Limited Information-Sharing Strategy for Taxi–Customer Searching Problem in Nonbooking Taxi Service

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One of the issues in current taxi service is the imbalance between supply and demand. In response to this issue, an automatic taxi-dispatching approach in which customers can book taxis through phones or mobile devices is widely used in many large cities worldwide. However, this approach is not satisfactory: most customers still prefer nonbooking taxi service (NBTS), taking the taxi by either waiting at a taxi stand or hailing one on the street. One important reason for this phenomenon is that customers take a lower risk in NBTS: they are free from complicated booking procedures and have no commitment to any as-yet-arrived taxis. To facilitate the taxi–customer matching process in NBTS, a novel control strategy is proposed—namely, the limited information-sharing strategy (LISS) for the taxi–customer searching problem in NBTS, in which both the taxi and the customer are equipped with mobile devices that can communicate with each other within limited searching ranges. The proposed LISS is based on the game theoretical formulation in which a learning algorithm to find the pure Nash equilibrium is developed. A microscopic traffic simulation model for evaluation of the LISS is developed. The simulation results show that the proposed LISS is an effective control strategy when taxi supply is low and will not increase the risk of the taxi driver in losing the total occupied time.

One issue in the taxi service market of today is the imbalance between taxi supply and demand (*1*), which may cause two negative impacts to the demand side and supply side of the taxi: one is the longer waiting time of customers at taxi stands or on the streets; the other is the longer cruising time of empty taxis. The two negative impacts not only waste social resources for both customers and taxi drivers but also cause environmental problems such as the emissions generated by taxis when they are searching and waiting for customers on the congested road network.

To alleviate the previous issues, automatic taxi-dispatching approaches have been widely used in many large cities worldwide, in which customers can book taxis directly through phones or mobile devices (*2, 3*). Compared with the traditional ways—hailing a taxi on the street or waiting at taxi stand—booking taxis through the dispatching system has more advantages: it provides an alternative way for customers and taxi drivers to find each other easily (*4*). However, one practical problem in adopting the dispatching system is that customers may not have a strong willingness to take taxis by booking. For example, in Singapore, the largest taxi company, ComfortDelGro, received an average of around 65,000 booking calls daily in 2010; however, these calls only accounted for about 17% of the total daily trips made by its taxi fleet (*5*). In Beijing, the taxi booking rate is even lower as compared with the case in Singapore (*6*). In other words, waiting at a taxi stand or hailing one on the street may still be the major and popular ways of getting taxis. To differentiate between taxi service with bookings and that without bookings, the following two terms are defined:

- "Booking taxi service" (BTS): taking taxis by booking through phones or mobile devices and
- "Nonbooking taxi service" (NBTS): taking taxis by either waiting at a taxi stand or hailing one on the street.

One obvious difference between these two types of taxi service is that customers need to reserve taxis in BTS but do not need to in NBTS. Furthermore, another important difference is that both taxis and customers who are searching for each other actually bear different levels of risk. For example, in BTS, the taxi takes a lower risk whereas the customer takes a higher one: once a taxi has confirmed a booking request, the customer who has made the booking should wait until the arrival of the taxi; however, in NBTS, the taxi takes a higher risk whereas the customer takes a lower one because the taxi–customer searching (or matching) process in NBTS is not bound by any agreement, so a customer can take any available taxi coming to his or her location, but a taxi receives no guarantee of finding a customer when it heads to a taxi stand.

Thus, the problem to be studied can be described as the taxi–customer searching problem (TCSP) in the NBTS (TCSP-NBTS). The objective of this study is an efficient control strategy for the TCSP-NBTS that not only improves the level of service in terms of reducing the customer waiting time (CWT) but also reduces (or mediates) the risk of taxis to a certain level when they are searching for customers.

Many modeling approaches for taxi service have been developed in recent years, mainly in the form of mathematical models and simulation models. Yang and others proposed a mathematical model for taxi service and performed a series of analyses (*7–9*). Cheng and Nguyen proposed a macroscopic simulation model for taxi service and studied the taxi fleet optimization problem (*10*). Both Lee et al. (*11*) and Seow and Lee (*4*) proposed microscopic simulation models to explore efficient dispatching approaches in the BTS: the former presented a

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Transportation Research Record: Journal of the Transportation Research Board, No. 2333, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 46–54.
DOI: 10.3141/2333-06

shortest-travel-time dispatching rule based on current traffic conditions, and the latter proposed an agent-based dispatching policy that enabled taxis to negotiate and cooperate with each other to achieve group objectives. There are still other studies on taxi service that are more or less based on or related to the aforementioned models (*12–15*).

However, the existing taxi modeling approaches are inadequate to study the control strategies for the TCSP-NBTS. On the one hand, the mathematical and macrosimulation models were formulated in highly aggregated forms, which makes it difficult to capture microlevel details such as dynamic customer behaviors (e.g., booking, cancellation) and the processes of control strategies (e.g., automatic dispatching, information sharing); on the other hand, even though microscopic simulation models could be used for studying taxi service and corresponding control strategies at a detailed level, dynamic customer behaviors were not considered. Moreover, the simulation-based models mostly focused on the BTS dispatching strategies but not the control strategies for NBTS. For these reasons, this study continues to model taxi service with the microscopic simulation approach and is integrated with more functions to meet the following research objectives:

- Model the TCSP-NBTS,
- Consider dynamic customer behaviors, and
- Propose and test a novel control strategy for the TCSP-NBTS, namely, the limited information-sharing strategy (LISS).

LISS is a decentralized control strategy that requires both the taxi and the customer to be equipped with mobile devices that can form an ad hoc network between them. Unlike other decentralized control strategies such as the agent-based dispatching approaches proposed by Seow and Lee (*4*), in which taxis could communicate with each other (but not with customers) to find the optimal solution, the proposed LISS will enable customers to communicate with taxis via mobile devices directly so as to reduce the taxi-to-taxi communication costs. The LISS proposed here will adopt the game theoretical formulation, which has been applied in a few other related areas, such as the vehicle–target assignment problem (VTAP) (*16–19*). The TCSP-NBTS is not simply a variant of VTAP but has the following distinctive characteristics:

- Dynamic behaviors of both the taxi and the customer need to be considered;
- Customers may wait at the same geographical locations, that is, queuing at the same taxi stand;
- The travel time between the taxi and the customer may be affected by road traffic conditions; and
- The definitions for the global utility of the game and the individual utility of the player (the taxi or the customer) in the game theoretical formulation may consider a number of theoretical and practical problems.

