INFLUENCE OF REAL-TIME INFORMATION PROVISION TO VACANT TAXI DRIVERS ON TAXI SYSTEM PERFORMANCE

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ABSTRACT

This paper assumes that all taxi drivers adopt a profit maximization strategy when searching for customers. Some taxi drivers are provided with real-time information on customer and taxi queue lengths at all taxi stands while others have no information at all. The questions to be investigated are: (1) will equipped taxi drivers earn a higher profit compared to the uninformed taxi drivers? (2) What is the impact of real-time information provision to a portion of all the taxi drivers on the overall taxi system performance? To find answers to these questions, a case study is conducted by assuming a hypothetical linear city with a single city centre, ten taxi stands and twenty residential zones. A discrete-event dynamic simulation model is adopted to simulate the movements of taxis and to estimate various taxi system performance characteristics, such as taxi operation profit and customer waiting time. The time period simulated is a 3-hour morning commune. The taxi fleet size, fare structure, taxi operation cost and customer demand pattern are all assumed given. The simulation model is used to investigate the variation of taxi system performance with the proportion of informed taxi drivers in the taxi fleet.

Keywords: public transport, taxi, information provision, customer-searching strategy

INTRODUCTION

As a supplement to the public transport system, taxis provide speedy, flexible and convenient service to customers in urban areas. In metropolitan areas with high population density, the taxi drivers mainly cruise in the road network and serve customers who are waiting on the roadside. Without precise information about customers' locations, taxi drivers can only rely on their own experiences and their priority to choose destination areas or taxi stands to seek potential customers. However, improved communication technologies have made it possible to provide taxi drivers with real-time information on customer and vacant taxi queue lengths at taxi stands. Will there be a market for this type of information system? Will it benefit the taxi drivers? Will it improve the performance of the taxi system? This paper tries to find answers to these questions.

Although not much research has been undertaken on the development of information systems for taxi drivers, the development of route guidance systems for car drivers is already a well researched topic. Route guidance systems provide complete traffic information to drivers. Based on the supplied information, equipped drivers can relocate their routes from the congested areas to the less congested ones, thus both the equipped drivers and the overall transport system may benefit from this redistribution of traffic.
The effectiveness of the route guidance system is influenced by the difference in route choice behaviour of equipped and unequipped drivers. User-equilibrium (UE), system-optimum (SO) and stochastic user-equilibrium (SUE) are three common route choice behaviour adopted by researchers for modelling this problem. Different combinations of these three kinds of behaviour have been used to investigate the benefits brought by the route guidance system. Harker (1988), Van Vuren et al. (1989) and Bennett (1993) assumed that equipped (unequipped) drivers follow SO (UE) behaviour. Since the unequipped drivers have less information about travel time in the transport system compared with equipped ones, a more realistic assumption about route choice behaviour is UE (SUE) for equipped (unequipped) drivers. This was proposed and investigated in Koutsopoulos and Lotan (1990), Ben-Akiva et al. (1991), Mahmassani and Jayakrishnan (1991). Later it was further assumed that equipped and unequipped drivers both follow SUE patterns with different variation level of perceived travel time (Lo and Szeto (2002), Yin and Yang (2003)). Huang and Li (2007) differentiated drivers into different classes according to their value of time and sub-classify them into equipped and unequipped ones with each sub-group having different route choice behaviours.

The influence of market penetration level of route guidance system has also been extensively investigated by lots of researchers (Koutsopoulos and Lotan (1990), Ben-Akiva et al. (1991), Mahmassani and Jayakrishnan (1991), Emmerink et al. (1995)). They found that there will be a 'win-win' situation for all the drivers and the overall system if the market penetration is set to an appropriate level. Exceeding this penetration level may deteriorate the network-wide performance. Yang (1998) proposed that the market penetration level of route guidance system should be treated as an endogenous variable and influenced by travel time saved by equipped drivers. System-optimum can be reached by a joint implementation of route guidance system and road pricing.

Since the private sector is often the provider of traffic information, such as in Japan and U. S., the benefits of this third party, together with drivers and transport management agency could be jointly considered in a static equilibrium model. Lo and Szeto (2002) suggested that the results were very complicated and sensitive to a lot of parameters such as the network and various cost parameters. Lo and Szeto (2004) extended this static model into a dynamic one by using a cell-based variational inequality approach. They found that the static and dynamic models give quite different results in the same scenario, and sometimes even with conflicting conclusions. Szeto and Lo (2005) further showed that without considering the service providers, the benefits of equipped drivers, the overall transport system and transport management agency may still conflict each other in some cases.

Compared with private cars, the behaviour of taxi drivers are quite different. Apart from the need to find an optimal path from origin to destination when they are serving a customer, they also need to formulate an optimal strategy to search for a new customer when their taxis become vacant. Hence, taxi drivers may benefit from an information system that provides them with real-time information about customers' locations, Kim et al. (2006) investigated the influence of real-time information provision on the quality and operational efficiency of taxi service by using a dynamic simulation model. They assumed that vacant taxis prioritize the available taxi stand by minimizing the expected vacant time (the sum of the expected travel time from its current position to the destination stand and the expected waiting time at that stand to get a customer). An information system provides them instantaneous information on customer location. They reported that "when more than 60% of taxis receive information, approximately 10% of the vacant travel distance can be reduced", and "average customer waiting time decreases as more taxis receive information".

Shi et al. (2009) proposed that when deciding on which taxi stand to go to seek a new customer, vacant taxi drivers tried to maximize their net profit considering the expected fare revenue, operation cost and waiting cost. They assumed that the information system provided real-time information about customer and taxi queue lengths at all taxi stands under a full penetration level. They investigated the influence of this behaviour on taxi system performance in a case study. Three different customer demand scenarios were set in a morning commute. They found that except for one particular scenario of customer demand pattern with a suitable taxi driver level of sensitivity to the information provided, the information system and profit maximization strategy is ineffective and results in reduced profit and longer waiting time for taxi drivers.

In this paper, the influence of penetration level of this assumed information system on taxi system performance will be explored according to various performance measures. Equipped (unequipped) taxi drivers follow profit maximization (random) customer search strategies.

The paper is organized in the following way. General assumptions on taxi driver behaviour are suggested in section 2. Section 3 lists and defines various measures used to evaluate taxi system performance. Section 4 describes the simulation model developed. Section 5 presents the case study and its results. Section 6 gives some general conclusions.

FORMULATION OF TAXI DRIVER BEHAVIOR UNDER THE INFLUENCE OF INFORMATION

It's assumed that real-time information about customer/taxi queue lengths at all taxi stands is available through a device equipped inside the taxi. This device and information service is charged, and taxi drivers are then classified into two groups. Some taxi drivers are sensitive to their profit income. They prefer to adjust their destination taxi stand dynamically according to the change of real-time information and try to maximize their profit every trip. So this group of taxi drivers (denoted as equipped taxi drivers) are will to pay for this device and information service and therefore adopt profit maximization strategy to choose destination taxi stand. The other taxi drivers believe that the device and information service is not worth the charge and troublesome to follow the real-time information. So this group of taxi drivers (denoted as unequipped taxi drivers) refuse to use this device and information service, and therefore randomly choose a taxi stand as their destination stand.

Information about customer/taxi queue lengths at all taxi stands is kept being updated to the equipped taxies through the devices located at taxi stands and information centre. When a new customer/taxi arrives at a taxi stand, the counting device at this stand update the total number of customer/taxi at this taxi stand and sends this piece of information to the information centre. Then the information centre sends this piece of updated information shown on the screen of the receivers equipped inside the taxis.

We further assume that when the taxi driver drops customers at their destination stand and becomes vacant, the driver cruises along a predetermined search path to search customers. The taxi driver can specify their destination stand in multi-step, which ensures that the real-time information is used as precise as possible. As shown in Figure 1, on the way to the destination area, the taxi driver makes choices at any exit slip road (denoted as a decision point) leading to a taxi stand. The driver can decide to go to the nearest taxi stand, or go on his/her predetermined search route to other taxi stands in the downstream of this decision point. The driver keeps making similar decisions along the search path until he/she chooses a specified taxi stand.

