Evaluation of Cruising Taxi Dispatching Taxi Operations in the Taipei Metropolitan Area

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ABSTRACT: The most common taxi operation service consists conventionally of cruising randomly around a city to search for passengers. Because of de-regulation policies, over-supply and high vacancy rates have caused inefficient operation and low performance in the taxi market. Therefore, this paper aims to create an innovative operational service and to evaluate the environmental benefits of this service as compared with conventional cruising services. It is shown that innovative dispatching service can result in 4.35 billion USD of energy savings per year in the Taipei metropolitan area. Numerical results have also shown other external effects of innovative dispatching services, including less air pollution, traffic accidents and traffic congestion.

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1. Introduction

Because of features of privacy, convenience, accessibility and speediness, taxies have become a crucial part of the public transportation modes in urban areas. The most common operational style is a conventional approach involving cruising randomly around a city to search for passengers. Because of de-regulation policies, over-supply and high vacancy rates have caused inefficient operation and low performance in the taxi market. Moreover, this has resulted in problems such as poor service, unhealthy competition, and legal violations. For example, up to the end of 2012, the total amount of taxis had reached 85,000 vehicles in Taiwan while there were about 54,000 vehicles in the Taipei metropolitan area. According to a survey, the vacancy rate for taxies is around 57% in the metropolitan areas of Taipei. These vacant vehicles have caused huge losses related to fuel costs, more than 0.15 billion USD, and may cause more than 280 thousand tons of CO_2 emissions (Chang, 2008). When considering congestion, noise, air pollution, and other external costs, the total social loss is too huge to be measured.

Therefore, this study is aimed at the creation of an innovative taxi operation service and at building an analytical method to compare this model with conventional cruising taxi services. It is worth exploring strategies to reduce vacancy rates and increase operational efficiency in view of such a huge generalized cost and the trend toward conservation of energy and minimizing the carbon footprint.

2. Literature review

Because there was a growing demand for taxi services in the middle of the 1990s, radio-paging systems could no longer serve the enlarged consumer market in Singapore and New York. In Singapore, three taxi companies decided to phase out the radio-paging systems and switch to the use of satellite-based dispatching systems. This application of advanced technologies resulted in a significant improvement in operational efficiency and service quality.

Several studies have applied mathematical models to analyze taxi industry features (Douglas, 1972; Williams, 1980; Shreiber, 1981; Yang et al., 2002). These studies explored the optimal fleet size for the taxi industry. However, these works mostly focused on the cruising situation, and they didn’t put an emphasis on the dispatching system. Therefore it is hard to understand the differences in operational performance between cruising and dispatching. The previous literature on this subject has been almost completely algebraic. It turns out, however, that a complete and precise diagrammatic analysis of the economics of cruising taxi services was developed by Ferna´ndez et al. (Ferna´ndez et al., 2006). In this research, the relationships among the free market equilibrium, social optimum and second best solution were analyzed.

Nevertheless, some of the basic conclusions coincided with those already presented in the literature by previous authors indicating that if this industry is given perfect adaptation of supply to demand, the taxi occupant rate will increase with the operational style according to dispatching rather than as a result of cruising. Lee and Cheng talked about the benefits of safety resulting from dispatching systems (Lee and

Cheng, 2008). However, there have been few studies that have quantified the impact of the externality between the two operational styles. This paper formulates two models including cruising taxies and innovative dispatching taxi services and then compares the optimal fleet size and the environmental benefits resulting from the adoption of an innovative dispatching system.

3. Analytical model assumptions

The objective of this research is to distinguish the difference between conventional cruising and innovative taxi services. The model is formulated to evaluate the performance related to environmental impact and external costs under different types of operation. If all taxi drivers wait in their vacant vehicles and cruise for their next passengers after each ride, this is defined as a cruising system. If all taxi drivers drive their vacant vehicles back to the nearest taxi stand after each ride and wait for the next dispatch, this is defined as an innovative dispatching system. The dispatching mechanism is described in Figure 1. Passengers make phone calls, visit websites or send digital messages to a control center with a set of location codes corresponding to their location. Second, the control center compiles and translates these codes into spatial coordinates or addresses and then sends this information to the drivers who are waiting in the nearby taxi stands.

