey time for riding passengers, the increase in the total travel time for a new passenger, the possibility of the new passenger being picked up in the next 5 min, and the total travel time for the two passengers. Their experimental results suggested that DRS has the potential to reduce the total service time (which includes the waiting time), travel time, and cost for users. The authors also discussed the optimal SAV fleet size from an economic viewpoint. However, they did not provide delivery rules for the customers in a shared taxi. This is important because these rules determine the remaining time and travel time for each individual customer. Burghout et al. [13] replaced private vehicles in Stockholm with the SAVs in a simulation study. The sharing schemes included passengers with the same origin and destination, the same origin but different destinations, and different origins but the same destination. Their results indicated that only 5% of the current number of private cars would be needed to transport commuters, but the travel time increased by 13% on average. Lioris et al. [14] suggested that if the detour time incurred by serving a potential customer exceeds a maximal detour time, that customer should be rejected. Levin et al. [15] reported that, when choosing between an occupied SAV and an unoccupied SAV, the one that is able to arrive at the customer location first should be assigned to the customer. They further proposed that SAVs would increase congestion because of the additional trips made to reach each customer's origin. It was found that the difference in the vehicle miles traveled between SAV scenarios and non-SAV scenarios was primarily due to the repositioning trips required to pick the next passenger up.

To optimize conventional taxi systems in terms of customer convenience and mitigation of traffic congestion, a major strategy has been to investigate dial-a-ride and shared taxi systems. Studies on this strategy can be found in the literature. Teal [16] found that commuters could be the major users of carpool ride sharing, which can reduce travel costs. Even though ride sharing is generally applied to private cars, commuters can call a taxi with the intention of sharing it. Dial [9] reported on an autonomous dial-a-ride taxi system in which customers request a taxi via telephone and only the customer is involved in the process of requesting a ride, assigning the trip, scheduling the arrival, and routing the vehicle. The task of a driver is to simply follow instructions provided by the vehicle's computers. The author also investigated an ideal autonomous taxi system that has the ability to assign a taxi to a customer in the shortest possible time. Tao [17] used each customer's choice for the maximum acceptable number of sharing customers and acceptable gender as inputs
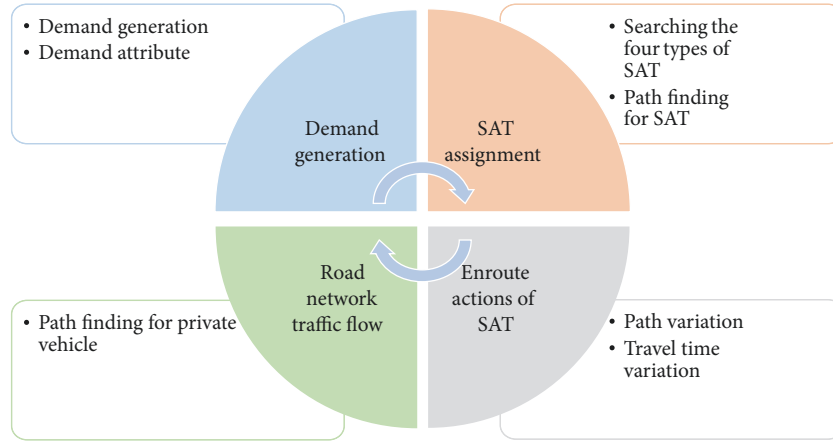
FIGURE 1: Shared autonomous taxi system (SATS) integrated into traffic flow.

to an algorithm, which then selects the taxi that is able to reach the customer's location most rapidly to provide the service. Orey et al. [18] proposed that a customer request be sent to all taxis or a subset of taxis and each taxi would respond with its cost associated with the trip to the customer. The customer would then determine the acceptable lowest cost for taxi sharing and choose a taxi to use. However, a customer finds it difficult to select one taxi from potential taxis. Ota et al. [19] studied a data-driven taxi ride-sharing simulation in which taxis cruise the road network even when empty. A trip is assigned to the taxi that provides the lowest additional cost if the passenger is assigned. Ma et al. [20] noted that a ride request, made through a smartphone app, should be assigned to whichever taxi that minimizes the increase in the travel distance resulting from the request while meeting the arrival time, capacity, and monetary constraints of both the new passenger and the existing passenger(s). Nourinejad and Roorda [21] verified the performance of ride sharing by maximizing the savings on the total vehicle kilometers traveled and maximizing the matching rate. Najmi et al. [22] investigated the effect of different dynamic sharing methods on the performance of the ride-sharing system.

Many previous studies have investigated SAV and taxi sharing. To correctly plan SAT paths, traffic information is essential in the SATS. However, providing sufficient information to enable accurate path selection is difficult. In this study, the link travel-time information collected by SATs was analyzed and the information applied to path finding for both SATs and private vehicles.

3. Shared Autonomous Taxi System

This section describes the components and implementation of an SATS. This system is an improvement of the system proposed in a previous study [23]. The SATS is built on two events: SAT assignment and enroute actions of the SAT, and the types of responses these actions warrant. The proposed system assumes that all SATs can be shared by two requests and these requests can only be made through a smartphone. It should be noted that a request can contain more than one customer.

This SATS operates on a network $G = (N, A, V, D)$, where N is the set of nodes and A is the set of links. The network has a set of SATs V that provides service to demand D. The integration of this system with road network traffic flow is illustrated in Figure 1. The implementation steps are grouped into four modules: (1) demand generation, (2) SAT assignment, (3) enroute actions of SAT, and (4) road network traffic flow. The remainder of this section describes these modules in detail.

3.1. Demand Generation. The demand generation module introduces customers to the proposed SATS. In each time step τ, this module outputs a set of new customers who request an SAT. The new customers and waiting customers are provided with the service during this time step, and the waiting customers are provided with this service before the new customers.

In this study, we assumed that demand can be separated into single requests. The origin and destination of each request $d \in D$ are denoted by O_d and D_d, respectively. For ride-sharing problems, departure time and arrival time are key factors in improving matching rate [24]; therefore, it was assumed that each request has an earliest departure time denoted by EDT_d, a latest arrival time denoted by LAT_d, and travel-time flexibility denoted by TTF_d [25]. Request d should be served in the time window (EDT_d, LAT_d) [26]. In this study, EDT was assumed to be the same as the SAT request time. Travel-time flexibility is the extra time that is acceptable to requests. If the minimum travel time from O_d to D_d is $T_{(O_d, D_d)}$, the travel-time flexibility of request d is $TTF_d = LAT_d - EDT_d - T_{(O_d, D_d)} \geq 0$. Once a request appears at τ, the SAT assignment event will be triggered.

3.2. SAT Assignment. The SAT assignment operates and responds to the appearance of new demand. This module describes the specific logic used to assign SATs to demand in the SATS.