In summary, the ultimate goal of this study is to develop and test the devised LISS for the TCSP-NBTS. A microscopic traffic simulation is adopted in this research as the approach for modeling and analysis of taxi operations. A plug-in based on the application programming interfaces of the traffic simulator is designed to simulate the dynamic customer behaviors and the control strategies. The performance of the LISS will be evaluated and compared with the strategy without the LISS in terms of two performance indicators: the taxi occupancy rate (OR), or the ratio between the total occupied time and the total operating time of all taxis, and the CWT, or the average waiting time of all customers.

PROBLEM FORMULATION

The objective here is to develop a LISS for the TCSP-NBTS, which is expected to reduce the CWT and reduce (or mediate) the risk of the taxi (e.g., the probability of losing the total occupied time) to a certain level. Moreover, the taxi–customer negotiation process, which is the core process in LISS, will also be introduced.

Problem Assumptions

Assumptions for taxi operations and customer behaviors in the TCSP-NBTS and the limited information-sharing mechanism in LISS are presented in the following.

Taxi Operations

Taxis are assumed to be running freely on a road network $G = (V, E)$ where V is the set of nodes (junctions) and E is the set of links (road segments). A vacant taxi VT_i can pick up a customer or customers at a taxi stand $\mathrm{TS}_j \in \mathrm{TS} \subset V$, where TS is the set of all taxi stands (for simplification, but without loss of generality, the case of picking up customers on a road segment $V_k \in V$ will not be considered in this problem). If a taxi has no customer during the operating time, the driver will randomly choose a destination (e.g., a taxi stand) to look for a new customer; otherwise, the taxi will be heading to the destination of the customer who currently occupies it.

Customer Behaviors

The arrival of customers at a taxi stand $\mathrm{TS}_j \in \mathrm{TS}$ is modeled as a Poisson point process, which is similar to the modeling of service requests by Arsie et al. (*18*). Arrived customers will then be queued at taxi stands waiting for taxis to arrive. If a customer has been waiting at a taxi stand for more than a certain period of time but no taxi arrives, the customer may decide not to wait any longer. This period of time is defined as the maximum CWT.

Limited Information Sharing

Both the taxi and the customer are assumed to be equipped with mobile devices that can communicate with each other. These mobile devices can form an ad hoc network (e.g., IEEE 802.11 wireless networks) as a decentralized control system. The customers' devices are detectable during their waiting periods. One constraint is that each mobile device has only a limited searching range (e.g., 500 to 1,000 m); that is, a mobile device can only communicate with others located within its searching range but not those who are outside the range.

Taxi–Customer Negotiation Process

The taxi–customer negotiation process (TCNP) is designed as the core process in the LISS, which will be performed periodically in the system. It is assumed that at time t a new round of the TCNP, which can be denoted TCNP(t), is about to start; there are $N_{\mathrm{VT}}(t)$ number of vacant taxis running on different locations of the road network G. At the same time, there are $N_{\mathrm{WC}}(t)$ waiting customers at $N_{\mathrm{WTS}}(t)$ number of taxi stands. It is possible that $N_{\mathrm{WC}}(t) \geq N_{WTS}(t)$, which means that customers can be queuing at the same taxi stand. Then the TCNP(t)

will be performed to provide the solution to which taxi goes to which stand so that a global objective can be achieved.

This strategy requires no commitment from the customer, which is an important difference from other strategies such as automatic and agent-based dispatching (*4, 11*). In this problem, a customer can at any time leave the taxi stand or choose another taxi even if a yet-arrived vacant taxi has already decided to pick up the customer. The TCNP(t) only concerns the negotiation process in time t but not any future scenarios.

A number of methods can be adopted for performing and solving the TCNP, for example, the decentralized agent-based approach proposed by Seow and Lee (*4*), in which taxis could communicate directly with each other (but not with customers) to find the optimal solution in the BTS. However, because of the huge demand for NBTS, taxi-to-taxi communication will be at a considerably higher level in the TCNP. Thus, a game-theoretical formulation is adopted to perform and solve the TCNP, which is also a decentralized system. In this type of formulation, only taxi-to-customer communication is allowed so that the cost of taxi-to-taxi direct communication is saved. Therefore, the potential computational resource of the customer's mobile device can be utilized.

Game-Theoretical Formulation for TCNP

The game-theoretical formulation for the TCNP can be described as follows: at time t, let the $N_{\mathrm{VT}}(t)$ vacant taxis be denoted $\mathrm{VT}(t) = \{\mathrm{VT}_1(t), \dots, \mathrm{VT}_{N_{\mathrm{VT}(t)}}(t)\}$, and the $N_{\mathrm{WC}}(t)$ waiting customers are denoted $\mathrm{WC}(t) = \{\mathrm{WC}_1(t), \dots, \mathrm{WC}_{N_{\mathrm{WC}(t)}}(t)\}$. A vacant taxi $\mathrm{VT}_i(t)$ can only communicate with a limited number of waiting customers (because of the constraint of a limited searching range), namely, the candidate customers denoted as set $\mathrm{CC}_i(t) \subset \mathrm{WC}(t)$:

$$|\mathrm{CC}_i(t)| = N_{\mathrm{CC}_i(t)}$$

and

$$\mathrm{WC}(t) = \bigcup_{1 \le i \le N_{\mathrm{VT}}(t)} \mathrm{CC}_i(t)$$

The vacant taxi $VT_i(t)$ can decide to choose any waiting customer in $CC_i(t)$, and the decision of $VT_i(t)$ can be denoted $a_i(t)$. If $VT_i(t)$ has decided to choose $WC_j(t) \in CC_i(t)$, it can be said that $VT_i(t)$ has been engaged by $WC_j(t)$, or $a_i(t) = WC_j(t)$. $VT_i(t)$ can also not be engaged by any waiting customer. The set of decisions of vacant taxis $VT_i(t) \in VT(t)$ for all $I \in \{1, \dots, |VT(t)|\}$, namely, the decision profile, can be denoted $a(t) = \{a_1(t), \dots, a_{N_{VT}(t)}(t)\}$, where $a(t) \in A(t)$ and $A(t)$ is the set of all possible decision profiles. Let $a_{-i}(t)$ be the set of decisions of all vacant taxis except $VT_i(t)$, so that $\{a_i(t), a_{-i}(t)\} = a(t)$. Let $A_{-i}(t)$ be the set of all possible $a_{-i}(t)$ so that $a_{-i}(t) \in A_{-i}(t)$. Each decision profile can return a global utility $U_g(a(t))$, whose maximization is the objective of the TCNP, and each vacant taxi $VT_i(t)$ has a utility function $U_{VT_i}(a(t))$.

The TCNP is formulated as a multiplayer game in which taxis behave as noncooperative agents that can make independent decisions. To get the solution of the game, or the agreement among all taxis, the concept of the Nash equilibrium (NE) is introduced; at time t, an NE is a decision profile $a^*(t) = \{a_1^*(t), \dots, a_{N_{VT}(t)}^*(t)\}$ satisfying the concept that no vacant taxi $VT_i(t)$ can do better to improve its own utility $U_{VT_i}(a(t))$ by engaging another waiting customer different from $a^*(t)$ (*20*).

