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A NETWORK MODEL OF URBAN TAXI SERVICES

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Abstract—A network model is developed to describe how vacant and occupied taxis will cruise in a road network to search for customers and provide transportation services. The model can determine a number of system performance measures at equilibrium, such as vacant taxi movements and taxi utilization for a given road network and the customer origin–destination demand pattern. The effects of the taxi fleet size and the uncertainty on the system performances are explicitly taken into account. The model offers some interesting insights into the nature of the equilibrium of taxi services, and offers some policy-relevant results for decision making. These include the findings that the average taxi utilization decreases sharply with the number of taxis operating, and that the higher the taxi utilization, the larger the average customer waiting time. © 1998 Elsevier Science Ltd. All rights reserved

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1. INTRODUCTION

Taxis are an important means which offers a speedy, comfortable and direct transportation service in most urban areas. The regulations of the taxi service have grown immensely as a subject of city government concern. Taxi regulations are generally concerned with two primary issues: price and entry controls. Firstly, what restrictions, if any, should be placed on the supply of taxis? Secondly, what controls should be placed on fares? These two questions have been examined extensively by economists in a number of different ways (e.g. Orr, 1969; Douglas, 1972; Beesley, 1973; De Vany, 1975; Beesley and Glaister, 1983; Schroeter, 1983; Frankena and Pautler, 1986; Hackner and Nyberg, 1995; Arnott, 1996; Cairns and Liston-Heyes, 1996). These studies have been developed mainly based on an abstract, aggregate demand and supply model or based on a simplified, specific structural model of either a dispatching or cruising taxi service in either competitive or monopolistic markets. There are generally three fundamental assumptions underlying the models: (a) expected passenger waiting time depending on the total number of vacant taxi-hours; (b) the number of taxi rides demanded depending on the expected fare and the expected waiting time; and (c) the cost of operating a taxi being a constant per hour. With these assumptions, analytical economic analysis can be conducted to derive some descriptive conclusions concerning the consequences of taxi regulation.

For instance, Manski and Wright (1976) provided a specific structural model of a single taxi stand. Arrivals at the taxi stand occur according to a Poisson process with the arrival rate linear in fare per unit occupied time and in waiting time. The single queue is assumed to have exponentially distributed service times, first-in first-out service order. Recently, Arnott (1996) investigated

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the first-best operations of dispatch taxi services by considering a uniform customer demand distribution over a spatially homogenous two-dimensional city. He elaborated the result that taxi travel should be subsidized at the social optimum. Cairns and Liston-Heyes (1996) showed that price regulation is necessary to produce an equilibrium in a simple model of taxi service, but if only price regulation is attempted, the second best with no subsidization cannot be attained because of an externality among passengers. The second best can be achieved only if at least fares and intensity of use of taxi-cabs are regulated, but intensity of service may be difficult to monitor.

It is commonly realized that the supply and demand relationships for taxi services are much more complicated than they are for many goods and services used as examples in classical economic analyses. The principal characteristic that distinguishes the taxi service from those used for traditional competitive markets is the role of the intervening variables of taxi availability (expected passenger waiting time) and taxi utilization (expected fraction of time a taxi is occupied) through which the demand for and supply of taxi services are interrelated. Generally, in equilibrium the quantity (vacant and occupied taxi-hours) of service supplied will normally be greater than the quantity (occupied taxi-hours) demanded and actually utilized, that is, there will always be a certain amount of slack in the system. The amount of this slack (vacant taxi-hours) is the crucial factor in determining the average passenger waiting time, an important aspect of the level of service (De Vany, 1975; Abe and Brush, 1976; Manski and Wright, 1976; Foerster and Gilbert, 1979).

In reality, demand for and supply of taxi services take place over space, and thus equilibrium modeling of the problem should be conducted in connection with a detailed road network structure and a customer origin–destination (O–D) demand pattern as done in a conventional network traffic assignment. This would have important implications for both assessment of road traffic congestion due to taxi movements and precise understanding of the equilibrium nature of taxi service. In fact, a simple modal split model of taxis has been developed in Hong Kong for prediction of taxi person and vehicle matrices and incorporated as an important component in comprehensive transport studies. In the urban area of Hong Kong, taxis make considerable demands on limited road space even when empty and cruising for passengers. Taxis currently form about 25% of the traffic stream overall, in some locations such as Central and Waterloo Road in Kowloon, taxis form as much as 50–60% of the traffic stream (Transport Department, 1989, 1993). On the other hand, annual taxi service surveys (surveys at sampled taxi stands and roadside observation points) have been conducted since 1986 to gather the information on passenger/taxi waiting time, taxi utilization and taxi availability over the whole urban area and the new territories. This information has been efficiently used for the evaluation of taxi services and government decision-making with respect as to whether to increase the number of taxis and/or adjust taxi fares (Transport Department, 1986–1996). Recently, the survey data have been utilized to develop and calibrate a macroscopic simultaneous equation model of urban taxi services (Yang *et al.*, 1997).