The SATS assumes the existence of a virtual central control system that knows the status of all SATs and requests; this system can also assign an SAT to each request and select the path for the SAT. The output of the SAT assignment is
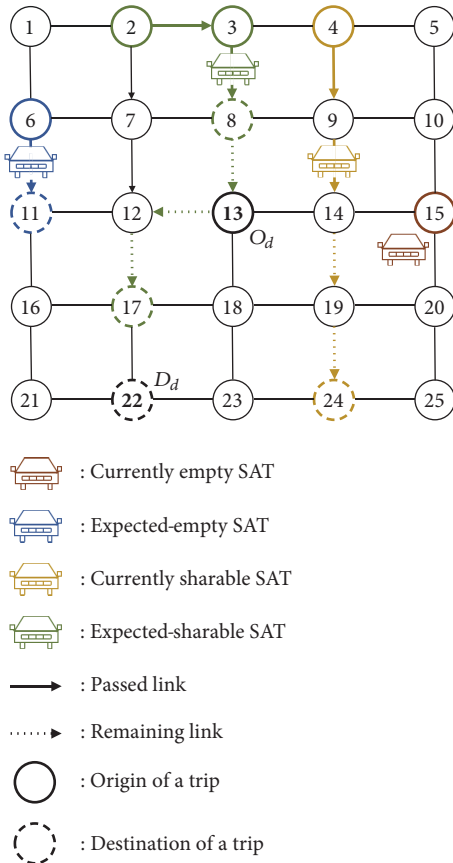
FIGURE 2: Four types of available SATs.

an update of the SAT status, including unoccupied, single-rider occupied, shared, and change-of-request status (i.e., in-service or waiting to be served). In this study, a rider corresponds to a request. Each SAT is either parked at a node or serving a customer at any given time; therefore, in this study, it was assumed that nodes have (infinite) parking space.

3.2.1. Four Types of Available SATs. In the SATS, once a new request is generated, the virtual central control system searches the available SATs for the request. All the searched SATs should be located within the distance D_{max} from the request, where D_{max} is the radius of the search area. There are four types of available SATs according to their status and possibility of sharing: currently empty, expected-empty, currently sharable, and expected-sharable SATs.

A currently empty SAT is an unoccupied SAT. As shown in Figure 2, when request d occurs at node O_d, the virtual central control system first tries to check whether a currently empty SAT is available. In this figure, an unoccupied SAT is parked at node 15.

An expected-empty SAT is a taxi that is occupied by other customer(s) presently, and the rider will get off within the maximum waiting time T_{max}. Next, the SAT can travel to d. As shown in Figure 2, the origin and destination of rider in an expected-empty SAT are node 6 and node 11, respectively, and the taxi is traveling on the planned path. In this case, this

SAT can first proceed to node 11 to drop the rider off and then travel to O_d to pick d up.

A currently sharable SAT is defined as a single-rider occupied taxi that can be shared with another request if the requirements for sharing can be met, which are threefold. The first requirement is that the origin of the new request O_d should be on a path in the path set of the rider c. The path set of each OD pair is predetermined using a k-shortest path algorithm [27, 28]. The k-shortest path algorithm can work in this study when the size of a network is not large. In addition, its application can reduce the time for processing every request since candidate SATs for sharing can be screened effectively. The second requirement is that the destination D_c of rider c should be on a path in the path set of the new request, or the destination of the new request D_d should be on a path in the path set of rider c. The third requirement is that both rider c and request d can arrive at their destinations within LAT_c and LAT_d, respectively. This is called sharing check in this SATS. As shown in Figure 2, the origin and destination of the rider are node 4 and node 24, respectively. The taxi may change its route from the original path ($4 \longrightarrow 9 \longrightarrow 14 \longrightarrow 19 \longrightarrow 24$) at node 14 to pick request d up, and the two trips will share this SAT on the link from 13 to 24.

An expected-sharable SAT is an SAT that is presently occupied by two riders and can be shared by request d and the remaining rider after one rider gets off the vehicle. For this type of SAT, the requirements for sharing are also threefold. The first two requirements are the same as the first two requirements for currently sharable SAT, and rider c in the sharing requirements is the rider who can arrive at their destination later than the other rider. The last requirement is that both the rider and request d can arrive at their destinations within their respective latest arrival time. As shown in Figure 2, an expected-sharable SAT is currently occupied by two riders. After one rider arrives at their destination (node 8), the SAT can be shared by the remaining rider and request d.

In this SATS, a currently sharable SAT is a single-rider occupied SAT, and a single-rider occupied SAT can also possibly be an expected-empty SAT. A two-rider occupied SAT can be an expected-empty SAT or an expected-sharable SAT. For searched occupied SAT, the virtual central control system checks the possibility of this SAT being a currently sharable or an expected-sharable SAT because the path set for each OD pair is found using the k-shortest path algorithm, and customers are prohibited from traveling on paths beyond the path set.

3.2.2. Path Finding for SAT. Before SAT assignment, the virtual central control system searches for a potential path for each of the four types of SATs using the shortest travel-time path algorithm. When an SAT is finally assigned, the SAT transports customers on the potential path. The path of a traveling SAT cannot be changed until customers arrive at their destination or the SAT is shared with a new request. For SATs that are not parked at O_d at the moment that path finding begins, to correctly find the shortest travel-time path, the mean travel time for each possible path should include the remaining part of the ongoing path. Figure 3 takes the

Links

		Path *o*		Path *p*		Path *q*	
	1	**2**	**3**	**4**	**5**	**...**	**m**
h	$\widehat{\mu}_{1,h}$	$\widehat{\mu}_{2,h}$	$\widehat{\mu}_{3,h}$	$\widehat{\mu}_{4,h}$	$\widehat{\mu}_{5,h}$	⋮	$\widehat{\mu}_{m,h}$
h + Δh		$h_0 + h_1 \geq h + \Delta h$	$\widehat{\mu}_{3,h+\Delta h}$	$\widehat{\mu}_{4,h+\Delta h}$	$\widehat{\mu}_{5,h+\Delta h}$	⋮	$\widehat{\mu}_{m,h+\Delta h}$
h + 2Δh	$\widehat{\mu}_{1,h+2\Delta h}$	$h_0 + h_2 \geq h + 2\Delta h$		$\widehat{\mu}_{4,h+2\Delta h}$	$\widehat{\mu}_{5,h+2\Delta h}$	⋮	$\widehat{\mu}_{m,h+2\Delta h}$
h + 3Δh	$\widehat{\mu}_{1,h+3\Delta h}$	$h_0 + h_3 \geq h + 3\Delta h$			$\widehat{\mu}_{5,h+3\Delta h}$	⋮	$\widehat{\mu}_{m,h+3\Delta h}$
h + 4Δh	$\widehat{\mu}_{1,h+4\Delta h}$		$h_0 + h_4 \geq h + 4\Delta h$			⋮	$\widehat{\mu}_{m,h+4\Delta h}$
⋮	⋮	⋮	$h_0 + h_{m-2} \geq h + 5\Delta h$		⋮	⋮	⋮