Consider a taxi system with equipped and unequipped drivers operating in a road network with a number of taxi stands for picking up customers. Immediately after a taxi becomes vacant and ready to start the search for a new customer, the taxi driver is assumed to travel along a search path which has a number of intervening taxi stands (see Figure 1).

When the taxi driver is travelling along the search path and reaches a decision point j with an exit ramp leading to a nearby taxi stand k, the driver has to make a decision on whether to stop the search and go to taxi stand k or to reject taxi stand k and to continue the search. The probability of stopping the search is given by

$$P_{jk} = \frac{e^{\beta V_{jk}}}{\sum_{s \in S} e^{\beta V_{js}}} \quad (1)$$

Where:

V_{jk} = utility of a taxi stand k when evaluated at decision point j, $j \in U$, $k \in S$
β = a coefficient that measures the sensitivity to utility differences between alternative taxi stands,
U = the set of decision points on the search path,
S = the set of taxi stands downstream of decision point j along the search path.

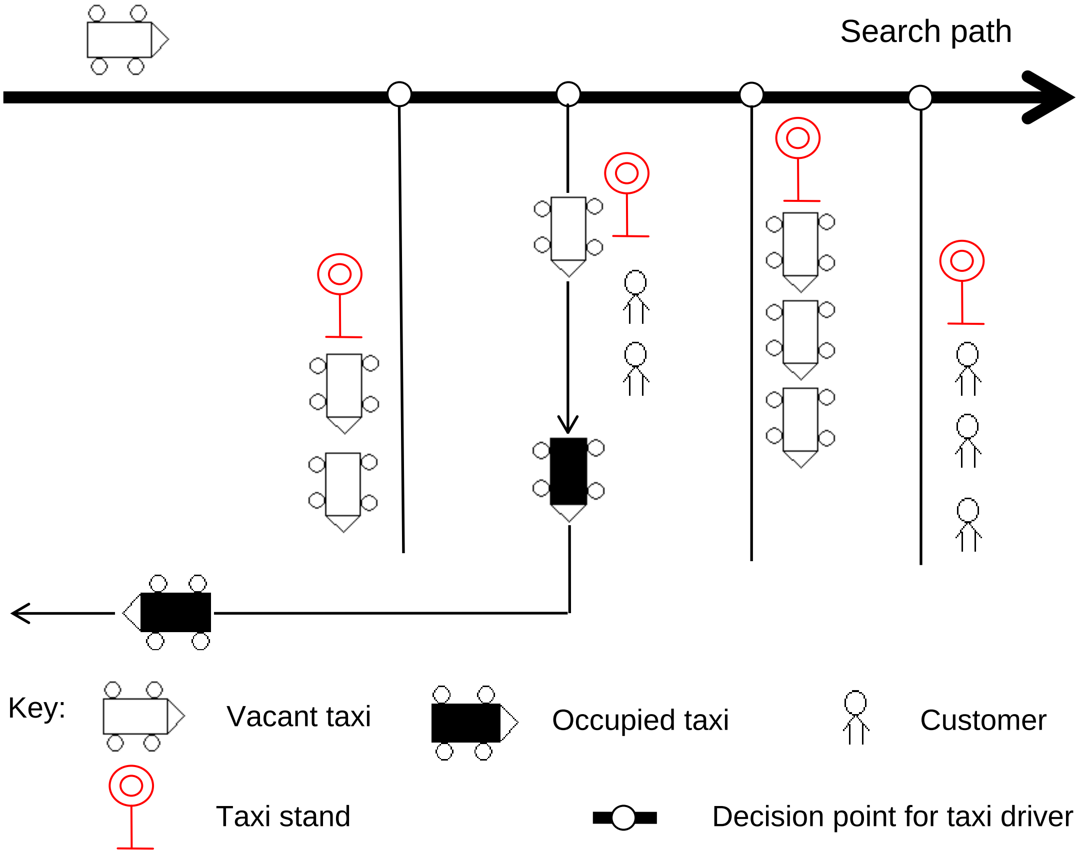

Figure 1 taxi driver's searching behaviour

Unequipped taxi drivers have no information about utility difference between alternative taxi stands and therefore randomly stops their search, so β=0 when they evaluate a nearby taxi stand at a decision point. Equipped taxi drivers should have more information on the utility difference between alternative taxi stands and hence they have a higher β, compared to unequipped taxi drivers. Profit maximization strategy is used to calculate the utility of the taxi stands downstream of decision point j. The utility of taxi stand k at decision point j is given by

$$V_{jk} = w_1 t_k^{\text{o}} - w_2 (t_{jk}^{\text{v}} + t_k^{\text{o}}) - w_3 t_k^{\text{w}} \tag{2}$$

Where:
t_k^{o} = the expected trip time of a customer picked up by a taxi at taxi stand k,
t_{jk}^{v} = trip time made by a vacant taxi travelling from decision point j to taxi stand k,
t_k^{w} = taxi queuing time at taxi stand k,
w_1 = taxi fare rate ($/unit time),
w_2 = cruising cost rate (when the taxi is in transit) ($/unit time),

w_3 = waiting cost rate (when the taxi is stationary) ($/unit time)

This utility function is equivalent to the expected net profit the tax driver can get at taxi stand k and is equal to fare revenue minus operation cost. Revenue and cost are both measured in time unit. w_1, w_2 and w_3 are constant coefficients to transform taxi's time span at different states (waiting, cruising or occupied) into correspondent revenue or cost. $w_1 t_k^{\mathrm{o}}$ is the expected fare revenue for the taxi to serve the customer waiting at taxi stand k. Operation cost is made up by two parts: cruising cost happened when the taxi is in transit ($w_2(t_{jk}^{\mathrm{v}} + t_k^{\mathrm{o}})$) and the waiting cost happened when the taxi is waiting ($w_3 t_k^{\mathrm{w}}$).

The uncertainty of this utility function is from t_k^{o}, t_{jk}^{v} and t_k^{w}, and thus influenced by various factors. As defined earlier, t_k^{o} is the expected trip time of a customer picked up by a taxi at taxi stand k. The value of t_k^{o} is greatly influenced by the uncertainty of customer's destination and traffic conditions. Since it's almost impossible to get the destination of the next customer in advance, the expected fare revenue used in the utility function is only based on the taxi driver's experience, which brings in relatively high uncertainty in the actual profit after the taxi driver serves the customer. When the customer gets on the taxi, the trip time is still greatly influenced by whether during peak or non-peak hour. And accidents in the road network also bring in unpredictable uncertainty in trip time. The uncertainty of t_{jk}^{v} is also mainly from traffic conditions, whether congested or non-congested.

With real-time information, the precision of t_k^{w} is still affected by other taxi drivers' behaviour. Since there's a time lag between the moment when the taxi driver makes his/her final decision and the moment when the taxi arrives at the chosen taxi stand. During this time period, the decision of this taxi driver can not be reflected on the number of taxis waiting at the taxi stand k, which introduces uncertainty in the information provided for other vacant taxis. And this uncertainty increases as β in equation (1) and the number of equipped taxis increases.

PERFORMANCE INDICATORS OF THE TAXI SYSTEM

Customer waiting time

Customer waiting time is a key indicator to evaluate the taxi system performance from customers' perspective. It's assumed that there are peak hour and non-peak hour during the study period. Therefore customer waiting time is calculated in different ways to give insight to the taxi service quality perceived by customers:
(1) Average customer waiting time;
(2) Customer waiting time during the peak hour;
(3) Customer waiting time at individual taxi stand.

Average customer waiting time is defined as the average waiting time for a customer to get a taxi during the whole study period. It's a general description of taxi service quality to customers. Customer waiting time during the peak hour describes taxi service in detail to customers travelling during the peak hour. Customer waiting time at individual taxi stand gives spatial information of taxi service quality to customers waiting at different taxi stands.

Taxi revenue and operation cost

Taxi revenue and operation cost reveals detailed information about revenue and operation cost of taxis during the study period. It's calculated in the following aspects:
(1) Fare revenue;
(2) Waiting cost;
(3) Occupied cruising cost;
(4) Vacant cruising cost.