From the definition of NE, it can be seen that each vacant taxi $VT_i(t)$ will try to maximize the utility $U_{VT_i}(a(t))$ for achieving an NE in the TCNP(t); however, the ultimate objective of the TCNP(t) is to maximize the global utility $U_g(a(t))$. Thus, to link the two irrelevant utility functions, the concept of an ordinal potential game used for formulating and solving the VTAP used by Arslan et al. (*19*) is adopted here.

Constructing Ordinal Potential Game for TCNP

Definition 1. Ordinal Potential Games for TCNP An ordinal potential game for the TCNP has a potential function $\phi(a)$: $A \mapsto R$ such that for every vacant taxi $VT_i(t) \in VT(t)$ with the utility $U_{VT_i}(a(t))$, for every $a_{-i}(t) \in A_{-i}(t)$, and for every $a_i'(t), a_i''(t) \in CC_i(t)$:

$$U_{VT_i}(a_i'(t), a_{-i}(t)) - U_{VT_i}(a_i''(t), a_{-i}(t)) > 0$$
$$\Leftrightarrow \phi(a_i'(t), a_{-i}(t)) - \phi(a_i''(t), a_{-i}(t)) > 0$$

If the potential function $\phi(a(t))$ is substituted for the global utility $U_g(a(t))$:

$$U_{VT_i}(a_i'(t), a_{-i}(t)) - U_{VT_i}(a_i''(t), a_{-i}(t)) > 0$$
$$\Leftrightarrow U_g(a_i'(t), a_{-i}(t)) - U_g(a_i''(t), a_{-i}(t)) > 0$$

The motivation for introducing the concept of ordinal potential games in TCNP is to forge a tight link between the utility function of the taxi $U_{VT_i}(a(t))$ and the global utility function $U_g(a(t))$; that is, taxis will maximize their own utilities. This function improves the global utility at the same time. So the next step is to properly choose the utility function of the taxi and the global utility function so that an ordinal potential game can be formed.

Definition 2. Global Utility Function The global utility function $U_g(a(t))$ will be defined as the summation of all waiting customers' utilities, which is from the perspective of the customers:

$$\max U_g(a(t)) = \sum_{1 \le j \le N_{WC}(t)} U_{WC_j}(a(t)) \tag{1}$$

In Equation 1, $U_{WC_j}(a(t))$ is the utility function of the waiting customer $WC_j(t)$. The difference between the two types of utility functions, $U_{WC_j}(a(t))$ and $U_{VT_i}(a(t))$, is that $U_{WC_j}(a(t))$ is the benefit that a waiting customer $WC_j(t)$ can get when more than one vacant taxi may be engaged by him or her. Further, $U_{VT_i}(a(t))$ is the benefit that a vacant taxi $VT_i(t)$ can get when it has been engaged by a waiting customer. The following factors will be considered when $U_{WC_j}(a(t))$ is calculated:

- A waiting customer $WC_j(t)$ may have a maximum CWT, denoted MCWT_j, for waiting at the taxi stand;
- $WC_j(t)$ has been waiting for a time $\Delta t = t - t_{j,0}$, where $t_{j,0}$ is the customer's arrival time at the taxi stand;
- $WC_j(t)$ can engage more than one vacant taxi; the set of vacant taxis engaged by $WC_j(t)$ is denoted $ET_j(t)$, and $|ET_j(t)| = N_{ET_j(t)}$; and
- The travel time between the current locations of $VT_i(t)$ and $WC_j(t)$ is denoted $TT(i, j, t)$, and the estimated arrival time of that taxi is denoted $t_{j,1} = t + TT(i, j, t)$.

Then the waiting customer's utility function can be defined as follows:

$$U_{WC_j}(a(t)) = \max\left\{0, \mathrm{MCWT}_j - (t - t_{j,0}) - \min_{VT_i(t) \in ET_j(t)} [TT(i, j, t)]\right\} \tag{2}$$

Thus, the waiting customer's utility can be interpreted as the opportunity cost that the customer can save during his or her waiting period at the taxi stand.

Definition 3. Utility Function of Taxi If the vacant taxi $VT_i(t)$ has been engaged by the waiting customer $WC_j(t)$—that is, $a_i(t) = WC_j(t)$—the utility function of the taxi $VT_i(t)$ is defined as the difference between $WC_j(t)$'s utilities when $VT_i(t)$ has or hasn't been engaged by $WC_j(t)$.

$$U_{VT_i}\left(a_i(t), a_{-i}(t)\right) = U_{WC_j}\left(a_i(t), a_{-i}(t)\right) - U_{WC_j}\left(\phi, a_{-i}(t)\right) \quad \text{if } a_i(t) = WC_j(t) \qquad (3)$$

This type of definition is called the wonderful life utility, in which the utility of the taxi is defined as the marginal contribution to the utility of the taxi engaged by the customer (*21*). It turns out that Definitions 2 and 3 ensure that an ordinal potential game can be formed.

SOLUTION ALGORITHM

On the basis of the game-theoretical formulation for TCNP introduced earlier, the solution algorithm for periodically performing TCNP is proposed in this section. It is assumed that at time t when the new round of TCNP(t) is to be performed, the pseudo code for TCNP(t) is as shown in Table 1.

There are two important submodules in TCNP(t): one is the calculation of customer utility $CCU_j(k)$ performed by the waiting customer $WC_j(t)$; the other is the generalized regret monitoring with fading memory and inertia, G-RM-FM-$I_i(k)$, performed by the vacant taxi $VT_i(t)$, where k is the sequence number of the negotiation rounds of TCNP(t). These two submodules are introduced in detail in the following subsections.

Calculation of Customer Utility, $CCU_j(k)$

At the kth round of TCNP(t), each waiting customer $WC_j(t) \in WC(t)$ needs to calculate two utilities, namely, the primary utility $U_{WC_j}(a(t, k))$ and the secondary utility $U'_{WC_j}(a(t, k))$, and then send them to all vacant taxis engaged by the customer—that is, $VT_n(t) \in ET_j(t, k)$—for further negotiation purposes.