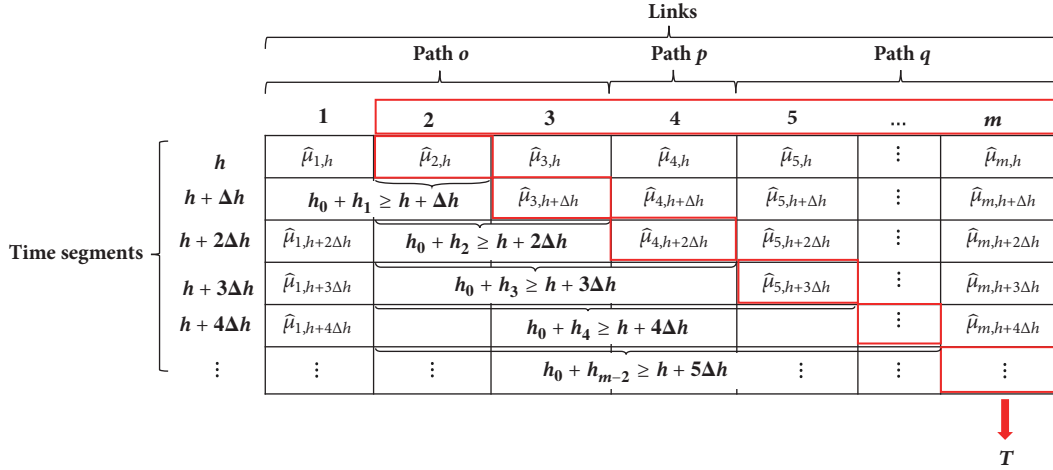(Time segments — label at left spanning the rows)

T

FIGURE 3: Path travel time of expected-empty taxi.

expected-empty SAT as an example. Information in this table is the mean travel time of each link in each time segment. In the figure, suppose that path *o* is the ongoing path of an expected-empty SAT and links 2 and 3 are the remaining links. The SAT travels to O_d through path *p*. Path *q* is one path from the origin of *d* to the destination. The travel time for this new path is the sum of the travel time for the remaining links of paths *o*, *p*, and *q*. The consideration of the transition in the traffic condition is explained in Section 4.

3.2.3. SAT Assignment and Status Update. To reduce the total travel time, a request is served by the SAT with the minimum travel time to its destination. The virtual central control system executes the following steps sequentially.

Step 1. The central control system searches for currently empty SATs within D_{max} from the origin of request *d* and then searches for the minimum travel-time paths for each searched SAT. The available path set of every currently empty SAT is the combination of two path sets: the path set from the SAT's location to O_d and the path set from O_d to D_d. The consideration of the combination of two path sets is reasonable because our aim is to ensure that the request arrives at the destination in the minimum travel time when time transition is considered, which is described in Section 4. The minimum travel times with each searched currently empty SAT can be recorded as $\{T_{ce,1}, T_{ce,2}, \ldots, T_{ce,n1}\}$, where $n1$ is the number of searched currently empty SATs. The minimum travel time is recorded as $T_{ce,min}$.

Step 2. The system searches for expected-empty SATs. The shortest travel-time path for each expected-empty SAT is searched as described in Section 3.2.2. The minimum travel times of each expected-empty SAT are $\{T_{ee,1}, T_{ee,2}, \ldots, T_{ee,n2}\}$, where $n2$ is the number of expected-empty taxis. The minimum travel time is recorded as $T_{ee,min}$.

Step 3. The system searches for currently sharable and expected-sharable SATs. The central control system first checks whether the searched SATs meet the requirements

for sharing. The searched SATs are feasible SATs if the requirements are met, and a potential path is assigned to each feasible SAT. The minimum travel times for the new request can be recorded as $\{T_{cs,1}, T_{cs,2}, \ldots, T_{cs,n3}\}$ with all feasible currently sharable SATs and as $\{T_{es,1}, T_{es,2}, \ldots, T_{es,n4}\}$ with all feasible expected-sharable SATs, where $n3$ and $n4$ are the number of feasible currently sharable and expected-sharable SATs. The minimum travel time with currently sharable SAT and that with expected-sharable SAT are $T_{cs,min}$ and $T_{es,min}$, respectively.

Step 4. The SAT with the minimum travel time, T_{min}, is assigned to the request eventually.

Step 5. If the virtual central control system cannot find T_{min}, which means that no SAT is available, the request, *d*, is added to the waiting list.

The SAT assignment procedure is shown in Figure 4. After the assignment of the SAT, the status of both the request and SAT will be updated. The completion of this module triggers the third module: enroute actions of the SAT.

3.3. Enroute Actions of SAT. When an SAT departs from the origin of a request, the module of enroute actions is triggered. In this process, the SAT takes the customer to the destination. The predicted travel time of the SAT varies with changing traffic conditions. The status and planned path of the SAT also change when the SAT proceeds to the destination or when the SAT is shared with a new request.