Fare revenue is defined as the average fare revenue for each taxi during the study period. It is the crucial factor to affect the level of net profit gained by taxis. Operation cost happens when the taxis are in service during the study period and can be divided into waiting cost and cruising cost based on the different state of taxis (stationary or cruising). Waiting cost is defined as the average waiting cost that a taxi needs to get a customer during the study period. Cruising cost is further split into occupied (when the taxi is occupied by a customer) and vacant (when the taxi is vacant and moving (cruising) to its destination stand) cruising cost, which gives detailed impacts of cruising cost on the net profit gained by the taxis. Besides, these measures can also be calculated separately for equipped and unequipped taxi drivers to show the impacts of information on different group of taxis.

Taxi utilization

Taxi utilization provides detailed information about taxi operation. It's measured in the following aspects:
(1) Occupied cruising time;
(2) Vacant cruising time;
(3) Vacant waiting time.

Occupied cruising time is defined as the total time when the taxi is occupied by customers during the whole study period. It also can be calibrated in distance from the customers' origin to their destination. Vacant cruising time measures the time when the taxi is vacant and cruising in the road network. Vacant waiting time measures the time when the taxi is vacant and waiting at a taxi stand for a customer. If uniform operation cost rate ($/unit time or $/unit distance) is assumed, these performance measures can be easily transformed into taxi revenue and operation cost. These measures can also be calculated for different groups of taxis to show the impacts of information in taxi operation.

DYNAMIC SIMULATION MODEL FOR TAXI SERVICE

The taxi operation is simulated by a series of events (as shown in Table 1) in a dynamic simulation model. When event 5 or 6 is triggered, the vacant taxi driver needs to decide whether to go to the nearest taxi stand or continue cruising in the downstream of its current location. Different customer-searching strategy will be adopted based on the group the taxi driver belongs to (unequipped or equipped). The decision about destination is made in multi-step. In each step, real-time information about customer/taxi queue lengths at all available taxi stands is updated to help equipped taxi drivers evaluate each taxi stand.

Table 1 List of events in the simulation model

	Event
1	Customer arrives at a stand
2	Vacant taxi arrives at a stand
3	Occupied taxi departs from a stand
4	Occupied taxi arrives at a stand
5	Vacant taxi departs from a stand
6	Vacant taxi arrives at a decision point

CASE STUDY

General assumptions

City shape and road network

A linear city with 20 residential zones and a single city centre is used as a case study to show the impacts of information on vacant taxi drivers. As shown in Figure 2, the road network consists of ordinary road links and junction links with various free-flow speed assumptions. The travel time on the road is assumed to be constant, with each taxi travelling at the average speed for road links and junction links. The average road link speed is assumed to be 30 km/h and the average junction link speed to be 12 km/h. There are 11 taxi stands, one located in the city centre and the other 10 in residential zones.

Customer demand

The study period is three hours covering the morning commute, during which all trips are from the residential zones to the city centre. As shown in Figure 3, the average customer demand at a taxi stand for the first half hour is one trip every two minutes. The next hour is the peak demand period, and the customer demand is two trips per minute. After this peak hour, the demand drops back to one trip every two minutes.

Three customer demand scenarios are generated: (1) uniform demand, (2) increasing demand with distance from the city centre (see Figure 4), and (3) decreasing demand with distance from the city centre (see Figure 5).

Operational parameters of taxi system

The taxi fleet size is 800. At the start of the simulation period, taxies are assumed to be evenly distributed along stands to pick up customers. The taxi fare rate is assumed to be \$4 per minute, the operation cost rate \$1 per minute, and the waiting cost rate \$0.5 per minute. For unequipped taxi drivers, β is 0. For equipped taxi drivers, β is 1.

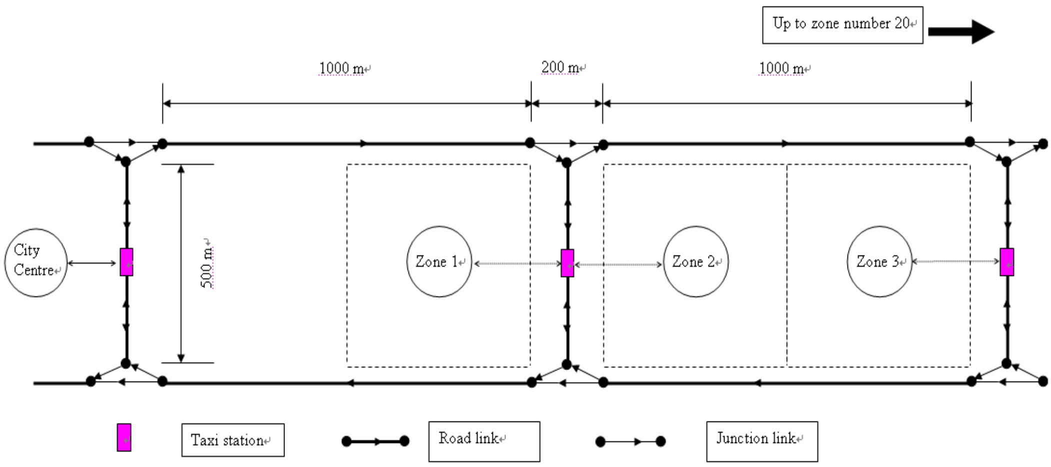

Figure 2 Road network

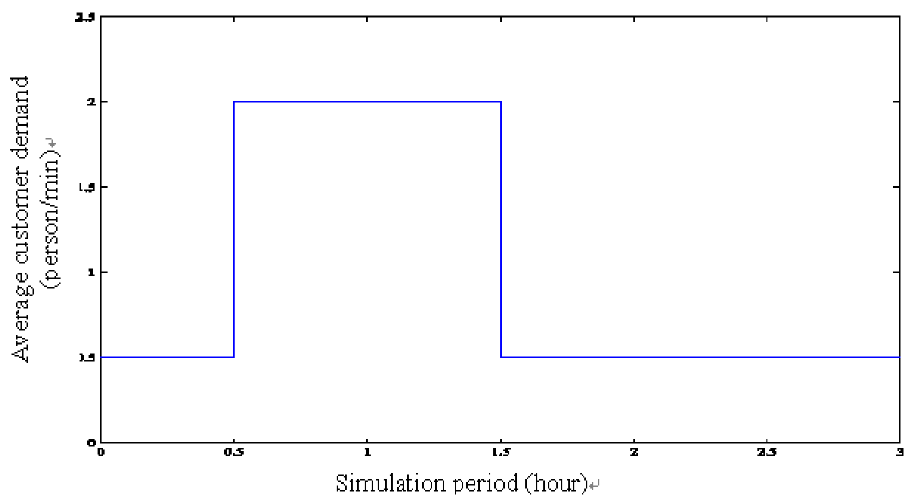

Figure 3 Average customer demand during three simulation hours

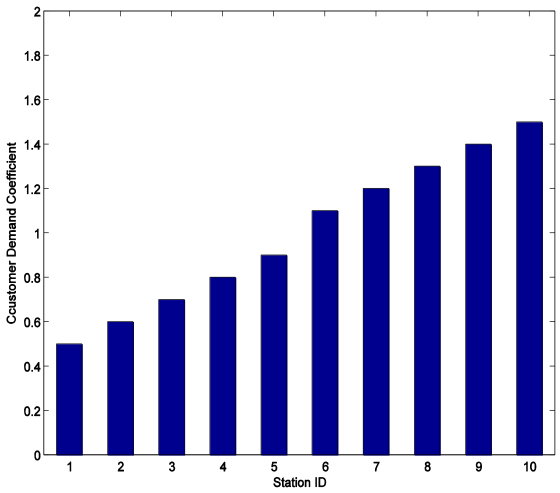

Figure 4 Increasing customer demand coefficients at taxi stands

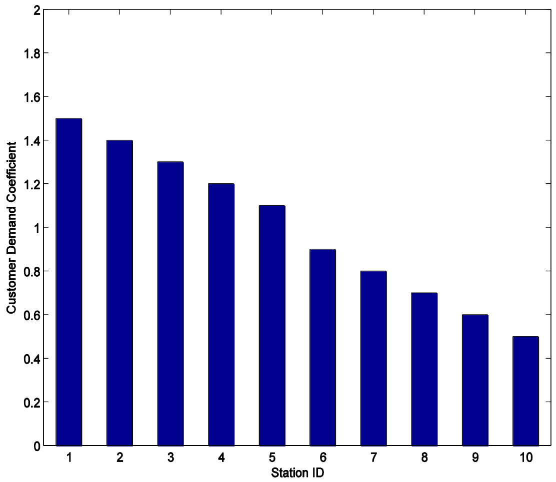

Figure 5 Decreasing customer demand coefficients at taxi stands

Simulation results

Customer waiting time

Figure 6 shows the change in customer waiting time (both the average and during the peak hour) as the percentage of equipped taxis increases in the fleet.