Definition of Primary Utility $U_{WC_j}[a(t, k)]$

At the kth round of TCNP(t), each waiting customer $WC_j(t) \in WC(t)$ has a set of engaged taxis $ET_j(t, k)$, where $|ET_j(t, k)| = N_{ET_j}(t, k)$. Then

EQUATION BOX 1 Pseudo Code for TCNP(t)

Input: Set of vacant taxis $VT(t)$ and set of waiting customers $WC(t)$
Output: $VT(t)$ allocated to $WC(t)$

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Phase 1. Initialization
  For Each vacant taxi VT_i(t)∈ VT(t)
  VT_i(t) constructs CC_i(t), which is the set of all waiting customers within VT_i(t)'s searching range
  Loop
Phase 2. Taxi–customer negotiation
  For k = 1:N, where N is the maximum number of negotiation rounds in TCNP(t)
    For Each vacant taxi VT_i(t)∈ VT(t)
      VT_i performs G-RM-FM-I_i(k) which may return a proposed waiting customer WC_m(t)∈ CC_i(t)
      If G-RM-FM-I_i(k) returns null
        Continue;
      Else
        VT_i(t) is engaged by WC_m(t), i.e., a_i(t, k) = WC_m(t)
        Insert VT_i(t) to ET_m(t, k), which is the set of vacant taxis engaged by WC_m(t) at time t, round k
      End If
    Loop
    Set U_g(a(t), k) = 0
    For Each waiting customer WC_j(t)∈ WC(t)
      WC_j(t) performs CCU_j(k), which sets U_WCj(a(t),k) and U'_WCj(a(t),k) to all VT_n(t)∈ ET_j(t, k)
      Set U_g(a(t),k) = U_g(a(t),k) + U_WCj(a(t),k)
    Loop
    If k > N
      Exit Loop
    Else
      k = k + 1
    End If
  Loop
Phase 3. Finalization
  For Each vacant taxi VT_i(t)∈ VT(t)
    VT_i(t) changes its direction based on the negotiation results from Phase 2
  Loop
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$$U_{WC_j}\left(a(t,k)\right)=\begin{cases}\max\left[0,\mathrm{MCWT}_j-(t-t_{j,0})-TT(i^*,j,t)\right] & \\ & \text{if } N_{ET_j(t,k)}>0\\ 0 & \text{if } N_{ET_j(t,k)}=0\end{cases}\tag{4}$$

where

$$TT\left(i^*,j,t\right)=\min_{VT_i(t)\in ET_j(t)}\left[TT\left(i,j,t\right)\right]$$

In other words, the waiting customer's primary utility $U_{WC_j}(a(t,k))$ is the utility that the waiting customer $WC_j(t)$ can get when the taxi is chosen in $ET_j(t,k)$ with the shortest travel time to him or her, and zero when no vacant taxi is engaged by $WC_j(t)$.

Definition of Secondary Utility $U'_{WC_j}[a(t,k)]$

At the kth round of TCNP(t), each waiting customer $WC_j(t)\in WC(t)$ has a set of engaged taxis $ET_j(t,k)$, where $|ET_j(t,k)|=N_{ET_j(t,k)}$. Then

$$U'_{WC_j}\left(a(t,k)\right)=\begin{cases}\max\left[0,\mathrm{MCWT}_j-\left(t-t_{j,0}\right)-TT(i^{**},j,t)\right] & \\ & \text{if } N_{ET_j(t,k)}>1\\ U_{WC_j}\left(a(t,k)\right) & \text{if } N_{ET_j(t,k)}=1\\ 0 & \text{if } N_{ET_j(t,k)}=0\end{cases}\tag{5}$$

where

$$TT\left(i^{**},j,t\right)=\min_{VT_i(t)\in ET_j(t),i\neq i^*}\left[TT\left(i,j,t\right)\right]$$

The waiting customer's secondary utility $U'_{WC_j}(a(t,k))$ can be interpreted as follows: if there is more than one vacant taxi engaged by $WC_j(t)$, and $VT_i^*(t)$ is the one with the shortest travel time to $WC_j(t)$, then $U'_{WC_j}(a(t,k))$ is the utility the waiting customer $WC_j(t)$ can get when he or she chooses the taxi in $ET_j(t,k)$ with the second-shortest travel time to him or her; if only one taxi is engaged by $WC_j(t)$, then $U'_{WC_j}(a(t,k))$ just equals the primary utility $U_{WC_j}(a(t,k))$; if no taxi is engaged by $WC_j(t)$, $U'_{WC_j}(a(t,k))$ equals zero.

The calculation of customer utility $\mathrm{CCU}_j(k)$ can facilitate the process of calculating the utilities in TCNP(t), which also ensures that the problem is an ordinal potential game throughout the entire TCNP(t).

Generalized Regret Monitoring with Fading Memory and Inertia, G-RM-FM-I$_i(k)$

At the kth round of TCNP(t), each vacant taxi $VT_i(t)\in VT(t)$ can choose to be engaged by a waiting customer $WC_m(t)\in CC_i(t)$; that is, $a_i(t,k)=WC_m(t)$. Since it is expected that the global utility $U_g(a(t))$ could converge after a certain round of negotiations, the approach G-RM-FM-I, is employed as the negotiation method. G-RM-FM-I$_i(k)$ needs feedback from the $\mathrm{CCU}_j(k-1)$ if $a_i(t,k-1)=WC_j(t)$, and G-RM-FM-I$_i(k)$ is performed before $\mathrm{CCU}_j(k)$, so G-RM-FM-I$_i(k)$ will not be performed for any vacant taxi $VT_i(t)$ in the first round ($k=1$) of the negotiation, and $VT_i(t)$ can make its proposal randomly in this round. The following steps elaborate how G-RM-FM-I$_i(k)$ works at the negotiation round as and when $k>1$.

Step 1. Calculate $U_{VT_i}(a(t,k-1))$, which is the utility of the vacant taxi $VT_i(t)$ with the wonderful life utility definition:

$$U_{VT_i}\left(a(t,k-1)\right)=\begin{cases}U_{WC_j}\left(a(t,k-1)\right) & \text{if } a_i(t,k-1)=\\ & WC_j(t)-U'_{WC_j}\left(a(t,k-1)\right),k>1\\ 0 & \text{if } a_i(t,k-1)=\phi,k>1\end{cases}\tag{6}$$

Step 2. Calculate $U_{VT_i}(CC_i^l(t),a_{-i}(t,k-1))$ for all $l\in\{1,\dots,|CC_i(t)|\}$. $U_{VT_i}(CC_i^l(t),a_{-i}(t,k-1))$ is the utility that the vacant taxi $VT_i(t)$ can get when it changes the choice to $CC_i^l(t)\in CC_i(t)$, whereas the choices of all other vacant taxis remain the same. Suppose that $CC_i(t)\neq\varphi$, and $VT_i(t)$ has been engaged by $WC_j(t)$ in round $k-1$; that is, $a_i(t,k-1)=WC_j(t)$. Four cases need to be considered in the calculation:

Case 1. If $CC_i^l(t)=WC_j(t)$, then

$$U_{VT_i}\left(CC_i^l(t),a_{-i}\left(t,k-1\right)\right)=U_{VT_i}\left(a\left(t,k-1\right)\right)\tag{7}$$