3.3.1. Status Variation of SAT and Its Causes. It is possible that the status of an SAT changes to an expected-empty SAT from a single-rider occupied SAT or shared SAT. This is because the SAT is selected to serve the next request. It is possible that the pick-up time for the next request is delayed or early according to variations in traffic conditions. In this study, we assume that once an SAT is assigned to a request, the request cannot refuse the assigned SAT. The SAT travels to the destination of the last rider and parks at the destination if it is not selected
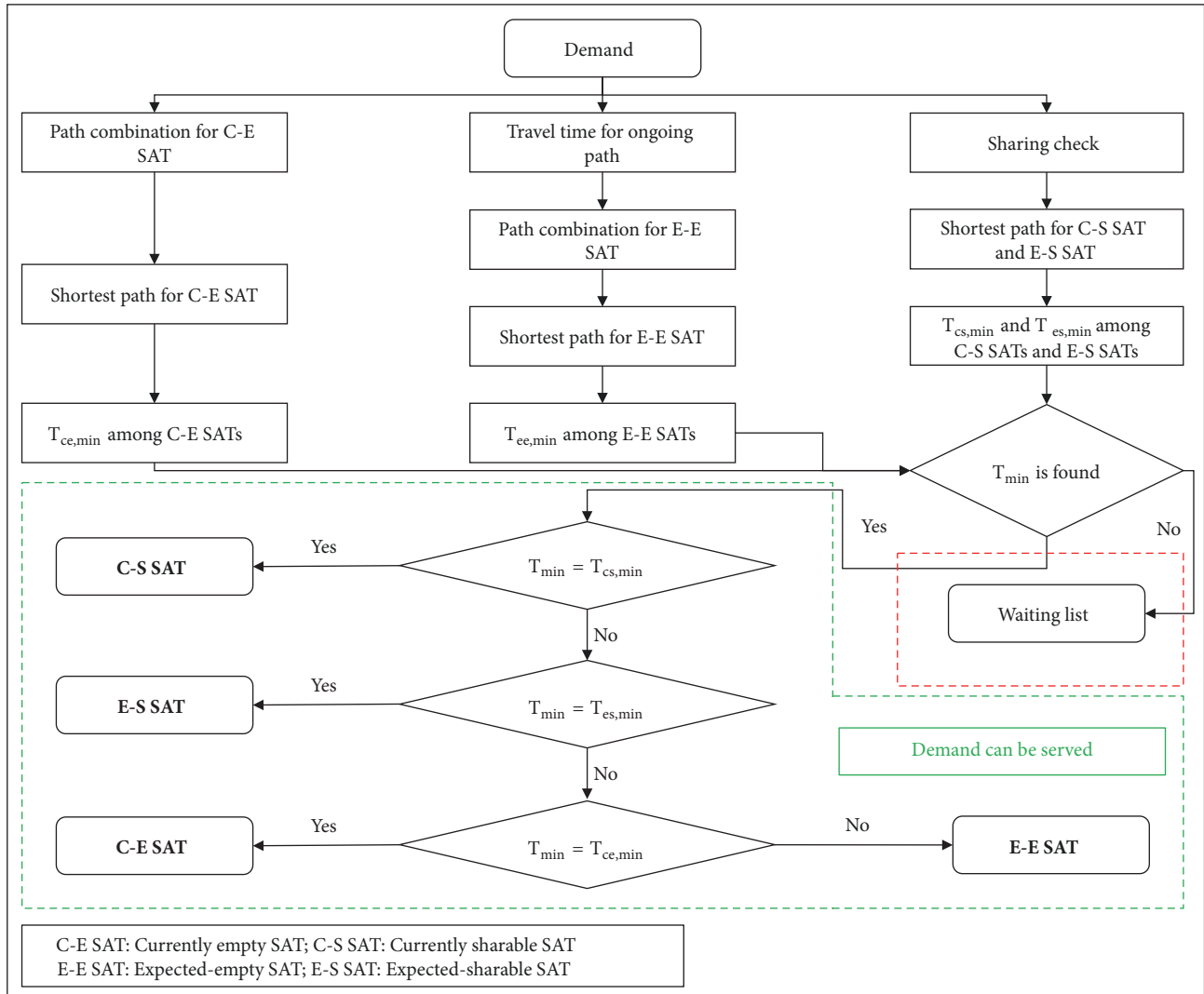
FIGURE 4: SAT assignment procedure.

to serve other requests soon. The status of the SAT is updated to unoccupied from single-rider occupied or shared.

The departed taxi is a single-rider occupied SAT or shared SAT. On the way to the destination, the status of the taxi can change from one of the two above statuses to another status. For a shared SAT, the status changes to single-rider occupied when one rider reaches the destination. The SAT can be shared with following requests, which results in SAT trip chaining [29]. The status of the SAT is still shared if it picks a new request up right at the node where one rider exits. If the departed SAT is only occupied by one rider, it can be shared with the following request on the way to the destination. In this study, two types of sharing are considered; these types determine the delivery sequence of the two riders and are described in Section 3.3.2. A new path is also necessary to be searched for picking up and dropping off customers; this aspect is described in Section 3.3.3.

3.3.2. Sharing Types and Customer-Delivery Rule. Based on the location of the origin and destination of the rider and those of the new request, sharing is divided into two types: extended-path sharing (EP sharing) and in-path sharing (IP sharing). EP sharing means that sharing extends the planned path of the taxi because the destination of the new request is not on any path in the path set of the rider, as shown in Figures 5(a) and 5(b). In IP sharing, both the origin and destination of the new request are on the k-shortest paths of the rider, as shown in Figures 5(c), 5(d), 5(e), and 5(f). Even if the origin and destination of the new request are located on different paths of the path set of the rider, the case can be considered provided there is a common node where SATs can detour to a new path to pick up or drop off a rider from the planned path.

In EP sharing, the first-in-first-out (FIFO) order is used as the customer-delivery rule; that is, the rider is delivered first.
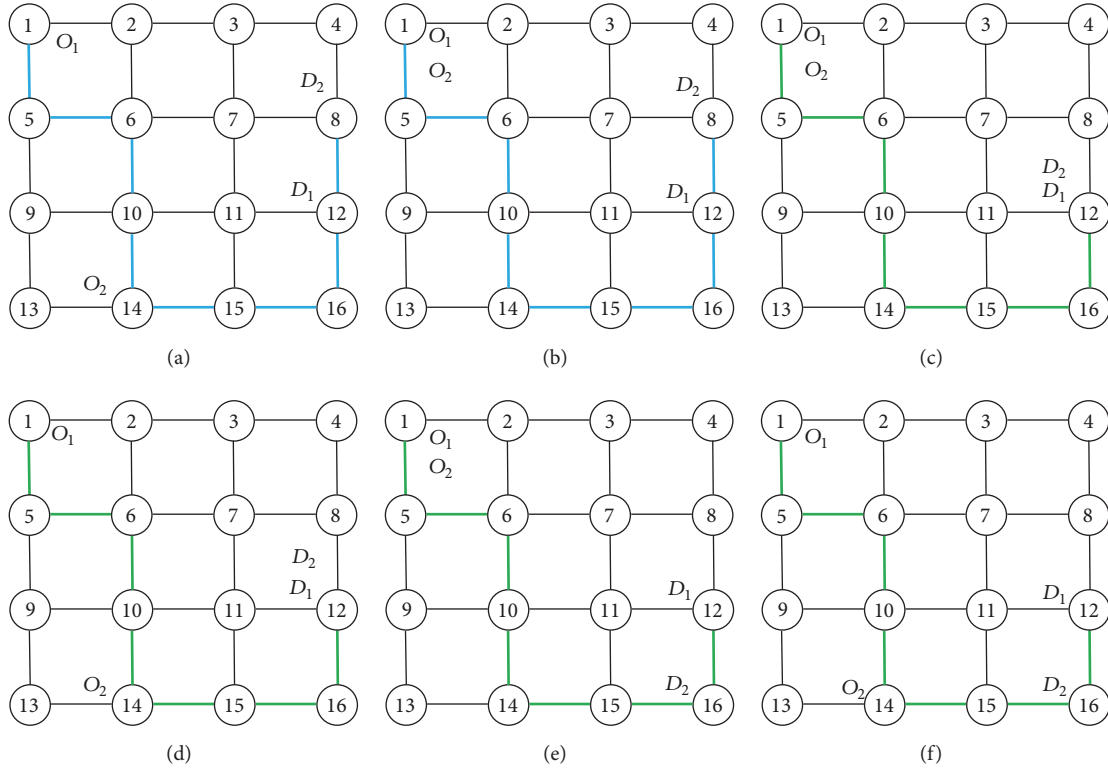
FIGURE 5: Sharing types in SATS.