In uniform demand scenario, as shown in Figure 6-1, average customer waiting time is monotonically increasing from 1 minute to 6.5 minutes with the percentage of equipped taxis. This is because profit maximization strategy favours further taxi stands away from the city centre. As the equipped taxis (with profit maximization strategy) increase in the fleet and more taxis choose the further taxi stands, the customers at the nearer taxi stands need to wait for a longer time to get taxis.

Meanwhile, Figure 6-4 shows that the customer waiting time during the peak hour (uniform demand scenario) is also monotonically increasing from 1.5 minutes to 9.3 minutes. This is logical that customer waiting time during the peak hour is higher that the average customer waiting time, in this case, 30-40% higher.

In decreasing demand scenario, as shown in Figure 6-2, average customer waiting time is similarly monotonically increasing from 2.3 minutes to 6.2 minutes. The increasing rate of customer waiting time is at a lower rate than that in Figure 6-1. This is because, the difference in utility among different taxi stands is the smallest (as stated in single-class profit maximization strategy) among the three customer demand scenarios and has a small influence on the taxi stand choice of equipped taxi drivers. Hence equipped taxis are more evenly distributed at all taxi stands than in uniform demand scenario.

Figure 6-5 shows that the customer waiting time during the peak hour is also monotonically increasing from 2.3 minutes to 8.9 minutes in decreasing demand scenario. It’s observed that when the percentage of equipped taxis is 0 in the fleet, the customer waiting time during the peak hour is no higher than the average customer waiting time. This is because that taxis at this predetermined fleet size (800) is adequate to serve all the customers, since the majority of customers take short trips in decreasing demand scenario.

In increasing demand scenario, as shown in Figure 6-3, average customer waiting time firstly decreases from 9.5 minutes down to 6.8 minutes and then starts to increase to 8.5 minutes. The minimum average waiting time is 6.8 minutes when equipped taxis take up 60% in the fleet. This is because both the demand pattern and profit maximization strategy favour further taxi stands away from the city centre.

Figure 6-6 shows the same trend for the customer waiting time during the peak hour for increasing demand scenario. The minimum average waiting time is 8.8 minutes when the percentage of equipped taxis is also 60.

Customer waiting time at individual taxi stand

Figure 7 presents the residual customer/taxi queue length every half hour (the study period is 3 hours) at taxi stand 1, 5 and 10 when the percentage of equipped taxis is 50 for all three demand scenarios. It’s logical that either the customer or the taxi queue length should be zero at any time. But due to the random effects in the simulation model, both the customer and taxi queue length may be non-zero in some cases after the results are averaged. It’s observed that in general taxis queue during the non-peak hour, and customers queue during the peak hour (0.5^{th}-1.5^{th} hour) and the half hour after that. Besides, taxi queue length at each stand firstly keeps decreasing to its minimum during the peak hour, and then increases until the end of the simulation period.

Figure 7-1 shows the customer and taxi queue length at taxi stand 1 for uniform demand scenario. Taxi queue length firstly decreases from 80 to 2, and then increases to 32. The minimum is reached at hour 1.5. Customer queues between the first to the second hour. This is logical, since there is a high customer demand during the peak hour and the taxis become inadequate during this time period.

Figure 7-2 shows the customer and taxi queue length at taxi stand 1 for decreasing demand scenario. The taxi queue length firstly decreases from 80 to 0, and the increase to 50. The minimum is reached when the time is 1.5th hour. The customer queue increases from 0 to 78, and then decreases to 0. The maximum is reached when the time is also hour 1.5. Compared with Figure 7-1, the customer queue length is much longer than that in uniform demand scenario. This is because that customer demand at taxi stand 1 in decreasing demand scenario is 50% higher than that in uniform demand scenario, and equipped taxis tend to prefer the further taxi stands away from the city centre.

Figure 7-3 shows the customer and taxi queue length at taxi stand 1 for increasing demand scenario. The taxi queue length firstly decreases from 80 to 51, and the increase to 70. The minimum is reached when the time is hour 1.5. There's no customer queue during the whole study period. Compared with Figure 7-1 and 7-2, the decreasing rate of taxi queue length during the first 1.5 hours is smaller. This is because the customer demand here is much smaller than that in uniform and decreasing demand scenario. Besides, some unequipped taxis still choose taxi stand 1 as their destination stand.

The customer and taxi queue length at taxi stand 5 for uniform demand scenario is shown in Figure 7-4. The taxi queue length firstly decreases from 80 to 0, and then increase to 60. The minimum is reached when the time is hour 1.5. The increasing rate during the 1.5th-3rd hour is higher than that in Figure 7-1. This is because equipped taxis prefer taxi stand 5 as their destination stand to taxi stand 1 due to profit maximization strategy. The customer queue length increases from 0 to 23, and then decreases to 0. The maximum is reached when the time is also hour 1.5. The maximal customer queue length is much higher than that in Figure 7-1. This is because equipped taxis prefer taxi stands further than taxi stand 5 to taxi stand 5 due to profit maximization strategy.

The customer and taxi queue length at taxi stand 5 for decreasing demand scenario is shown in Figure 7-5. The taxi queue length firstly decreases from 80 to 11, then increases to 73 and again decreases to 69. The minimum is reached when the time is hour 1. There's almost no customer queue in this scenario. Compared with Figure 7-2, the customer queue length is much smaller than that in taxi stand 1. This is because that customer demand in taxi stand 5 is much smaller than that in taxi stand 1. Compared with Figure 7-4, the customer queue length in decreasing demand scenario is also much smaller than that in uniform demand scenario. This is because the utility difference between taxi stand 5 and the other taxi stands further than taxi stand 5 is smaller than that in uniform demand scenario. So more equipped taxis will choose taxi stand 5 as their destination in decreasing demand scenario than in uniform demand scenario.

The customer and taxi queue length at taxi stand 5 for increasing demand scenario is shown in Figure 7-6. The taxi queue length firstly decreases from 80 to 1, and then increases to 28. The minimum is reached when the time is hour 1.5. The customer queue length increases from 0 to 14, and then decreases to 0. The maximum is reached when the time is also hour 1.5. Compared with Figure 7-3, the customer queue length is higher at hour 1.5 than that at taxi stand 1. This is because that customer demand at taxi stand 5 is much higher than that at taxi stand 1. Compared with Figure 7-4, the customer queue length at hour 1.5 is smaller.

This is because the customer demand at taxi stand 5 in increasing demand scenario is smaller than that in uniform demand scenario.

As shown in Figure 7-7, the taxi queue length at taxi stand 10 in uniform demand scenario firstly decreases from 80 to 25, and then increases to 103. The minimum is reached at hour 1. There's no customer queue at taxi stand 10 at any time. This is because that equipped taxis prefer this taxi stand than any other taxi stand due to profit maximization strategy.

As shown in Figure 7-8, the taxi queue length at taxi stand 10 in decreasing demand scenario firstly decreases from 80 to 42, then increases to 75 and again decreases to 72. The minimum is reached at hour 1. There's no customer queue at taxi stand 10. This is because that customer demand at taxi stand 10 is the smallest among the 10 taxi stands.

As shown in Figure 7-9, the taxi queue length at taxi stand 10 in increasing demand scenario firstly decreases from 80 to 0, then increases to 100. The minimum is reached at hour 1. The customer queue length increases from 0 to 19 and then decreases to 0. The maximum is also reached at hour 1. Compared with Figure 7-3 and 7-6, the customer queue length is higher than that in taxi stand 1 and 5. This is because there's a much higher customer demand at taxi stand 10 than at taxi stand 1 and 5.

Taxi profit

Influence of percentage of equipped taxis on average taxi profit and taxi profit of two groups is shown in Figure 8.