This paper makes an initial attempt to model urban taxi services at a network level. We develop a network model to describe how both vacant and occupied taxis will circulate over a given network to search for customers and provide transportation services with a given customer O–D demand pattern. The model attempts to deal explicitly with the impact of the taxi fleet size and the uncertainty on various system performance measures at equilibrium, and thus provide information for government decision-making about taxi regulations. In the next section, we introduce the network model of taxi services. In Section 3, we develop a simple algorithm for solving the model, and in Section 4, we introduce some effectiveness measures for system performances. In Section 5, a numerical example is presented, and a summary and suggestions for future studies are provided in Section 6.

2. THE MODEL

2.1. Basic assumptions

Consider a road network $G(V,A)$ where V is the set of vertices (nodes) and A is the set of arcs (links) in the network. Suppose stationary taxi movements and customer demands exist in the network. In any given hour, the number of customers demanding taxi ride from origin zone i to destination zone j is D_{ij} (trips/hour), D_{ij} is assumed to be fixed and given (demand elasticity is not considered here). Let I and J be the set of customer origin and destination zones, respectively, and $O_i = \sum_{j \in J} D_{ij}$ and $D_j = \sum_{i \in I} D_{ij}$ be the customer trip ends at $i \in I \subset V, j \in J \subset V$, respectively. Let

h_a be the travel time on link $a \in A$, and h_{ij} be the travel time via the shortest path from origin $i \in I \subset V$ to destination $j \in J \subset V$, both times measured as a fraction of an hour. For simplicity, h_a and h_{ij} are assumed to be constant (traffic congestion is not considered here).

Suppose that there are N cruising taxis operating in the network. It is assumed that all occupied taxies will follow an 'all-or-nothing' routing behavior. Namely, a taxi, once occupied by a customer at origin $i \in I$, will move to the customer's destination $j \in J$ via the shortest path. Once a customer ride is completed, the taxi becomes vacant and cruises either in the same zone or goes to other zones to seek its next customer. In doing this, each taxi driver is assumed to attempt to minimize his/her expected search time required to meet the next customer.

2.2. *Taxi service time constraint*

Consider one *unit* period (1 h) operations of taxis in the network with a given customer demand in a stationary state. The total occupied time (TOT) of all taxis is the taxi-hours required to complete all $T^o_{ij} = D_{ij}$, $i \in I, j \in J$ trips, and is thus given by

$$\mathrm{TOT} = \sum_{i \in I} \sum_{j \in J} T^o_{ij} h_{ij} \tag{1}$$

where T^o_{ij} is the occupied taxi movements (vehicle h^{-1}) from zone $i \in I$ to $j \in J$. On the other hand, the total unoccupied time (TUT) consists of the moving (searching) times of vacant taxis from zone to zone and waiting (searching) times within zones. This time is given by

$$\mathrm{TUT} = \sum_{j \in J} \sum_{i \in I} T^v_{ji} \{h_{ji} + w_i\} \tag{2}$$

where T^v_{ji} is the vacant taxi movements (vehicle h^{-1}) from zone $j \in J$ to $i \in I$; w_i, $i \in I$ is the taxi waiting time at zone $i \in I$.

The sum of occupied taxi-hours TOT and vacant taxi-hours TUT should be equal to the total taxi service time. Therefore, the following taxi service time constraint must be satisfied in view of the 1 h period modeled here:

$$\sum_{i \in I} \sum_{j \in J} T^o_{ij} h_{ij} + \sum_{j \in J} \sum_{i \in I} T^v_{ji} \{h_{ji} + w_i\} = N \tag{3}$$

2.3. *Behavior of taxi drivers*

Once a customer ride is completed at a destination zone $j \in J$, the taxi driver could either stay in the same zone or move to other zones to find a customer. We suppose each driver tries to minimize individual expected search time required to meet the next customer, and the expected search time in each zone is a random variable due to variations in perceptions and the random arrival of customers. This random variable is assumed to be identically distributed with a Gumbel density function. With these behavior assumptions, the probability that a vacant taxis originating in zone $j \in J$ meets a customer eventually in zone $i \in I$ is specified by the following logit model:

$$P_{i/j} = \frac{\exp\{-\theta(h_{ji} + w_i)\}}{\sum_{m \in I} \exp\{-\theta(h_{jm} + w_m)\}}, \quad \text{for any } i \in I,\ j \in J \tag{4}$$

where $P_{j/j}$ when $i = j$ represents the probability of a taxi that takes a customer to zone j to search and meet the next customer in the same zone, θ is a nonnegative parameter that can be calibrated from observational data. The value of θ reflects the degree of uncertainty on customer demand and taxi services in the whole market from the perspective of individual taxi drivers. A small value of θ means a large random variation is present, and less information on the whole market is available to taxi drivers. On the other hand, if θ is very large, the random error is small and/or more information is available, drivers will tend to choose a zone that requires less expected search time to meet a customer. In particular, as θ tends to infinite, our model will lead to a deterministic case where perfect information is available concerning searching time.