In IP sharing, the new request can arrive at the destination earlier than or at the same time as the rider. It is necessary to determine the sharing type and delivery rule because it determines the minimum total travel time for the two trips.

3.3.3. Shared Path for Currently Sharable SAT and Expected-Sharable SAT. If an SAT meets the first two sharing requirements described in Section 3.2.3, the central control system finds a new path for each feasible sharable SAT as the shared path. The path set of this SAT is the combination of the path sets of the rider c and the new request d. The method mentioned in Section 3.2.2 is used to select paths that can make the rider c arrive at the destination within LAT_c. The travel times for these paths for the new request are $\{T_{s,s1}, T_{s,s2}, \ldots, T_{s,sn5}\}$, and the minimum time is $T_{s,smin}$. In this case, the path with $T_{s,smin}$ is assigned as the shared path to the taxi. The SAT travels on the shared path if it is finally selected to provide service to the new request.

The above three modules constitute the implementation of the SATS, which is integrated to the traffic system.

3.4. Road Network Traffic Flow. In the simulation, it was assumed that road network traffic flow consists of taxis and private vehicles. The path of a private vehicle was selected statistically. Considering the diverse preferences of private vehicle drivers, the path choice probability was calculated by using the path size logit model [30–32]. The model is formulated as follows [32]:

$$P\left(\frac{i}{C_n}\right) = \frac{PS_{in}e^{V_{in}}}{\sum_{j\in C_n} PS_{jn}e^{V_{jn}}} \tag{1}$$

$$PS_{in} = \sum_{a\in\Gamma_i}\left(\frac{l_a}{L_i}\right)\frac{1}{\sum_{j\in C_n}\left(L_i/L_j\right)\delta_{aj}} \tag{2}$$

where V_{in} is the systematic term of utility of path i for user n, C_n is the path set, PS_{in} is the size of path i, l_a is the length of link a, L_i is the length of path i, δ_{aj} is 1 if link a is in path j and 0 otherwise, and Γ_i is the set of links of path i.

4. Travel-Time Information

Like probe vehicles, traveling SATs can also collect traffic information, including data pertaining to the vehicle location and link travel time. The collected travel-time information can be used for path finding by both SATs and private vehicles. Link travel velocities are assumed to be calculated as $v_a = 16.1 * \ln(215/k_a)$ [33], where 215 vehicles/mile are the density of the traffic jam and k_a is the density of link a. The link density is updated every minute. The travel time for an SAT or a private vehicle on link a is assumed to be random and is normally distributed with $t_a \sim N(\mu_a, \sigma_a^2)$, where $\mu_a = (l_a/v_a)$ and $\sigma_a^2 = \alpha(l_a/v_a)^2$, in which μ_a and σ_a^2 are the population mean value and variance of the link

Links

	1	2	3	...	a	...	m	
Time segments — h	$\hat{\mu}_{1,h}$	$\hat{\mu}_{2,h}$	$\hat{\mu}_{3,h}$	...	$\hat{\mu}_{a,h}$	...	$\hat{\mu}_{m,h}$	→ T_1
h + Δh								

(a) Case of real-time traffic information

Links

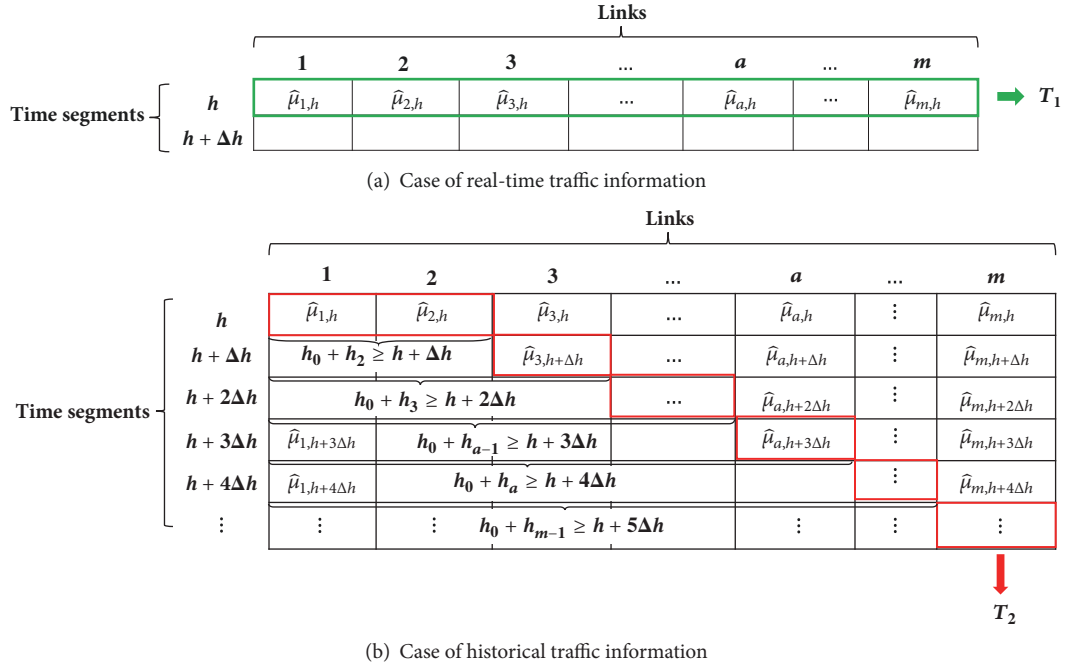|	1	2	3	...	a	...	m
h	$\hat{\mu}_{1,h}$	$\hat{\mu}_{2,h}$	$\hat{\mu}_{3,h}$	...	$\hat{\mu}_{a,h}$	⋮	$\hat{\mu}_{m,h}$
h + Δh	$h_0 + h_2 \geq h + \Delta h$		$\hat{\mu}_{3,h+\Delta h}$	...	$\hat{\mu}_{a,h+\Delta h}$	⋮	$\hat{\mu}_{m,h+\Delta h}$
h + 2Δh	$h_0 + h_3 \geq h + 2\Delta h$			...	$\hat{\mu}_{a,h+2\Delta h}$	⋮	$\hat{\mu}_{m,h+2\Delta h}$
h + 3Δh	$\hat{\mu}_{1,h+3\Delta h}$	$h_0 + h_{a-1} \geq h + 3\Delta h$			$\hat{\mu}_{a,h+3\Delta h}$	⋮	$\hat{\mu}_{m,h+3\Delta h}$
h + 4Δh	$\hat{\mu}_{1,h+4\Delta h}$	$h_0 + h_a \geq h + 4\Delta h$				⋮	$\hat{\mu}_{m,h+4\Delta h}$
⋮	⋮	⋮	$h_0 + h_{m-1} \geq h + 5\Delta h$		⋮	⋮	⋮