In uniform demand scenario, as shown in Figure 8-1, the average taxi profit slowly decreases from $ 54.7 to $52.5. This is because the increase in taxi's waiting cost as the percentage of equipped taxis increases. However, equipped taxis enjoy significantly higher profit that group1 taxis. This is because equipped taxis drivers can always choose further taxi stands with higher profit, compared with unequipped taxis. As more taxis in the fleet can use real-time information and compete for the customers with higher profit, the marginal profit brought by real-time information gets smaller. This suggests that real-time information can significantly help taxis to derive higher profit, but does not improve the average taxi profit.

In decreasing demand scenario, as shown in Figure 8-2, the average taxi profit slowly increases from $36.4 to $38 and then decreases to $36.8. The optimal average taxi profit is derived when the percentage of equipped taxis is 40. This is because real-time information provision helps improve the distribution of taxis to reduce the average taxi waiting time and thus get higher average profit. Equipped taxis still have much higher profits than unequipped taxis, which is similar to uniform demand scenario.

In increasing demand scenario, as shown in Figure 8-3, the average taxi profit firstly increases from $69.5 to $75.5 and then decreases to $67.0. The maximum taxi profit is derived when equipped taxis take up 20% of the fleet. Equipped taxis also have higher profit than unequipped taxis, which is consistent with the previous two scenarios. When the percentage of equipped taxis is small (i.e. 10%), equipped taxis have much higher (2 times) profit that unequipped taxis. Meanwhile, the decreasing rate of equipped taxis profit in increasing demand scenario is the greatest among these three scenarios when the percentage of equipped taxis is between 1 and 40. This is because 'crowding effect' of profit maximization strategy is the most significant for the further stations away from the city centre with higher utility in increasing demand scenario. This case clearly shows that real-time information helps equipped taxis get much higher profit than unequipped taxis, and when the information is limited to a few taxis (i.e. 20% of the fleet), it also helps the average taxi profit reach its maximum. It also shows that real-time information can help improve average taxi profit under certain conditions.

Taxi waiting time

Figure 9 presents the influence of percentage of equipped taxis on average taxi waiting time during the whole study period (denoted as average) and during the peak hour (denoted as peak).

In uniform demand scenario, as shown in Figure 9-1, the average taxi waiting time firstly decreases from 29.7 minutes to 28.0 minutes and then increases to 28.3 minutes. The minimal taxi waiting time is reached when the percentage of equipped taxis is 60. This is jointly influenced by increase in taxi waiting time at further taxi stands and decrease at nearer taxi stands. When equipped taxis are more than 20% in the fleet, equipped taxis have a higher waiting time than unequipped taxis. This is logical that when equipped taxis queue at further taxi stands to get customers, unequipped taxis enjoy shorter queue lengths at nearer taxi stands.

Figure 9-4 shows the taxi waiting time during the peak hour for uniform demand scenario firstly decreases from 3.6 minutes to 2.5 minutes and then increases to 4.6 minutes. The minimal waiting time is reached when the percentage of equipped taxis is 20. It's logical that taxi waiting time during the peak hour is much smaller than average taxi waiting time.

In decreasing demand scenario, as shown in Figure 9-2, the average taxi waiting time is monotonically increasing from 28.8 minutes to 31.8 minutes. Unequipped taxis have a waiting time 20% higher than equipped taxis. This is because that real-time information helps improve the distribution of equipped taxis and decrease their waiting time to get customers, but didn't improve the average taxi waiting time.

Figure 9-5 shows that in decreasing demand scenario, the taxi waiting time during the peak hour is monotonically increasing from 3.8 minutes to 5.9 minutes. Unequipped taxis have a waiting time 15% higher that equipped taxis, which is consistent with Figure 9-2.

In increasing demand scenario, as shown in Figure 9-3, the average taxi waiting time is monotonically decreasing from 27.8 minutes to 26.6 minutes. However, unequipped taxis' waiting time increases from 27.8 minutes to 29.9 minutes, and decreases to 27.0 minutes. The maximum value is reached when the equipped taxis take up 50% of the fleet. Equipped taxis' waiting time monotonically increases from 15.6 minutes to 26.6minutes. Unequipped taxis have a higher waiting time than equipped taxis. This is because real-time information helps distribute equipped taxis to further taxi stands to meet higher customer demand there. These results show that real-time information does help reduce average waiting time and waiting time of equipped taxis.

Figure 9-6 shows that the taxi waiting time during the peak hour is also monotonically decreasing from 4.0 minutes to 2.0 minutes. Equipped taxis don't have to wait to get customers, when the percentage of equipped taxis is less than 50. This suggests that customers are waiting for taxis and the predetermined taxi fleet size is not sufficient in this case. Equipped taxis always have a lower waiting time than unequipped taxis, which also suggests that real-time information helps reduce taxi waiting time.

Taxi utilization ratio

Figure 10 presents influence of percentage of equipped taxis on utilization ratio during the peak hour for three scenarios. Utilization ratio is defined as the following.

$$\text{utilization ratio} = \frac{\text{occupied time}}{\text{service time}} \tag{5}$$

In uniform demand scenario, as shown in Figure 10-1, the average utilization ratio during the peak hour keeps uniform. The utilization ratio of equipped taxis is monotonically decreasing from 0.28 to 0.22, and that of unequipped taxis is also monotonically decreasing from 0.22 to 0.19 as the percentage of equipped taxis increases. These results show that the fleet size is adequate to support current customer demand, so there's little fluctuation in the average utilization ratio. However, real-time information deteriorates the utilization ratio of both equipped and unequipped taxis.

As shown in Figure 10-4, utilization ratio during the peak hour is monotonically decreasing from 0.37 to 0.33, utilization ratio of unequipped taxis is monotonically increasing from 0.37 to 0.39 and that of equipped taxis is monotonically decreasing from 0.35 to 0.33. These results clearly show that real-time information deteriorates the utilization ratio of the taxi fleet and equipped taxis which use this information during the peak hour. This is because equipped taxis tend to go to the further away taxi stands to pick up customers and therefore have higher vacant cruising time.

In decreasing demand scenario, Figure 10-2 shows the utilization ratio during the study period. The average utilization ratio slightly increases from 0.188 to 0.19 when the percentage of equipped taxis increase from 0 to 100. Utilization ratio of unequipped taxis monotonically decreases from 0.188 to 0.17. And utilization ratio of equipped ones monotonically decreases from 0.30 to 0.19. These results show that real-time information deteriorates the waiting time of both equipped and unequipped taxis.

As shown in Figure 10-5, utilization ratio during the peak hour is monotonically decreasing from 0.33 to 0.30. Utilization ratio of unequipped taxis is monotonically decreasing from 0.33 to 0.31. But utilization ratio of equipped taxis is firstly increasing from 0.29 to 0.31, and then decreasing to 0.30. These results show that real-time information does not help improve the utilization ratio of the taxi fleet, but do help improve that of equipped taxis under certain conditions (when the percentage of equipped taxis is less than 40) during the peak hour.

In increasing demand scenario, as shown in Figure 10-3, the average utilization ratio during the study period firstly increases from 0.23 to 0.26 and then decreases slightly to 0.25. The maximum point is when the percentage of equipped taxis is 50. The utilization ratio of equipped taxis firstly increases from 0.36 to 0.37 and then decreases to 0.25. The optimal point is derived when the percentage of equipped taxis is 10. The utilization ratio of unequipped taxis is monotonically decreasing from 0.23 to 0.21. It's observed that utilization ratio of equipped taxis are much higher than that of unequipped ones, especially when the percentage of equipped taxis is set to a certain level (e.g. 50).

As shown in Figure 10-6, average utilization ratio during the peak hour firstly increases from 0.33 to 0.34, and then decreases to 0.32. Utilization ratio of unequipped taxis monotonically increases from 0.33 to 0.36. Utilization ratio of equipped taxis monotonically decreases from 0.33 to 0.32. These results show that real-time information improves the utilization ratio during the peak hour, but deteriorates that of equipped taxis.

SUMMARY AND CONCLUSIONS

In this paper, a multi-class customer-searching strategy is proposed and the influence of real-time information on taxi system performance is investigated in a case study. The results are summarized in Table 2 and the major findings are described below:

(1) Influence of information provision on average customer waiting time

- (a) Uniform demand scenario – harmful. The average customer waiting time monotonically increases with the penetration level of the information system.
- (b) Decreasing demand scenario – harmful. Same with uniform demand scenario.
- (c) Increasing demand scenario – decrease average customer waiting time by 30% when the penetration level of the information system is optimally set to 60% of the taxi fleet.