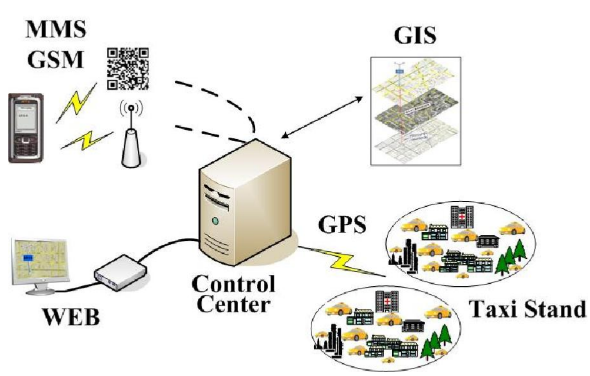

Figure 1. The Framework of the Dispatching System

The following scenarios are the service processes of the taxi market as proposed in this study. There are N taxis providing services, and each taxi service can be directly applied to a many-to-many trips route. Taxi services are available in a given "service region" whose length and width is K; the total road network length of the service area is L kilometers, and it is characterized by homogeneous internal characteristics. The fixed demand for taxis inside the service region is D trips per km/hr, and the average waiting time for each passenger riding a taxi is W minutes. In the service region, the taxi drivers drive at a constant speed S, and the average trip length of passengers is Y. At the end of the ride, the passengers pay the taxi fare P and leave the vehicle.

4. Conventional Cruising Model, Model Ⅰ

It is assumed that all drivers are cruising on the road. According to Daniel (Daniel, 2003), an important feature of taxi markets is that increasing expected waiting times for passengers may reduce their willingness to pay for the service; therefore, it is assumed that a passenger has a maximum willing to pay price P_0 to get on a taxi, and that the actual taxi fare for each trip decreases as the waiting time increases. With this assumption, the actual taxi fare paid by passenger for each trip is given as Eq. (1):

$$P = P_0 - tW^{\phi} \tag{1}$$

Where ϕ is the tolerable coefficient of waiting time and is always positive. The average value of time for each passenger is t NTD per minute.

From the preceding assumptions, the total operating kilometers per hour can be expressed as NS, and the total occupancy distance, known as the total demand LD multiplied by the average round trip distance Y, is LDY. We can obtain the total vacant distance as $V_T = NS - LDY$. Therefore, the average waiting time per trip is formulated as follows:

$$W = \frac{2L}{V_T/60} = \frac{120L}{NS - LDY} \tag{2}$$

The objective function of maximum total profit can be presented by total revenue minus total operation cost. Since the operation cost for drivers is c NTD per kilometer, the objective function (3) is as in the follows:

$$Total\pi = TR - TC = PLD - cNS \tag{3}$$

To find the optimal solution, Eq. (1) and Eq. (2) should be substituted into Eq. (3), and then the first order condition as Eq. (4) is determined as:

$$\frac{\partial \pi}{\partial N} = 120^{\phi} t\phi S L^{\phi+1} D (NS - LDY)^{-\phi-1} - cS \tag{4}$$

Let Eq. (4) equal zero, and we can obtain the optimal fleet size for the cruising taxi market as follows (5):

$$N^* = \frac{L}{S}\left[\left(\frac{120^{\phi} t\phi D}{c}\right)^{\frac{1}{\phi+1}} + DY\right] \quad (5)$$