→ T_2

(b) Case of historical traffic information

FIGURE 6: Use of two types of traffic information in SATS.

travel time on link a, respectively [34]. In the proposed SATS, it is assumed that the link travel times are independent. The mean value of the path travel time can be expressed by $\hat{\mu}_p = \sum_{a \in p} \hat{\mu}_a$, where $\hat{\mu}_a$ is the expected value of the travel time (t_a) experienced by SATs on link a. Considering the online information paradox [35], which means that the provision of incomplete or inaccurate information could deteriorate the transportation system, it is urgent and necessary to provide accurate information and use the information in an appropriate manner. In this study, two methodologies for using the collected information, real-time information, and historical information were investigated. However, this study has the limitation that no exogenous disturbance was considered. The reason for this lack of consideration is that the traffic environment is expected to become more stable and traffic safety can be improved in the autonomous vehicular transportation system.

In the case of real-time traffic information, the information collected by SATs at time segment h is used for path finding at $h + \Delta h$. That is, the link travel-time information for link a at $h + \Delta h$ is $\hat{\mu}_{a,h}$. The information update interval is Δh. As shown in Figure 6(a), if the path of an SAT at $h + \Delta h$ contains m links, the travel-time information for the path will be the sum of the $\hat{\mu}_{a,h}$ for the m links. This is the same for the current travel-time system.

In the case of historical traffic information, a traffic information database is first established, as shown in Figure 6(b). The information in the database is the mean value of the link travel time experienced by SATs in every time segment until the previous day. Through traffic information collection and accumulation, information in the database is updated each day. This information is utilized for path finding in the same time segment in the following days. In this methodology, the transition of traffic condition is also considered [36]. As shown in Figure 6(b), the departure time of an SAT is h_0, which is greater than h and less than $h + \Delta h$. The total travel time for the first a links is h_a. The traffic information for link 3 at $h + \Delta h$ is used for path finding because the total travel time for the first two links exceeds $h + \Delta h - h_0$ and is less than $h + 2\Delta h - h_0$.

5. Simulation Design and Results

To determine the effect of traffic information and how different SAT fleet sizes perform in the SATS, in this study, several sets of simulation experiments were conducted in MATLAB on an Intel Core CPU running at 3.00 GHz.

The experiments were performed on the Sioux Falls network, as shown in Figure 7. The network had 24 nodes, 76 links, and 552 OD pairs. The metric used in the k-shortest path algorithm was distance, and k was set 10. The free-flow speed of all the links was set to 40 km/h. The travel time for a link was calculated using its length and the speed obtained using the equation in Section 4. In this study, α was set to 0.21 [37, 38].

The trip demand by taxi requests and private vehicle users is shown in Figure 8. The demand was generated from a Poisson distribution every minute and spread over a 24-h period based on the temporal distribution of US NHTS trip-start rates in 2009 [39]. The origin and destination of each trip were generated randomly.

Each experiment was simulated for 80 days. Initially, SATs were distributed evenly on every node in the network. We assumed that all SATs could be relocated at 0:00 a.m. to
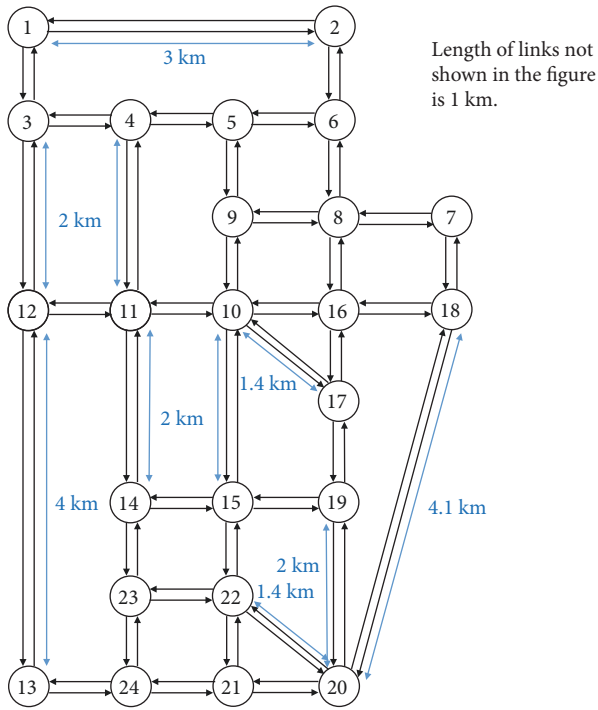
FIGURE 7: Sioux Falls network.

handle the demand of the next day. D_{max} was set as 10 km, and T_{max} was set as 10 min. The latest arrival time of a request was the sum of the travel time from its origin to the destination at the average travel speed (20 km/h) and an acceptable time that follows $U(0, 10)$. Δh was set as 5 min in all the scenarios. Both on the first simulation day of the historical traffic information-based scenario and in the first time segment of the real-time traffic information-based scenario, the travel-time information used for path finding was considered to have been obtained under free flow. The simulation results are shown in Figures 9–11.

5.1. Effect of Traffic Information. Figure 9(a) presents the day-to-day change in the mean travel time for PV users and SAT requests with real-time traffic information, Figure 9(b) illustrates the travel times with historical traffic information, and Figure 9(c) shows the mean waiting times for SAT requests in the case where the SAT fleet size was 30% of the fixed peak hour demand of SAT requests.

All the travel times and the waiting time in the historical traffic information-based scenario decreased gradually as the number of simulation days increased, and the times converged on approximately the 30th simulation day. The travel times and waiting time in the real-time information-based scenario were stable at a larger time level during the entire simulation. All the travel times at the stable level in the historical traffic information-based scenario had less fluctuation than those in the real-time traffic information-based scenario. In the historical information-based scenario, the times decreased because with the collection and accumulation of traffic information and the consideration of time transition, the central control center can find a more accurate

shortest travel-time path for each SAT compared to the past simulation days and the real-time traffic information-based scenario. These results confirm that historical traffic information is better than real-time traffic information for path finding in the proposed SATS. This is consistent with the conclusions in the literature [38].