We mention that since a meeting between a waiting customer and a vacant taxi in a particular zone is characterized by a logit-based probability, our model does not exclude the possibility that a vacant taxi passes through some zones before meeting a customer. In fact, similar probabilistic search model can be derived based on an opportunity model which could have a close representation of the taxi driver's search behavior, or from an entropy–maximization distribution model of vacant taxi movements.

In a stationary equilibrium state, the movements of vacant taxis over the network should meet the customer demands at all origin zones, or every customer will eventually receive taxi service after the waiting and searching process. Since there are D_j taxis to complete services at destination zone $j \in J$ per hour, we thus have

$$\sum_{j \in J} D_j \cdot P_{i/j} = O_i, \quad i \in I \tag{5}$$

In eqns (4) and (5), O_i, D_j, h_{ij}, $i \in I, j \in J$ are given exogenously, w_i, $i \in I$ are treated as endogenous variables. Note that once w_i, $i \in I$ are determined, $P_{i/j}$, $i \in I$, $j \in J$ will be specified uniquely, we thus have $|I|$ variables, w_i, $i \in I$, to be determined, where $|I|$ represents the number of customer origin zones, and we have $|I|$ equation constraints specified in eqn (5). However, there is one dependent equation in the system of eqns (5) in view of the following fact:

$$\sum_{i \in I} \left\{ \sum_{j \in J} D_j \cdot P_{i/j} \right\} = \sum_{j \in J} D_j \left\{ \sum_{i \in I} P_{i/j} \right\} = \sum_{j \in J} D_j = \sum_{i \in I} O_i = \text{ const. since } \sum_{i \in I} P_{i/j} = 1 \tag{6}$$

In fact, one additional constraint of eqn (3) must be satisfied. Consequently, we have $|I|$ independent equations that can uniquely determine the values of $|I|$ variables, w_i, $i \in I$, for a given total number of taxis N and the customer demand pattern D_{ij}, $i \in I, j \in J$.

2.4. *Minimum taxi fleet size*

For a given demand pattern of customers in the network, taxi fleet size makes a great impact on the level of service (taxi availability or customer waiting time) and taxi utilization. If the fleet size is large, taxi availability (a possible measure could be the expected waiting time of customers and/or vacant taxi headways on the roads) might increase, whereas taxi utilization (a possible measure could be the expected fraction of time a taxi is occupied) will decrease, and vice verse. In particular, if the fleet size is too small, a steady-state equilibrium solution may not exist.

We thus consider the minimum taxi fleet required to ensure the existence of a stationary equilibrium state. Equation (3) actually indicates the relationship between taxi fleet size and taxi movements under stationary operations. Therefore, the minimum taxi fleet can be found by minimizing the left-hand side of eqn (3) with respect to w_i, $i \in I$ subject to the behavior constraint (4) of taxi drivers and demand balance eqn (5).

If all taxi drivers follow a central dispatching strategy such as in a monopolistic taxi market, then w_i, $i \in I$ must be zero at the minimum number of taxis operating. Since the first-term of the left-hand side of eqn (3) is a constant, minimizing the fleet size N requires that the second term is minimized. Thus the minimum fleet size can be determined from the following optimal dispatching problem of vacant taxis (all taxis are guided by a central manager with full information of customer demand):

$$\text{minimize } F(T_{ji}^{v}) = \sum_{j \in J} \sum_{i \in I} T_{ji}^{v} h_{ji} \tag{7}$$

subject to

$$\sum_{j \in J} T_{ji}^{v} = \sum_{j \in J} D_{ij} \tag{8}$$

$$\sum_{i \in I} T_{ji}^{v} = \sum_{i \in I} D_{ij} \tag{9}$$

Constraint eqn (8) is the taxi supply equation, which means that, in a steady-state of equilibrium, the number of taxis to become available or vacant in a zone should be equal to the total number of customers whose destination is that zone, constraint (9) is the demand equation, which means that the taxis should be dispatched so that all customers will eventually receive taxi service.

Denote the optimal solution of problem (7)–(9) as $T_{ji}^{v^*}$, $j \in J$, $i \in I$. Then the minimum taxi fleet size to satisfy the given customer demand is given by

$$N_{\min} = \sum_{i \in I} \sum_{j \in J} D_{ij} h_{ij} + \sum_{j \in J} \sum_{i \in I} T_{ji}^{v^*} h_{ji} \tag{10}$$

3. A SOLUTION ALGORITHM

Since eqn (5) contains an extra constraint, as mentioned earlier, we can drop one equation associated with any origin zone $z \in I$ where z is an arbitrarily selected origin zone. Substituting eqn (4) into eqn (5) and rearranging the equations, we have

$$\exp\,(-\theta w_i)\cdot \sum_{j \in J} \frac{D_j \cdot \exp\{-\theta h_{ji}\}}{\sum_{m \in I} \exp\{-\theta (h_{jm} + w_m)\}} = O_i, \quad i \in I$$

Taking logarithms of both sides gives rise to

$$w_i = -\frac{1}{\theta} \ln O_i + \frac{1}{\theta} \ln \left\{ \sum_{j \in J} \left(\frac{D_j \exp(-\theta h_{ji})}{\sum_{m \in I} \exp\{-\theta (h_{jm} + w_m)\}} \right) \right\}, \quad i \in \{I - z\} \tag{11}$$