(2) Influence of information provision on average net profit of all taxis (equipped and unequipped)

- (a) Uniform demand scenario – harmful.
- (b) Decreasing demand scenario – average taxi net profit increases by 4% when the penetration level of the information system is optimally set to 40%.
- (c) Increasing demand scenario – average taxi net profit increases by 8.5% when the penetration level of the information system is optimally set to 20%.

(3) Influence of information provision on average profit of equipped taxis

In all three scenarios, equipped taxis earn higher net profit compared to unequipped taxis. Although the net profit of equipped taxis decreases as the penetration level of the information system increases, equipped taxis still attain a net profit at least 10% higher than unequipped ones.

(4) Influence of information provision on average waiting time of all taxis (equipped and unequipped)

- (a) Uniform demand scenario – useful. To minimize waiting time, the optimal penetration level of the information system should be set to 60%
- (b) Decreasing demand scenario – harmful. Average taxi waiting time increases monotonically with information system penetration level.
- (c) Increasing demand scenario – useful. Average taxi waiting time decreases monotonically with information system penetration level.

(5) Influence of information provision on average waiting time of equipped taxis

- (a) Uniform demand scenario – harmful. Average waiting time of equipped taxis first increases and then decreases with information system penetration level, but the waiting time when the penetration level is 100% is still larger than that when the penetration level is 0.
- (b) Decreasing demand scenario –harmful. Average waiting time of equipped taxis increases monotonically with the penetration level of the information system.
- (c) Increasing demand scenario – harmful. Average waiting time of equipped taxis increases monotonically with information system penetration level.

(6) Influence of information provision on utilization ratio of all taxis (equipped and unequipped)

- (a) Uniform demand scenario – no effect during the study period but harmful during the peak hour. The utilization ratio of all taxis during the study period does not change with penetration level. But during the peak hour, the utilization ratio monotonically decreases with the penetration level.
- (b) Decreasing demand scenario – useful during the study period and harmful during the peak hour. The utilization ratio of all taxis during the study period is monotonically slightly increasing with the penetration level of the information system, although the utilization ratio decreases monotonically during the peak hour.
- (c) Increasing demand scenario – useful. The utilization ratio of all taxis during the whole study period also monotonically increases with the information system penetration level. The utilization ratio during the peak hour is optimized when the penetration level is set to 30%.

(7) Influence of information provision on utilization ratio of equipped taxis

(a) Uniform demand scenario – harmful. The utilization ratio of equipped taxis is monotonically decreasing with the information system penetration level during both the whole study period and the peak hour.

(b) Decreasing demand scenario – harmful during the whole study period and useful during the peak hour. The utilization ratio of equipped taxis during the study period monotonically decreases with the information system penetration level. However, during the peak hour, the utilization ratio is optimized when the penetration level is 40%.

(c) Increasing demand scenario – useful during the study period and harmful during the peak hour. The optimal utilization ratio of equipped taxis during the study period is achieved when the penetration level is set to 10%. During the peak hour, the utilization ratio is monotonically non-decreasing with the penetration level.

From the above results it can be concluded that under favourable conditions of customer demand pattern and penetration level, the information system can improve the taxi system performance as well as the average taxi profit. But under unfavourable conditions the information system can be harmful. It is noted however that for all the different operating conditions tested in the case study, equipped taxis will always earn a higher net profit compared to unequipped taxis.

ACKOWLEDGMENTS

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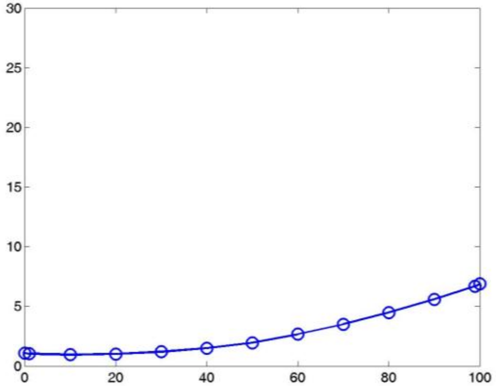
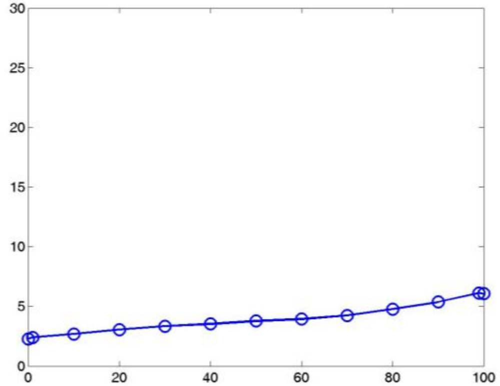
	Uniform demand scenario	Decreasing demand scenario	Increasing demand scenario
Average	6-1	6-2	6-3
Peak	6-4	6-5	6-6

Average



6-1



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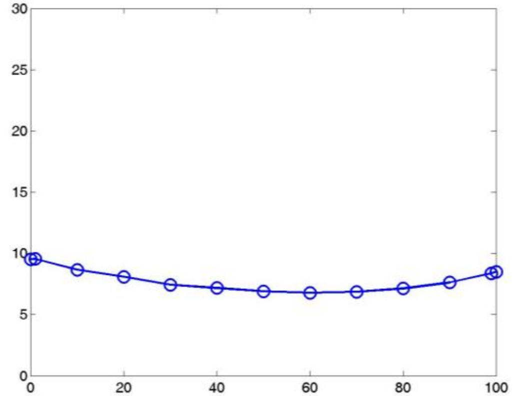
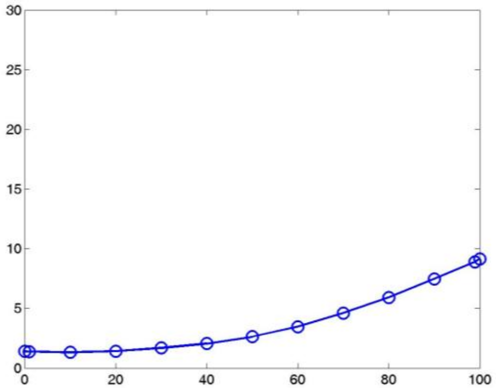


6-3

Peak



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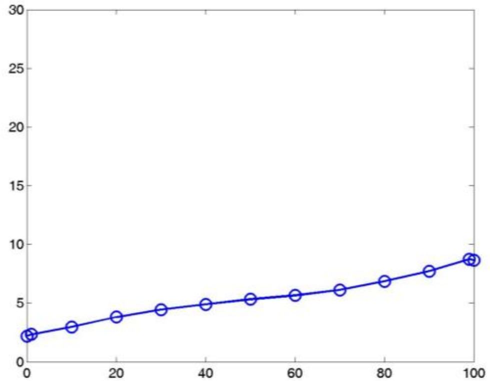