In both scenarios, the total travel times for taxi requests are greater than those for private vehicle users. This is reasonable because the total travel time includes the waiting time until the SAT's arrival. The in-vehicle travel times for taxi requests are smaller than those for private vehicle users because the probabilistic path choice behavior of private vehicles is considered and some private vehicles do not select the shortest travel time path.

5.2. Effect of SAT Fleet Size. Figures 10 and 11 present the day-to-day changes in the total travel times and waiting times for the two traffic information source cases. The SAT fleet size was set to 30%, 40%, and 50% of the fixed peak hour demand of SAT requests.

The figures clearly show that the total travel time for the taxi requests in both scenarios decreases as the taxi fleet size increases. The difference among the different fleet sizes is due to the difference in the waiting time. The in-vehicle travel time does not vary significantly among different fleet sizes. That is, as the supply of SATs increases, the number of taxi requests who have to wait for taxis decreases. In particular, the difference between the cases with 30% and 40% of fleet sizes is considerably greater than the difference between the cases with 40% and 50% of fleet sizes. These results demonstrate that an insufficient fleet size in the SATS would nonlinearly worsen the service level of the SATS.

In addition, Figure 11(b) indicates that as the number of taxis increases, convergence occurs earlier in the historical information-based scenario. This is because in the case with a larger fleet size, the statistical reliability of the travel-time information accumulated in the historical information database can become higher because of the larger amount of collected data. Accordingly, the accuracy for searching for available SATs and the accuracy of path findings can increase.

6. Conclusions and Future Work

This paper proposed a framework for an SATS that utilizes collected travel-time information to reduce taxi demand and increase the possibility of reducing the travel time for taxi customers. In the proposed SATS framework, in which there are no drivers, SATs utilize collected travel-time information for path finding. The use of two types of information was investigated: historical information and real-time information. The results of the simulation experiments conducted in this study verify that using the two types of information is effective.

More specifically, the simulations demonstrated the effect of using historical travel-time information for path finding and reducing the travel time in the SATS. In particular, as the number of simulation days increased, the customers in the SATS with the historical traffic information obtained increasingly smaller travel times until the travel time converged
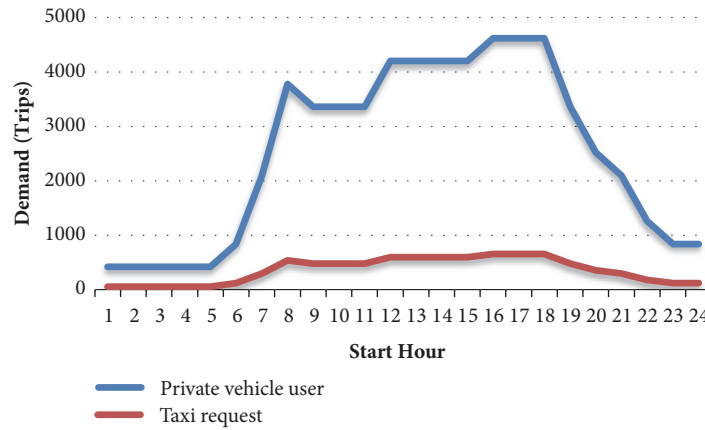
FIGURE 8: Trip demand by taxi requests and private vehicle users.

(a) Travel time with real-time traffic information

(b) Travel time with historical traffic information
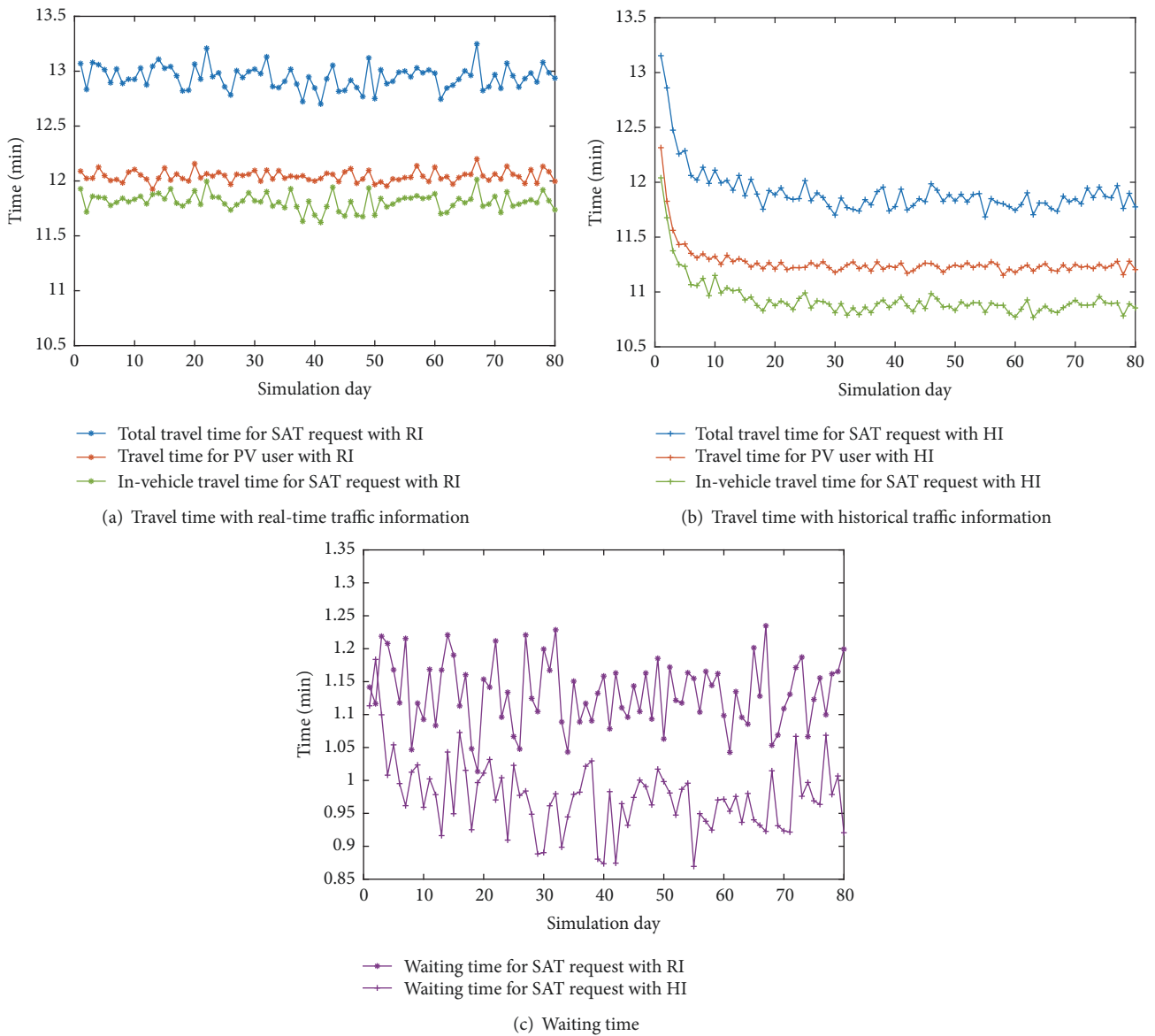