Furthermore, solving eqn (3) for taxi waiting time, w_z, at the particular selected origin zone z, we have

$$w_z = \frac{N - \sum_{i \in I} \sum_{j \in J} (T_{ij}^{o} h_{ij} + T_{ji}^{v} h_{ji}) - \sum_{i \in \{I - z\}} \sum_{j \in J} T_{ji}^{v} w_i}{\sum_{j \in J} T_{jz}^{v}} \tag{12}$$

Therefore, eqns (11) and (12) constitute a system of nonlinear equations which can be solved using the following fixed-point algorithm:

Step 0. Set a set of initial values, $w_i^{(0)}$, $i \in I$. Let $k = 0$.

Step 1. Calculate vacant taxi movements according to:

$$T_{ji}^{v(k)} = D_j P_{i/j}^{(k)} = D_j \frac{\exp\{-\theta (h_{ji} + w_i^{(k)})\}}{\sum_{m \in I} \exp\{-\theta (h_{jm} + w_m^{(k)})\}}, \quad i \in I, j \in J$$

Step 2. Update taxi waiting times w_i, $i \in I$ according to:

$$w_z^{(k+1)} = \frac{N - \sum_{i \in I} \sum_{j \in J} (T_{ij}^{o} h_{ij} + T_{ji}^{v(k)} h_{ji}) - \sum_{i \in \{I - z\}} \sum_{j \in J} T_{ji}^{v(k)} w_i^{(k)}}{\sum_{j \in J} T_{jz}^{v(k)}}$$

$$w_i^{(k+1)} = -\frac{1}{\theta}\ln O_i + \frac{1}{\theta}\ln\left\{\sum_{j\in J}\left(\frac{D_j \exp(-\theta h_{ji})}{\sum_{m\in I}\exp\{-\theta(h_{jm} + w_m^{(k)})\}}\right)\right\}, \quad i \in \{I - z\}$$

Step 3. If $|w_i^{(k+1)} - w_i^{(k)}| \leqslant \varepsilon$ for all $i \in I$ then stop where ε is a predetermined convergence tolerance. Otherwise, let $k := k + 1$ and return to Step 1.

4. SYSTEM PERFORMANCE MEASURES

For a given network we can determine the equilibrium solution of the model eqns (3)–(5) using the fixed-point algorithm if the customer O–D demand and the number of taxis are given. We are thus able to evaluate the system efficiency of the taxi services based on the equilibrium solution. The following various measures of system performances are introduced.

4.1. Vacant taxi headway

A closely relevant measure of taxi availability is the average vacant taxi headway on all roads.

$$\bar{H}^{vt} = \frac{\sum_{a\in A} H_a^{vt}}{|A|} \tag{13}$$

where $|A|$ is the number of links in the network (number of elements in A), H_a^{vt} is the headway of vacant taxis on link $a \in A$, which can be measured on a road link for the purpose of model calibration (Wong and Yang, 1997); $\bar{H}^{vt}$ is the average vacant taxi headway over all links in the network. We mention that $\bar{H}^{vt}$ will depend on the O–D distribution pattern of customer demand. If customer O–D distribution is symmetrical ($O_i \approx D_i$ for all $i \in I$), a higher value of $\bar{H}^{vt}$ would be expected. Note that $1/\bar{H}_{vt}$ is the flow rate of vacant taxis, and could be considered one of the measures of system inefficiency. A larger value of $1/\bar{H}_{vt}$ means higher extravagant taxi movements that add to traffic congestion, environmental pollution, as well as fuel consumption.

4.2. Average taxi waiting time

The expected waiting or search time of taxis for customers will vary across origin zones; we thus adopt the weighted average waiting time that could be considered as one of the measures of taxi utilization.

$$\bar{W}_t = \frac{\sum_{i\in I} O_i w_i}{\sum_{i\in I} O_i} \tag{14}$$

where $\bar{W}_t$ is the average taxi waiting time in the system. Note that the number of taxis that search for and eventually meet customers per unit time at each origin zone must be equal to the total customer demand at the same zone in a stationary equilibrium.

4.3. Average taxi utilization

A more accurate measure of taxi utilization is the ratio of total occupied taxi-hours to total taxi-hours in service (the expected fraction of time a taxi is occupied):

$$\bar{U}_t = \frac{\sum_{i\in I}\sum_{j\in J} D_{ij} h_{ij}}{N} \tag{15}$$

Clearly, $\bar{U}_t$ reflects profitability of the taxi service market at a regulated price.

Note that customer waiting time is an important measure of the level of taxi services, but it cannot be determined directly from our model, and thus is not pursued here. We also mention that all the aforementioned system performance measures will depend on the number of taxis, N, supplied to the market for given customer demand, D_{ij}, $i \in I$, $j \in J$ on the network, and the value of uncertainty parameter θ in the logit model.