Case 2. If $CC_i^l(t)=WC_{j'}(t)$, where $j'\neq j$, and $N_{ET_{j'}(t,k-1)}=0$, then

$$\begin{aligned}U_{VT_i}\left(CC_i^l(t),a_{-i}\left(t,k-1\right)\right)&=U_{WC_{j'}}\left(CC_i^l(t),a_{-i}\left(t,k-1\right)\right)\\&\quad-U_{WC_{j'}}\left(a\left(t,k-1\right)\right)\\&=U_{WC_{j'}}\left(CC_i^l(t),a_{-i}\left(t,k-1\right)\right)-0\\&=\max\left[0,\mathrm{MCWT}_{j'}-\left(t-t_{j',0}\right)\right.\\&\quad\left.-TT\left(i,j',t\right)\right]\end{aligned}\tag{8}$$

Case 3. If $CC_i^l(t)=WC_{j'}(t)$, where $j'\neq j$ and $TT(i,j',t)\geq\min_{VT_{i'}(t)\in ET_{j'}(t,k-1)}[TT(i',j',t)]$, $N_{ET_{j'}(t,k-1)}>0$, then

$$U_{VT_i}\left(CC_i^l(t),a_{-i}\left(t,k-1\right)\right)=0\tag{9}$$

Case 4. If $CC_i^l(t)=WC_{j'}(t)$, where $j'\neq j$, and $TT(i,j',t)<\min_{VT_{i'}(t)\in ET_{j'}(t,k-1)}[TT(i',j',t)]$, $N_{ET_{j'}(t,k-1)}>0$, then

$$\begin{aligned}U_{VT_i}\left(CC_i^l(t),a_{-i}\left(t,k-1\right)\right)&=U_{WC_{j'}}\left(CC_i^l(t),a_{-i}\left(t,k-1\right)\right)\\&\quad-U_{WC_{j'}}\left(a\left(t,k-1\right)\right)\\&=\left[\mathrm{MCWT}_{j'}-\left(t-t_{j',0}\right)-TT\left(i,j',t\right)\right]\\&\quad-\left\{\mathrm{MCWT}_{j'}-\left(t-t_{j',0}\right)\right.\\&\quad\left.-\min_{VT_{i'}(t)\in ET_{j'}(t,k-1)}\left[TT\left(i',j',t\right)\right]\right\}\\&=\min_{VT_{i'}(t)\in ET_{j'}(t,k-1)}\left[TT(i',j',t)\right]-TT\left(i,j',t\right)\end{aligned}\tag{10}$$

Step 3. Calculate $\tilde{R}^{l}_{VT_i}(t, k)$ for all $l \in \{1, \ldots, |CC_i(t)|\}$:

$$\tilde{R}^{l}_{VT_i}(t,k) = \rho \tilde{R}^{l}_{VT_i}(t,k-1) + (1-\rho) R^{l}_{VT_i}(t,k) \quad \text{for all } l \in \{1,\ldots,|CC_i(t)|\} \tag{11}$$

where $R^{l}_{VT_i}(t, k) = U_{VT_i}(CC^{l}_{i}(t), a_{-i}(t, k-1)) - U_{VT_i}(a(t, k-1))$.

$\tilde{R}^{l}_{VT_i}(t, k)$ is the regret of the vacant taxi $VT_i(t)$ for not being engaging by $CC^{l}_{i}(t) \in CC_i(t)$ in the kth round of negotiation. $\tilde{R}^{l}_{VT_i}(t, k)$ can be interpreted as the accumulated regret of $VT_i(t)$ for not being engaged by $CC^{l}_{i}(t) \in CC_i(t)$ in its historical rounds of negotiation; $\rho \in (0,1]$ is the discount factor that enables each vacant taxi to have a fading memory, that is, let each vacant taxi discount the influence of its past regrets when $\tilde{R}^{l}_{VT_i}(t, k)$ is calculated.

Step 4. Calculate the probability distribution vector $P_i(k)$

$$P_i(k) = \alpha RM_i\left(\tilde{R}_{VT_i}(t,k)\right) + (1-\alpha)\,\mathbf{v}^{a_i(t,k-1)} \tag{12}$$

where

$$RM_i(x) = \frac{[x]^+}{\mathbf{1}^T [x]^+} \qquad \text{when } \mathbf{1}^T [x]^+ > 0 \tag{13}$$

- $\alpha \in (0,1]$ = willingness to propose a different waiting customer for $VT_i(t)$ at each round of negotiation, so that $1 - \alpha$ represents $VT_i(t)$'s inertia on proposal;
- $\mathbf{v}^{a_i(t,k-1)}$ = $|CC_i(t)|$-dimensional vector; and
- $v_l^{a_i(t,k-1)}$ = lth element of $\mathbf{v}^{a_i(t,k-1)}$.

If $a_i(t, k-1) = CC^{l}_{i}(t)$, then $v_l^{a_i(t,k-1)} = 1$; otherwise $v_l^{a_i(t,k-1)} = 0$, for all $l \in \{1, \ldots, |CC_i(t)|\}$. $[x]^+$ is an n-dimensional vector of which the ith element equals $\max(x_i, 0)$ if x is also an n-dimensional vector.

Step 5. $VT_i(t)$ is engaged by a waiting customer $WC_m(t) \in CC_i(t)$. On the basis of the probability distribution vector $P_i(k)$ calculated in Step 4, the vacant taxi $VT_i(t)$ will be engaged by a waiting customer $WC_m(t) \in CC_i(t)$ as the return value of G-RM-FM-I$_i(k)$. $VT_i(t)$ can also propose nothing and then G-RM-FM-I$_i(k)$ just returns a value of null.

It has been proved by Arslan et al. (*19*) that if a VTAP can form an ordinal potential game and each vehicle has no indifferent utility response to different strategies (or decisions), the G-RM-FM-I will almost surely enable the negotiation process to converge to a pure NE. The TCNP proposed here has the same properties as those in the case by Arslan et al. (*19*), so it also has the same convergence ability when the G-RM-FM-I is applied.

The NE obtained by G-RM-FM-I may be a suboptimal solution in terms of maximizing $U_g(a(t))$ for TCNP(t), which is a trade-off between the operational efficiency and the theoretical optimality. On one hand, even though there are negotiation mechanisms such as the spatial adaptive play that can lead to an optimal or near-optimal solution (*16*), those mechanisms are too time-consuming to be implemented in the TCNP, where states of both the taxi and the customer are changed quickly; on the other hand, the convergence tests by the simulation experiments in the next section show that G-RM-FM-I has a good convergence performance, which results in a better operational performance.