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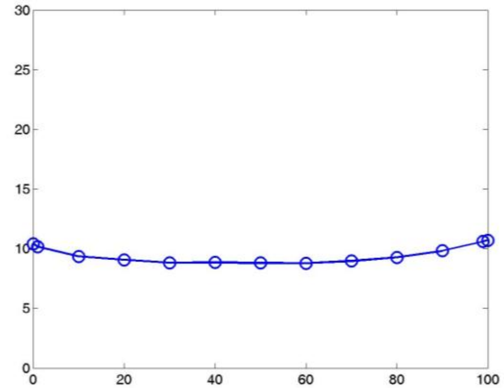
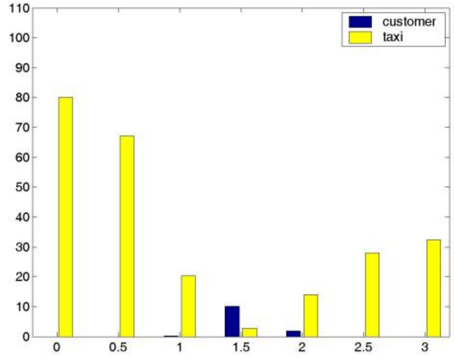
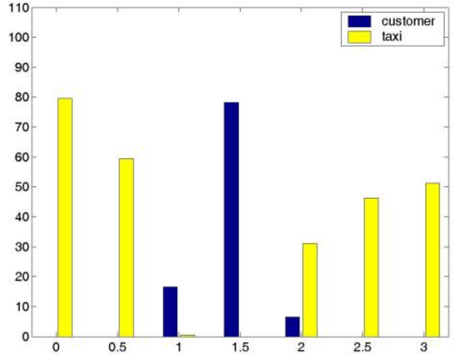
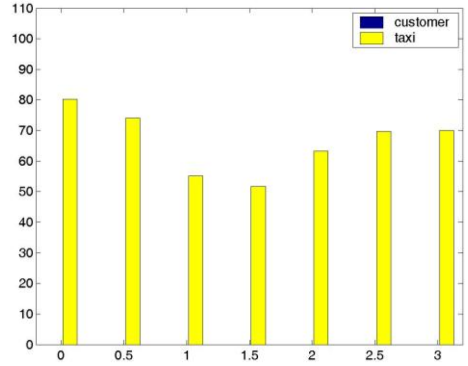
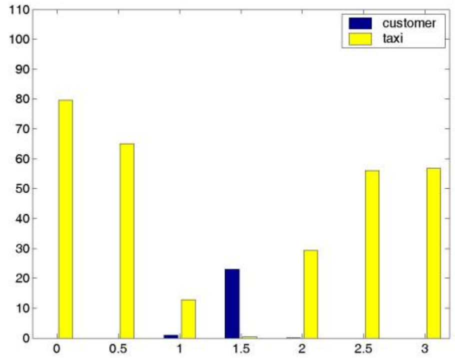
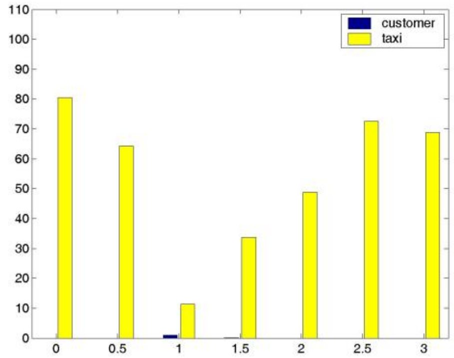
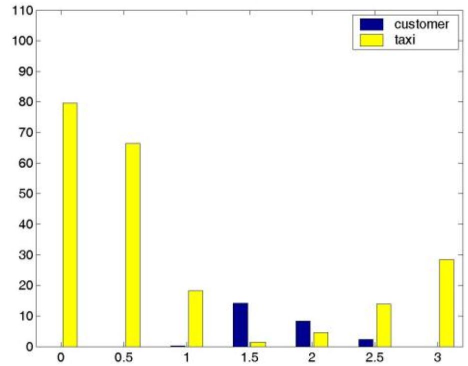
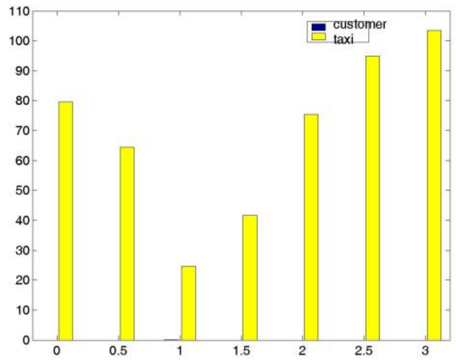


6-6

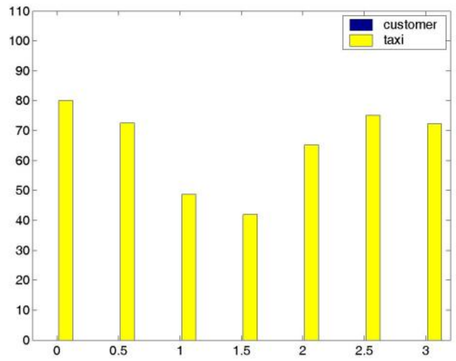
Figure 6. Influence of percentage of equipped taxis on customer waiting time (min)

	Uniform demand scenario	Decreasing demand scenario	Increasing demand scenario
Stand 1	 7-1	 7-2	 7-3
Stand 5	 7-4	 7-5	 7-6

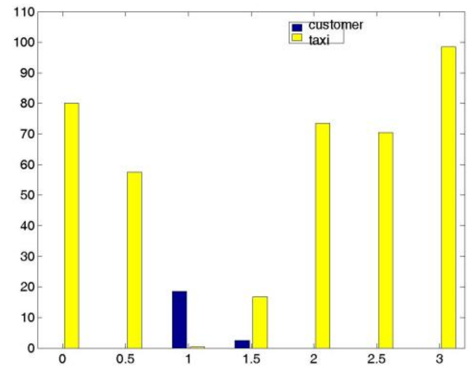
Stand 10



7-7



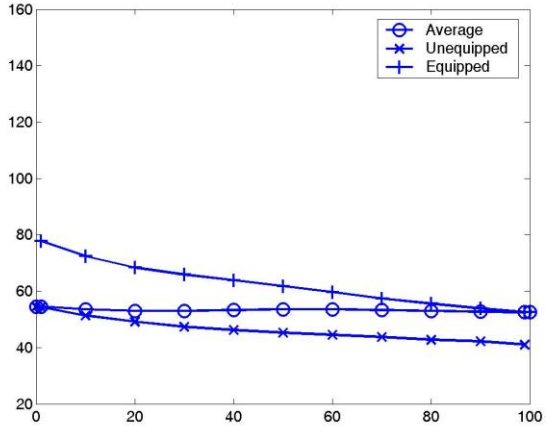
7-8



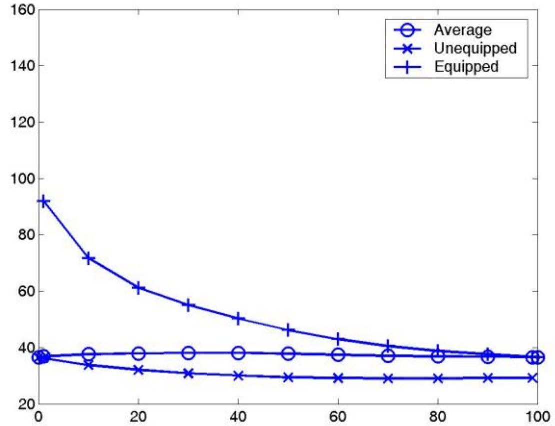
7-9

Figure 7 Customer and taxi queue lengths at taxi stand 1, 5 and 10 when the percentage of equipped taxis is 50

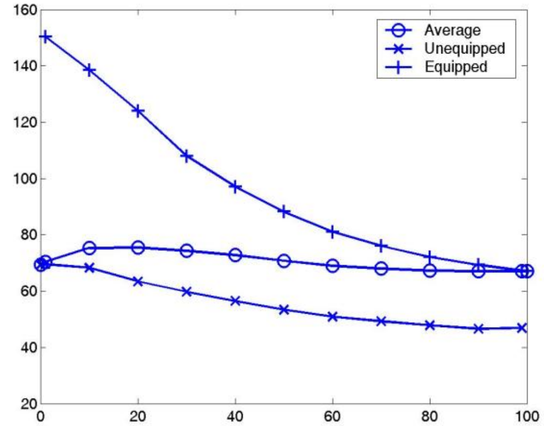
Uniform demand scenario	Decreasing demand scenario	Increasing demand scenario



8-1



8-2



8-3

Figure 8. Influence of percentage of equipped taxis on taxi profit ($)