5. A NUMERICAL EXAMPLE

Here we present a simple numerical example to illustrate the convergence of the fixed-point algorithm and highlight some interesting characteristics of the taxi traffic problem considered above. The network is depicted in Fig. 1 with twelve customer O–D pairs. Link travel time and customer O–D demand are presented in Tables 1 and 2, respectively.

The convergence of the iterative fixed-point algorithm in terms of the changes of taxi search times w_i, $i \in I$ vs the number of iterations is shown in Fig. 2. The algorithm approaches the final convergent equilibrium point in approximately six iterations for this simple network example in the case of $\theta = 5.0$, $N = 300$.

The various system performance measures versus taxi fleet size, N, and uncertainty parameter θ are shown in Figs 3–7. Specifically, Fig. 3 depicts a graph of the minimum taxi fleet required for the existence of a stationary network equilibrium. In a monopolistic taxi market with a central optimal dispatching strategy, the minimum taxi fleet is obtained by solving the linear program (7)–(9), and the minimum number of taxis is 93 (exactly, 92.25). In a regulated competitive market, the minimum taxi fleet is dependent upon the value of uncertainty parameter θ, their relationships

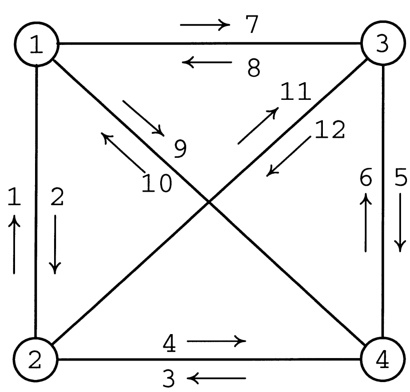

Fig. 1. A simple network used for numerical example.

Table 1. Link travel time for network in Fig. 1

Link no.	Start	End	Travel time (h)
1	2	1	0.25
2	1	2	0.25
3	4	2	0.20
4	2	4	0.20
5	3	4	0.25
6	4	3	0.25
7	1	3	0.30
8	3	1	0.30
9	1	4	0.35
10	4	1	0.35
11	2	3	0.30
12	3	2	0.30

Table 2. Customer origin–destination demand for network in Fig. 1

	1	2	3	4	O_i
1	0	50	20	20	90
2	40	0	15	25	80
3	20	10	0	50	80
4	10	20	30	0	60
D_j	70	80	65	95	310

are shown in the same figure. The minimum required taxi fleet is obtained by increasing the number of taxis one by one until all nonnegative values of taxi waiting times, w_i, $i \in I$ are obtained using the fixed-point algorithm. Clearly, as parameter θ increases or as taxi drivers have better knowledge of customer demand and other taxi movements, the minimum required number of taxis operating would decrease because the search time of vacant taxis for customers is reduced. In the

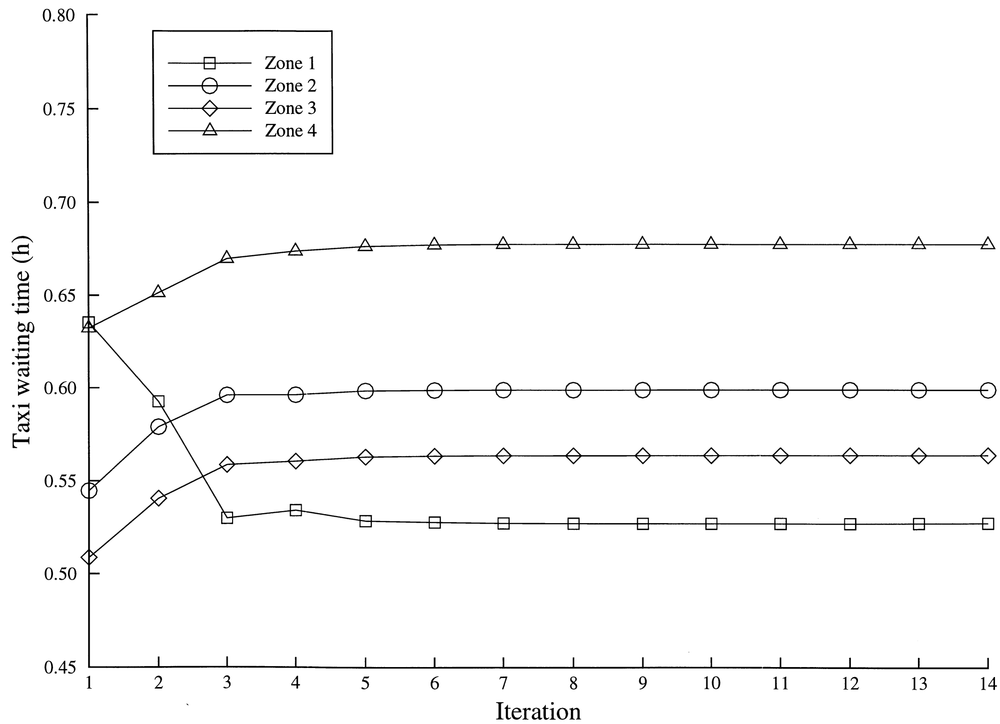

Fig. 2. Convergence of the fixed-point algorithm in terms of the changes of taxi waiting time with respect to iteration numbers for $\theta = 5.0$, $N = 300$.