SIMULATION EXPERIMENTS

Microscopic Simulation Model

A microscopic simulation model is developed based on the concept of a customized simulation environment. It includes microscopic traffic simulation software—PARAMICS (*22*)—and a plug-in designed by programming with the application program interfaces, which enables the software to simulate the customer dynamic behaviors and the taxi operations as well as the LISS. A fictitious road network covering an area of around 3 km × 3 km is created in PARAMICS as shown in Figure 1, which includes two types of taxi stand:

- Taxi stands located within the study area (the boundary of the study area is shown by the dashed line in Figure 1) and
- Taxi stands located outside the study area (in fact, these taxi stands can be considered as located in the fringe areas adjacent to the study area).

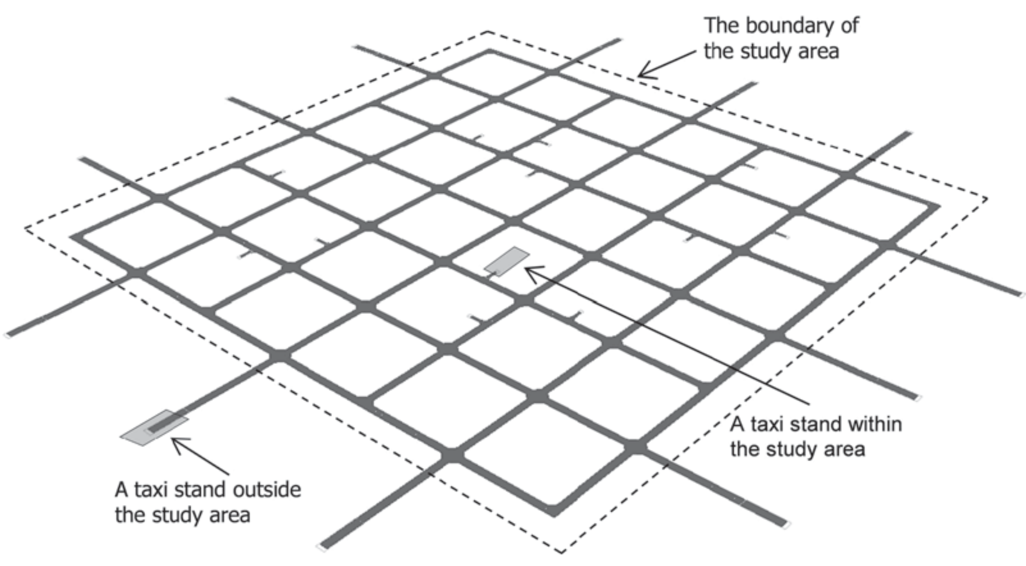


FIGURE 1 Road network for simulation.

In the simulation, the customer behaviors and taxi operations as well as the LISS are simulated strictly following the assumptions presented in the section on problem formulation. The customer demand is set to 400 arrivals/h for the taxi stands located outside the study area and 520 arrivals/h (30% higher) for the taxi stands located inside the study area. The purpose of this setting is to mimic the boom in customer demand of a specific area during a specific period of time, such as the central business district during the peak hour.

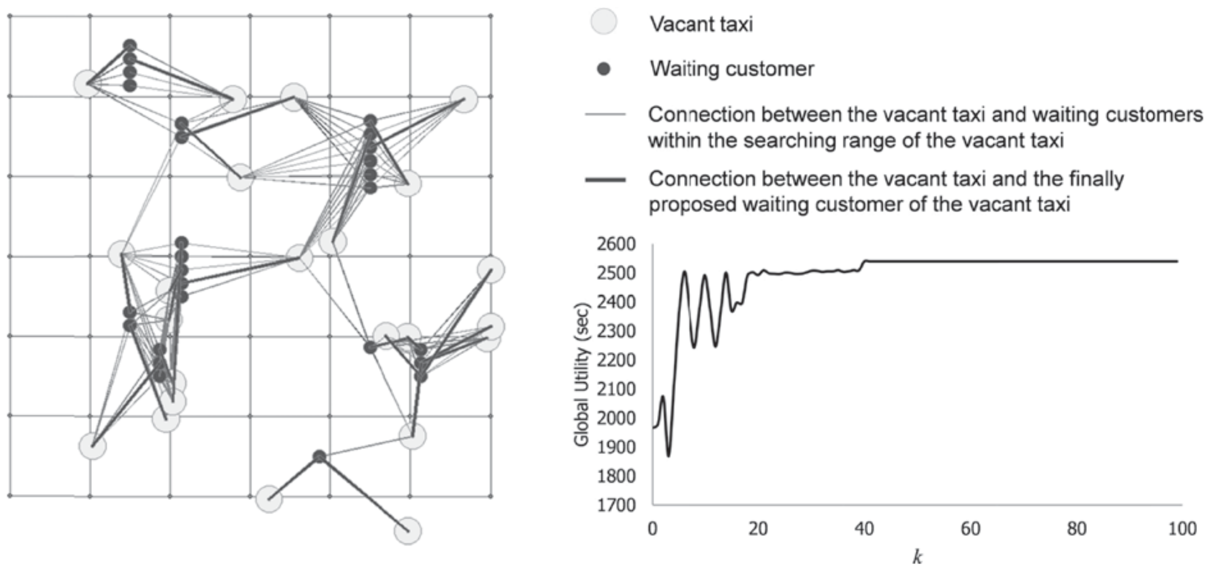
A sensitivity analysis is performed by varying the taxi fleet size from 100 to 250 at increments of 50 taxis, in which the performance of the LISS is evaluated and compared with the strategy without control (i.e., the free-search strategy) in terms of OR and CWT for each taxi fleet size.

Other parameters of the simulation are set as follows: in the LISS, the TCNP will be performed every 100 s, in which ρ and α are set to 0.1 and 0.5 for the submodule G-RM-FM-I$_i(k)$. The searching range of the taxi is set to 500 m. The maximum CWT of the customer is arbitrarily set to 1 h, which is purposely to test the maximum CWT. The total simulation period is 2 h with 20 min warm-up time.