(c) Waiting time

FIGURE 9: Day-to-day changes in (a) travel time with RI, (b) travel time with HI, and (c) waiting time for SAT request and PV user (RI: real-time information; HI: historical information).
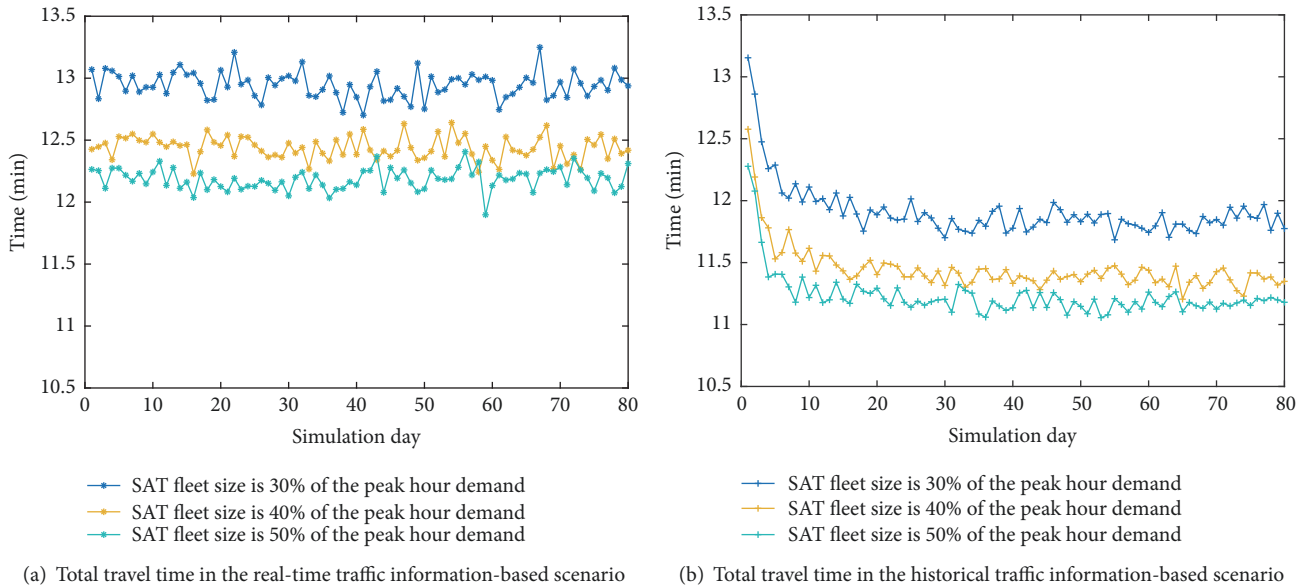
(a) Total travel time in the real-time traffic information-based scenario

(b) Total travel time in the historical traffic information-based scenario

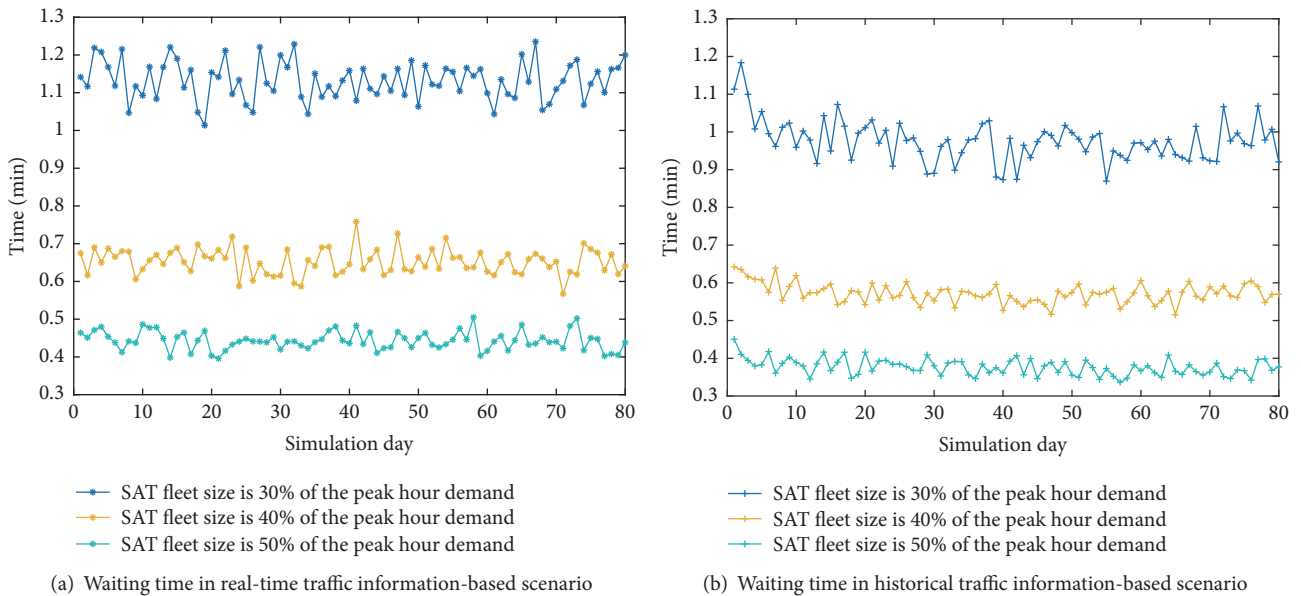FIGURE 10: Day-to-day changes in total travel time for taxi requests in SATS with several SAT fleet sizes.

(a) Waiting time in real-time traffic information-based scenario

(b) Waiting time in historical traffic information-based scenario

FIGURE 11: Day-to-day changes in waiting time for taxi requests in SATS with several SAT fleet sizes.

to a steady level. The stable travel times were also smaller than those in the real-time traffic information-based system, where the travel times fluctuated slightly around the constant values. The study results also indicate that insufficient fleet size in the SATS would nonlinearly worsen the service level of the SATS and that as the number of SATs increases, convergence occurs earlier in the historical information-based scenario.

Future study on this topic can focus on the relocation process of SATs. Routing strategies for SATs and information use under exogenous disturbances also need to be studied. The variation in SAT demand to the different service level should

be considered in our future research. This consideration will provide more realistic process until the convergence of traffic states. Another area of future research in order to offer a better level of service is examination of the effect of reassigning a new taxi to a request when the pick-up time of the assigned taxi increases owing to variations in traffic conditions.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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