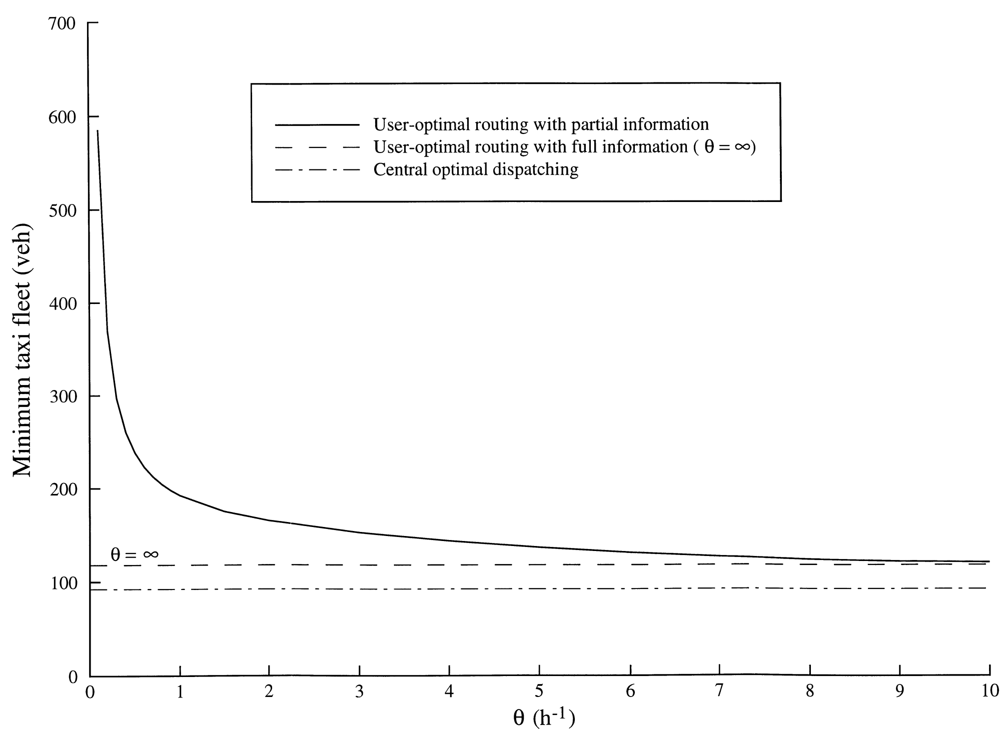

Fig. 3. Minimum taxi fleet size vs uncertainty parameter.

most extreme case, as in $\theta \to \infty$, the minimum required number of taxis is about 118, that being 25 more than at system-optimal dispatching. In this case, all individual taxi drivers have full information of the market and follow a user-optimal routing strategy.

Figure 4 depicts the relationship between the average vacant taxi headway over all links vs taxi fleet size with varied values of uncertainty parameters. It is noteworthy that the overall average

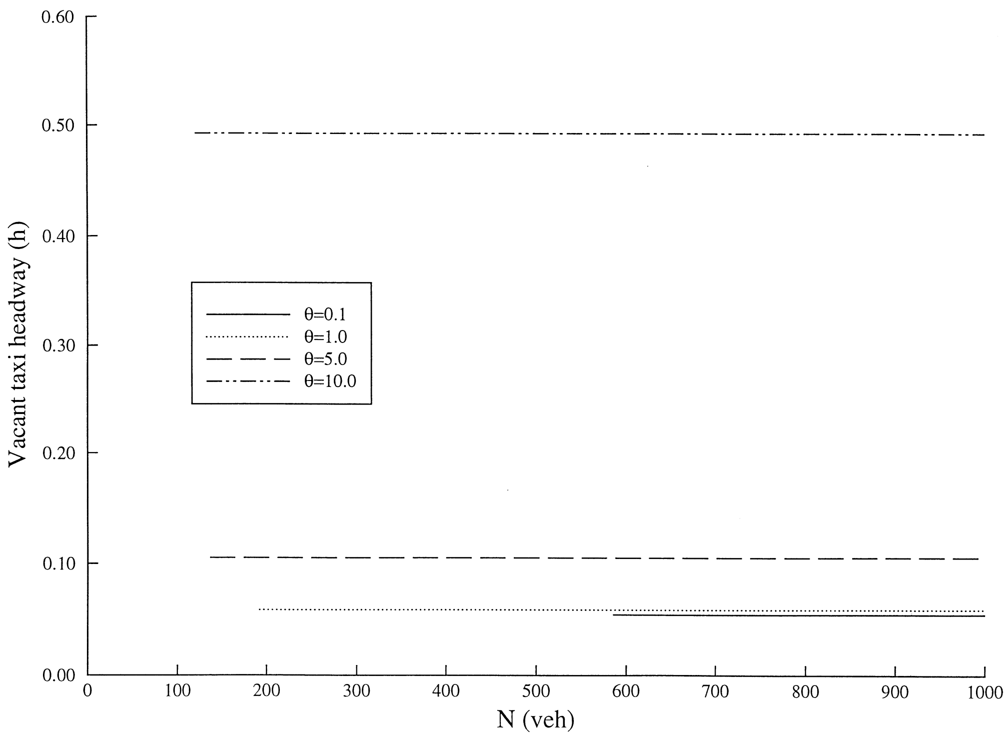

Fig. 4. Average vacant taxi headway vs taxi fleet size with varied values of uncertainty parameter.