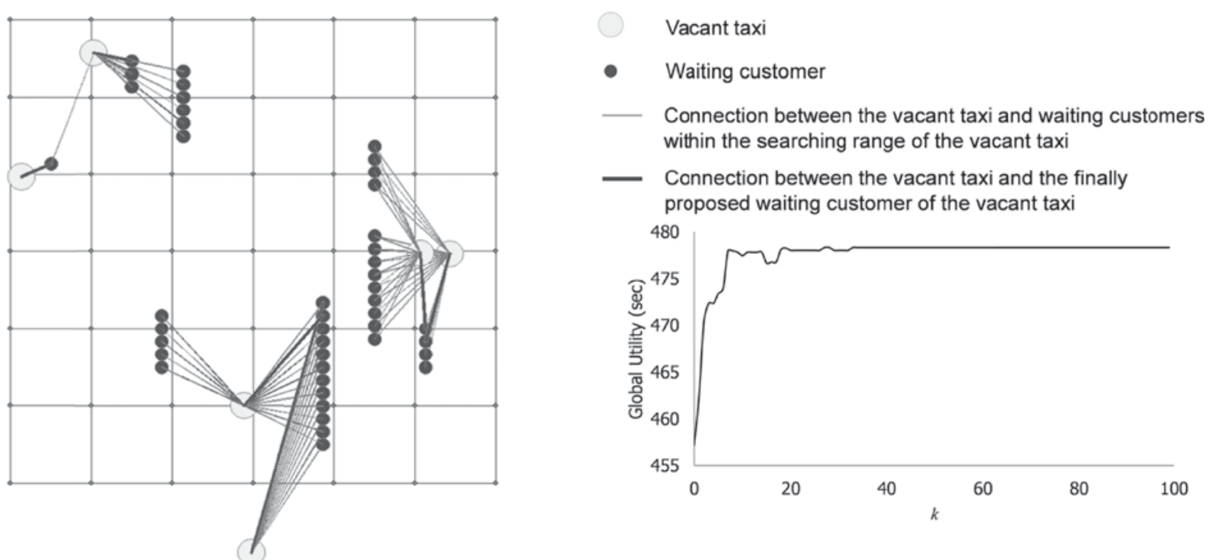
Simulation Results

Convergence Tests

The convergence tests for the TCNP in the case of taxi fleet size = 100 are shown in Figure 2. Figure 2*a* shows that the global utility converges in negotiation round $k = 40$ at $t = 1{,}200$ s, and Figure 2*b* shows that the global utility converges in negotiation round $k = 33$ at $t = 6{,}000$ s. The convergence tests show that the TCNP has good convergence performance.



(a)



(b)

FIGURE 2 Convergence tests for TCNP in LISS: (*a*) $t = 1{,}200$ s and (*b*) $t = 6{,}000$ s.

Sensitivity Analysis

The overall performance of the two strategies (free-search strategy and LISS) in terms of OR and CWT for different fleet sizes is shown in Figure 3.

For all taxi stands, as shown in Figure 3*a*, when the taxi supply is low (taxi fleet size < 175), the LISS can effectively reduce the CWT to around 50% (taxi fleet size = 100) compared with the free-search strategy. However, when the taxi supply is high (taxi fleet size > 175), the LISS is no better than the free-search strategy in terms of reducing the CWT. This result is because the number of available taxis is much higher in such a situation, so the customer can quickly find a taxi at the stand (even under the free-search strategy), which makes the LISS less attractive.

For taxi stands located within the study area, as shown in Figure 3*b*, when the taxi supply is low (taxi fleet size < 150), the LISS can effectively reduce the CWT to around 80% (taxi fleet size = 100) compared with the free-search strategy. When the taxi supply is high (taxi

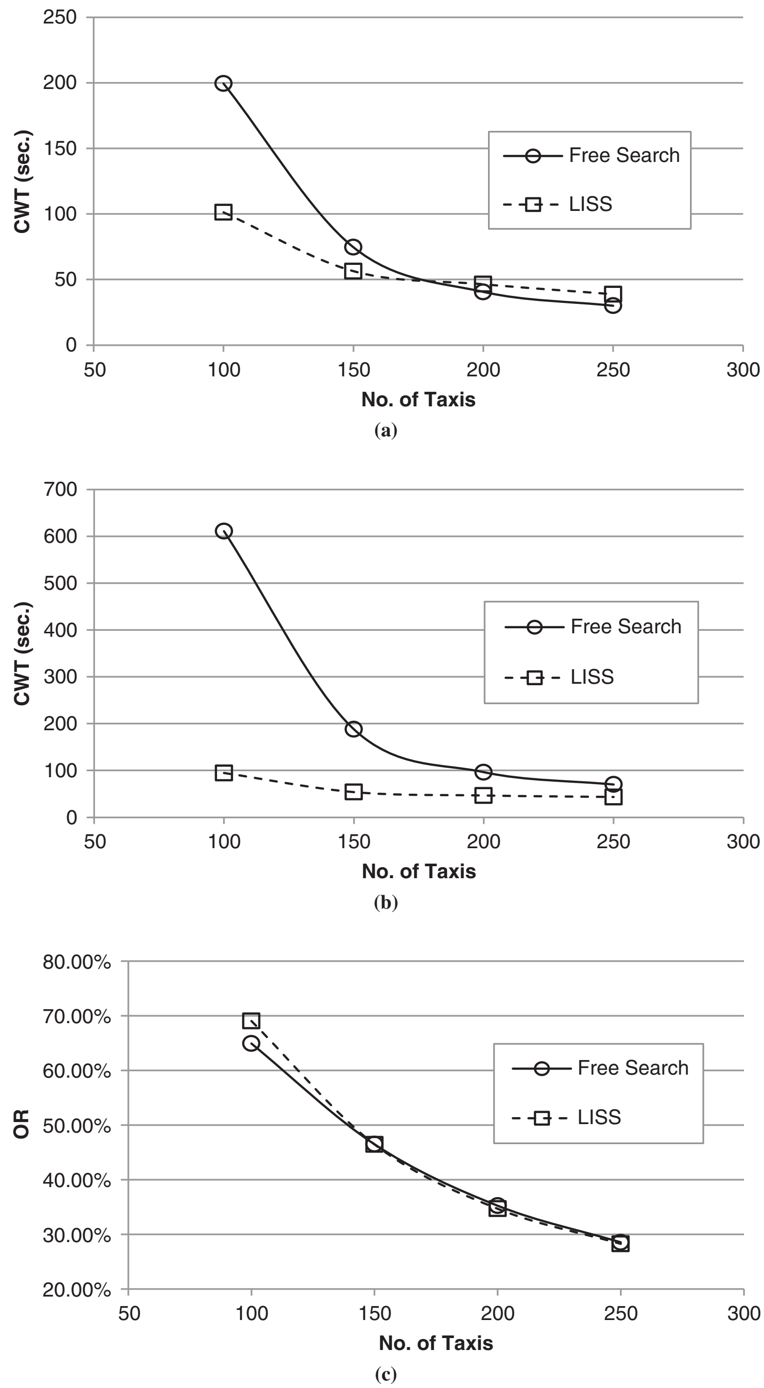


FIGURE 3 Overall performance of control strategies: (*a*) average CWT at all taxi stands, (*b*) average CWT at taxi stands within study area, and (*c*) overall performance of control strategies.

fleet size > 150), the LISS is still (slightly) better than the free-search strategy in terms of reducing the CWT.

As shown in Figure 3*c*, the OR of taxis under the LISS is no lower than that under the free-search strategy when the taxi supply is high (taxi fleet size > 150), and the OR of taxis under the LISS is slightly higher than that under the free-search strategy when the taxi supply is low (taxi fleet size < 150). This finding indicates that the LISS will not increase the risk of the taxi, that is, the probability of losing the total occupied time.