Based on the consequence N^*, the optimal vacancy mileage V_T^*, optimal vacancy rate R^*, optimal average waiting time W^*, and optimal average taxi fare per trip P^* can be obtained as follows (6~9):

$$V_T^* = N^* S - LDY \quad (6)$$

$$R^* = \frac{V_T^*}{N^* S} = \frac{N^* S - LDY}{N^* S} \quad (7)$$

$$W^* = \frac{2L}{V_T^*/60} = \frac{120L}{N^* S - LDY} \quad (8)$$

$$P^* = P_0 - tW^* \quad (9)$$

Innovative Dispatching Model, Model Ⅱ

It is assumed that all drivers provide services using the innovative dispatching system. From the previous analysis, it can be assumed that the total fleet size N^* is the dispatching taxi market. They operate through direct telephone requests to the control center, and then the dispatching center assigns a taxi from the nearest taxi stand. The taxi stands work as a first-come first-served queue, so that the first taxi arriving on the stand serves the first passenger request. Unlike the cruising model, the commutation cost for each trip u should be considered in the pricing so that the actual taxi fare for each trip is defined in Eq. (10):

$$P = P_0 - tW^{\phi} - u \quad (10)$$

In the innovative dispatching model, drivers should drive their taxi back to the nearest taxi stand. Therefore, it is assumed that the total number of taxi stands in the service region is n. It is also assumed that the allocation and road network are symmetrical, so the vacancy mileage before and after the dispatching service is equal. All the demand in this given service region generates a uniform distribution, and then the vacancy mileage for each taxi providing a single service can be represented as Eq. (9):

$$V = 2\frac{Ke}{4n^{\lambda}} = \frac{Ke}{2n^{\lambda}} \quad (11)$$

Where, e is geometric coefficient of the road network;

λ is the allocation coefficient of the taxi stands.

By multiplying total demand LD, the total vacancy mileage V_T and vacancy rate R can be obtained in Equations 12 and 13:

$$V_T = LDV = \frac{LDKe}{2n^{\lambda}} \quad (12)$$

$$R = \frac{V_T}{LDY + V_T} = \frac{V}{Y + V} \quad (13)$$

For each passenger, the waiting time W, which includes the waiting time for the taxi driver to reach the passenger and the waiting time M for the control center to dispatch the service request to the driver, can be expressed as follows:

$$W = 60\frac{V_T/2}{S} + M = \frac{15Ke}{Sn^{\lambda}} + M \quad (14)$$

Therefore, the total cost is the summation of passenger cost C_p, taxi driver cost C_d and taxi stand operating cost C_o. Passenger cost is composed of the cost of communication, the wait for the taxi and the time required for the control center to dispatch a vehicle. The taxi driver cost includes the cost of both occupant and the vacancy duration. The operating cost is directly changed with the number of taxi stands, and the incremental operating cost coefficient of the taxi stands is γ. Therefore, it can be assumed that the cost of the taxi stands is non-linear. Since the marginal operating cost is marginally decreased with the number of taxi stands, the value of γ should be between 0 and 1. The marginal operational cost is b NTD per vehicle-hour. With these assumptions, each cost component is shown as follows:

$$C_p = uDL + \frac{tDLKe}{4Sn^{\lambda}} + tDLM \quad (15)$$

$$C_d = cDLY + \frac{cDLKe}{2Sn^{\lambda}} \quad (16)$$

$$C_o = nb\left(\frac{N}{n}\right)^{\gamma} \quad (17)$$

The objective function of maximum social welfare under a fixed demand condition can then be represented as a minimum total cost. Therefore, the objective function for the innovative dispatching model is presented in Eq. (18):

$$Min \quad TC = C_p + C_d + C_o \tag{18}$$

Take differential with respect to the decision variable n, the equation becomes a non-closed form. By applying the excel programming solver, it can be computed with the optimal solution n^* and also, V_T^*, R^*, W^* and P^* can be obtained.

$$V_T^* = \frac{LDKe}{2(n^*)^{\lambda}} \tag{19}$$

$$W^* = \frac{15Ke}{S(n^*)^{\lambda}} \tag{20}$$

$$R^* = \frac{V^*}{Y + V^*} \tag{21}$$

$$P^* = P_0 - t(W^*)^{\phi} \tag{22}$$

5. Case study in Metropolitan taipei

After formulating these two models, a case study was conducted for the Taipei metropolitan area based on a survey report on taxi operation for Taipei in 2012 (Chang, 2012) with a total network length of 2,732 kilometers, a demand density of 27.33 trips per km/hr, and an average operating speed of 18 km/hr. Other features for demand include that the average trip distance is about 4.95 kilometers while the average distance cost for taxi drivers is 0.96 USD/km. Based on the findings of Chang and Chu (Chang and Chu, 2008), the value of the waiting time for each passenger is 0.15 USD per minute.