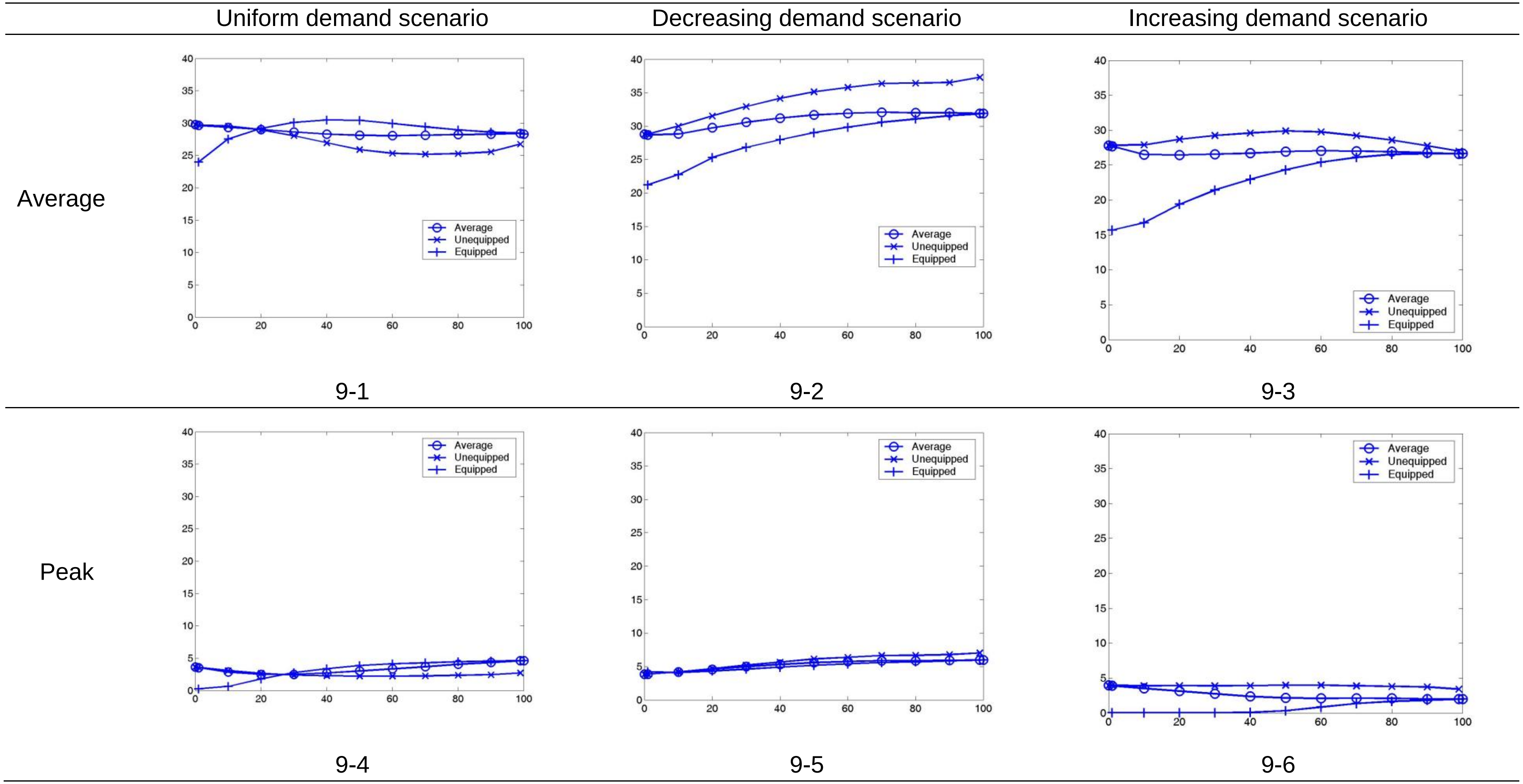


Figure 9. Influence of percentage of equipped taxis on taxi waiting time (min).

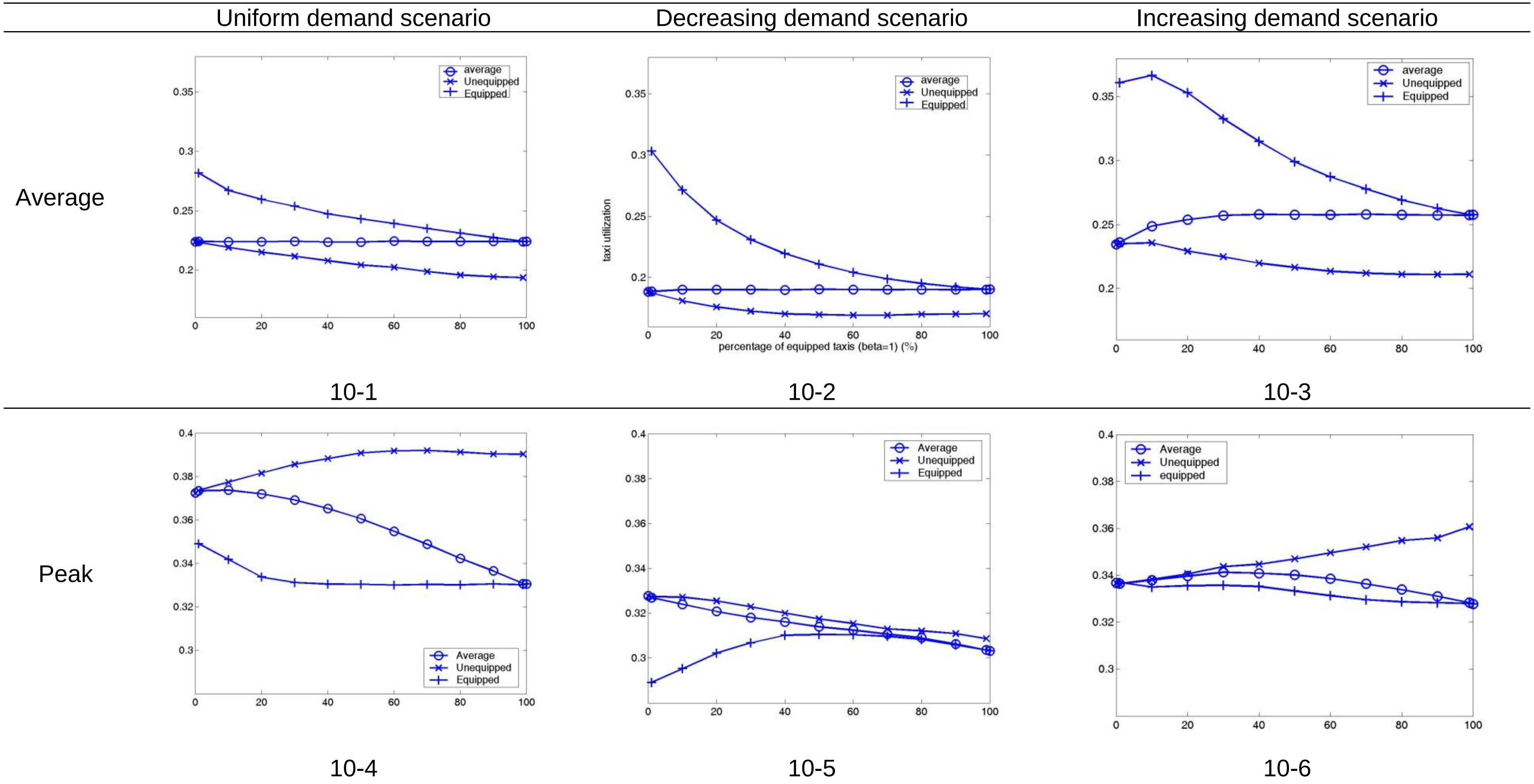


Figure 10. Influence of percentage of equipped taxis on taxi utilization ratio during the peak hour

Table 2 Impact of increasing percentage of equipped taxi drivers on taxi system performance

		Uniform demand scenario		Decreasing demand scenario		Increasing demand scenario	
		Average	Peak	Average	Peak	Average	Peak
Customer waiting time		↗	↗	↗	↗	↘ ↗	↘ ↗
Taxi profit	Average	↘	----	↗ ↘	----	↗ ↘	----
	Unequipped	↘	----	↘	----	↘	----
	Equipped	↘	----	↘	----	↘	----
Taxi waiting time	Average	↘ ↗	↘ ↗	↗	↗	↘	↘
	Unequipped	↘ ↗	↘	↗	↗	↗ ↘	↘
	Equipped	↗ ↘	↗	↗	↗	↗	↗
Taxi utilization ratio	Average	→	↘	↗	↘	↗ ↘	↗ ↘
	Unequipped	↘	↗	↘	↘	↘	↗
	Equipped	↘	↘	↘	↗ ↘	↗ ↘	↘