In all, the simulation results show that the LISS is an effective control strategy to reduce the CWT when the taxi supply is low, especially during a boom in customer demand in a specific area during a specific period of time, for example, the central business district during peak hours; moreover, the LISS will not increase the risk of the taxi even though it requires no commitment from the customer side, as stated earlier.

CONCLUSIONS AND FUTURE WORK

A novel control strategy is proposed, namely, the limited information-sharing strategy (LISS) for the taxi–customer searching problem (TCSP) in nonbooking taxi service (NBTS), or TCSP-NBTS. It offers the following contributions:

- Game theory was adopted to formulate the LISS; the global utility of the game and the individual utilities of the players (taxi and customer) are specifically defined by considering a number of theoretical and practical problems;
- A negotiation mechanism, the generalized regret monitoring with fading memory and inertia (G-RM-FM-I), was adopted in the LISS to find the Nash equilibrium (NE); and
- The operational performance of the LISS was evaluated by comparison with the strategy without any control (i.e., the free-search strategy).

Microscopic traffic simulation was adopted as the modeling approach. A sensitivity analysis by varying the taxi fleet size was conducted by the simulation in which the occupancy rate and the customer waiting time are calculated for all scenarios in each control strategy. Some implications were obtained from the results of the simulation experiments:

- The LISS is an effective control strategy when the taxi supply is low, especially for a boom in customer demand in a specific area during a specific period of time, for example, the central business district during peak hours, and
- The LISS will not increase the risk of a taxi even though it requires no commitment from the customer side.

Meanwhile, the microscopic simulation model developed for this research needs further improvement if it is employed for a larger study area (e.g., the entire island of Singapore) and for a long period of operation (e.g., 24 h of a typical day). That future work includes the following studies:

- Taxis' searching behaviors, such as the choice of destination for picking up passengers, in a large study area will be considered and modeled and
- The customers' elasticity in a long period of operating time will be considered and modeled.

REFERENCES

1. Santani, D., R. K. Balan, and J. C. Woodard. Spatio-Temporal Efficiency in a Taxi Dispatch System. Presented at 6th International Conference on Mobile Systems, Applications, and Services, Breckenridge, Colo., 2008.
2. Xu, Z. C., Y. F. Yuan, H. L. Jin, and H. Ling. Investigating the Value of Location Information in Taxi Dispatching Services: A Case Study of DaZhong Taxi. *Proc., 9th Pacific Asia Conference on Information Systems,* Bangkok, Thailand, 2005.
3. Liao, Z. Q. Taxi Dispatching via Global Positioning Systems. *IEEE Transactions on Engineering Management,* Vol. 48, 2001, pp. 342–347.
4. Seow, K. T., and D. H. Lee. Performance of Multiagent Taxi Dispatch on Extended-Runtime Taxi Availability: A Simulation Study. *IEEE Transactions on Intelligent Transportation Systems,* Vol. 11, 2010, pp. 231–236.
5. ComfortDelGro. *ComfortDelGro's Taxi Bookings Soar to a New Record of 24,000,000.* Publication ComfortDelGro, Singapore, 2011.
6. Beijing Taxi Dispatching Center. *Introduction of the Beijing Taxi Dispatching Center.* http://www.car-gps.com/Jkservice.html. Accessed 2010.
7. Yang, H., and S. C. Wong. A Network Model of Urban Taxi Services. *Transportation Research Part B: Methodological,* Vol. 32, 1998, pp. 235–246.
8. Yang, H., S. C. Wong, and K. I. Wong. Demand–Supply Equilibrium of Taxi Services in a Network Under Competition and Regulation. *Transportation Research Part B: Methodological,* Vol. 36, 2002, pp. 799–819.
9. Yang, H., and T. Yang. Equilibrium Properties of Taxi Markets with Search Frictions. *Transportation Research Part B: Methodological,* Vol. 45, 2011, pp. 696–713.
10. Cheng, S.-F., and T. D. Nguyen. TaxiSim: A Multiagent Simulation Platform for Evaluating Taxi Fleet Operations. *Proc., IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology (WI-IAT),* Lyon, France, IEEE, New York, 2011.
11. Lee, D.-H., H. Wang, R. L. Cheu, and S. H. Teo. Taxi Dispatch System Based on Current Demands and Real-Time Traffic Conditions. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1882,* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 193–200.
12. Aquilina, M. Quantity De-restriction in the Taxi Market Results from English Case Studies. *Journal of Transport Economics and Policy,* Vol. 45, 2011, pp. 179–195.
13. Sirisoma, R., S. C. Wong, W. H. K. Lam, D. Wang, H. Yang, and P. Zhang. Empirical Evidence for Taxi Customer-Search Model. *Proceedings of the Institution of Civil Engineers—Transport,* Vol. 163, 2010, pp. 203–210.
14. Kattan, L., A. de Barros, and S. C. Wirasinghe. Analysis of Work Trips Made by Taxi in Canadian Cities. *Journal of Advanced Transportation,* Vol. 44, 2010, pp. 11–18.
15. Chang, S.-K. J., and C.-H. Chu. Taxi Vacancy Rate, Fare, and Subsidy with Maximum Social Willingness-to-Pay Under Log-Linear Demand Function. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2111,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 90–99.
16. Chapman, A. C., A. Rogers, and N. R. Jennings. Benchmarking Hybrid Algorithms for Distributed Constraint Optimisation Games. *Autonomous Agents and Multi-Agent Systems,* Vol. 22, 2011, pp. 385–414.
17. Kalam, S., M. Gani, and L. Seneviratne. A Game-Theoretic Approach to Non-Cooperative Target Assignment. *Robotics and Autonomous Systems,* Vol. 58, 2010, pp. 955–962.
18. Arsie, A., K. Savla, and E. Frazzoli. Efficient Routing Algorithms for Multiple Vehicles with No Explicit Communications. *IEEE Transactions on Automatic Control,* Vol. 54, 2009, pp. 2302–2317.
19. Arslan, G., J. R. Marden, and J. S. Shamma. Autonomous Vehicle-Target Assignment: A Game-Theoretical Formulation. *Journal of Dynamic Systems Measurement and Control: Transactions of the ASME,* Vol. 129, 2007, pp. 584–596.
20. Osborne, M. J. *An Introduction to Game Theory.* Oxford University Press, New York, 2004.
21. Wolpert, D. H., and K. Tumer. Optimal Payoff Functions for Members of Collectives. *Advances in Complex Systems (ACS),* Vol. 4, 2001, pp. 265–279.
22. Quadstone. *Microscopic Traffic Simulation.* http://www.paramics-online.com. Accessed 2010.

The Transportation Network Modeling Committee peer-reviewed this paper.