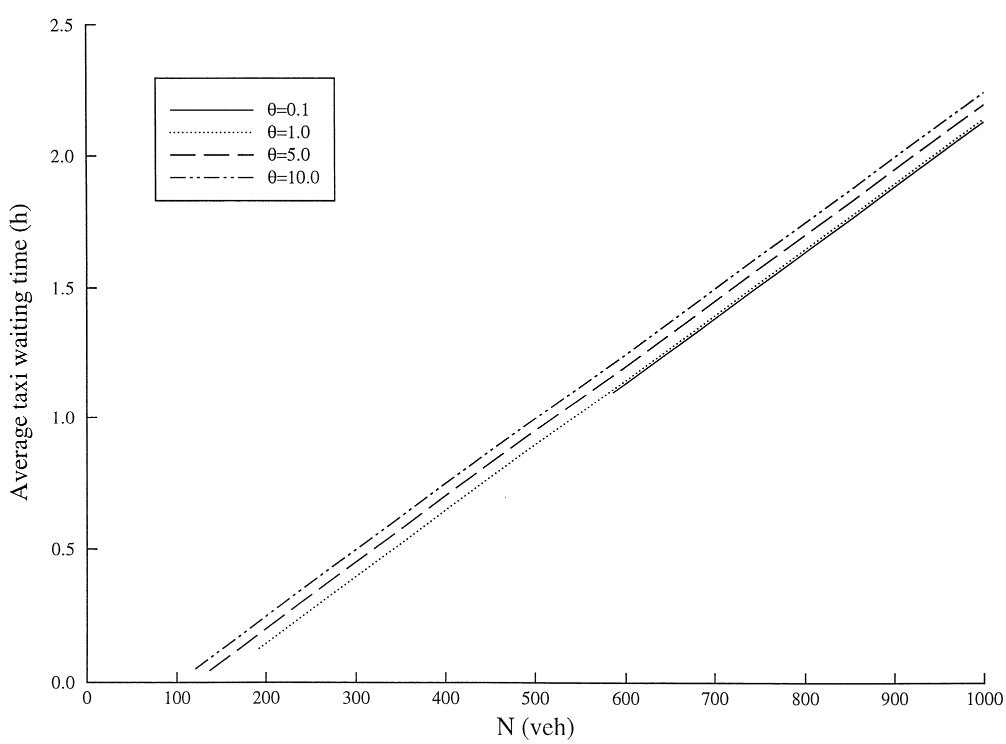

Fig. 5. Average taxi waiting time vs taxi fleet size with varied values of uncertainty parameter.

vacant taxi headway is almost constant irrespective of taxi fleet size, but depends greatly on the value of uncertainty parameter. This is intuitively understandable because taxi drivers will tend to choose and stay in a zone to find a customer if they have a clear picture of the customer demand pattern over the whole city; otherwise they will tend to circulate randomly over the network in search of a customer. Indeed, as shown in Figs 5 and 6, the average taxi waiting time increases

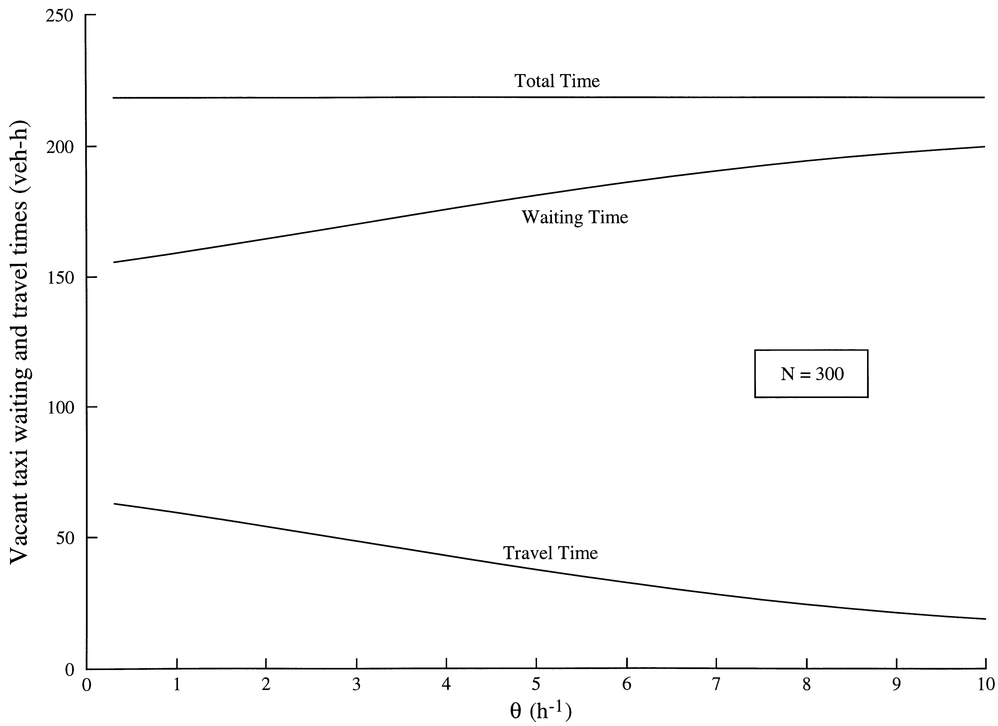

Fig. 6. Total taxi waiting time and running time vs the value of uncertainty parameter.

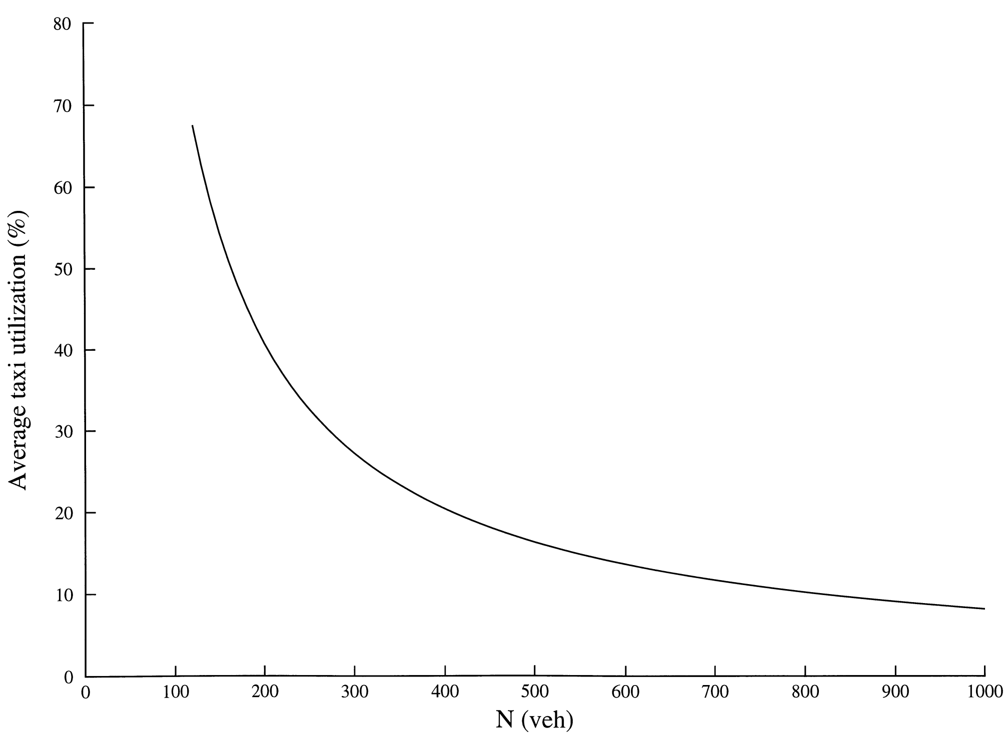

Fig. 7. Average taxi utilization vs taxi fleet size.

nearly proportionally with taxi fleet size for a given value of parameter θ, the total vacant taxi running time decreases, while the average and total taxi waiting time increases, respectively, with the values of parameter θ, which indicates the degree of information availability in the market.

Figure 7 indicates the change of the average taxi utilization with respect to taxi fleet size. We can see that the average taxi utilization will decrease sharply with the number of taxis operating. Note that for fixed customer demand, the average taxi utilization is independent of the value of uncertainty parameter, but solely dependent on the number of taxis operating. In addition, it is expected that the taxi utilization will greatly affect the level of taxi services in terms of customer waiting time: the higher the taxi utilization, the longer the average customer waiting time.

In summary, for a given customer demand pattern in a given urban network, taxi fleet size and information availability are two important policy factors that should be considered in order to achieve both better taxi utilization and a better level of service. Control of the taxi fleet size is essential to achieve better taxi utilization and maintain a certain level of service. Meanwhile, a better information service to the taxi market would reduce unnecessary vacant taxi movements, thereby reducing the environment impact and customer waiting time.

6. CONCLUSIONS

This paper has presented a first network model of cruising taxi operations in a transportation network with given customer O–D demand. The model offered some interesting insights into the nature of taxi service equilibrium, and even at this early stage, offered some preliminary policy-relevant numerical results. The model is well suited to an analysis of the outcomes of taxi service regulation such as the impact of taxi fleet control. Further research is being undertaken to incorporate traffic congestion into our model, and to incorporate the demand and supply equilibrium of the taxi service under competition and regulation (Yang and Wong, 1997).

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