The average waiting time W* for each passenger under an optimization situation can be derived from Model Ⅰ by changing the tolerable coefficient of waiting time ϕ as plotted in Figure 2(a). It is intuitively clear that if passengers lack patience, they cannot endure the wait for the taxi service. This result implies that as long as ϕ is large, then the optimal average waiting time will be less. However, it is not sensitive when the value of ϕ is beyond a specific threshold. It is also shown in Figure 2(b) how the quantity of total taxis in Taipei area changes as the tolerable coefficient of waiting time ϕ increases. This result states that the vacancy rate is usually considered as one component of the service level, and the reasonable vacancy rate for the Taipei area is about 30~35% (Chang and Huang, 2003). The parameter can be adopted in Model Ⅰ to find the reasonable value of coefficient ϕ. The relationship between vacancy rate and ϕ can be expressed as Figure 2(c). It can be found that the value of ϕ is near to 2.5 when the optimal vacancy rate is 33%, while the optimal taxi fleet size is about 29,627 vehicles.

Therefore, the following calculation in the research for Model Ⅱ, the number of optimal taxis in a service region N^*, will be adopted as 29,627 in Taipei.

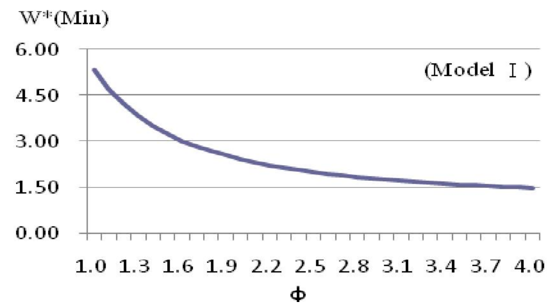

Figure 2(a). Effect of Tolerable Coefficient on Optimal Waiting Time

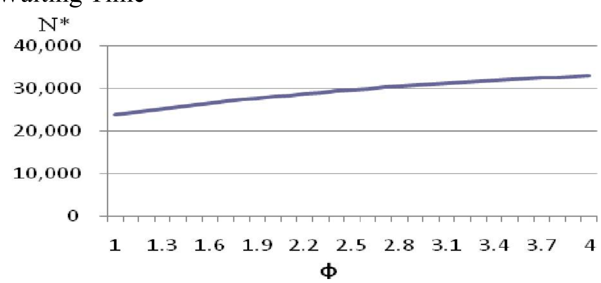

Figure 2(b). Effect of Tolerable Coefficient on Optimal Number of Taxi Vehicles

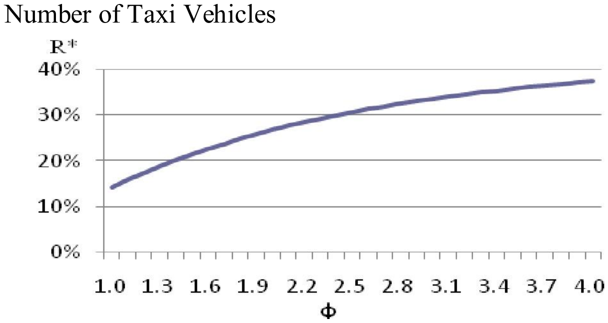

Figure 2(c). Effect of Tolerable Coefficient on Optimal Vacancy Rate

In the innovative dispatching model, the allocation coefficient λ represents the efficiency of the location set up for these taxi stands. As shown in Figure 4, the allocation coefficient λ varies with different types of taxi stands. The larger λ it is, the fewer taxi stands there will be. This result indicates that when the value of λ is becoming larger; the allocation type is more efficient, so fewer taxi stands will provide a similar service level.

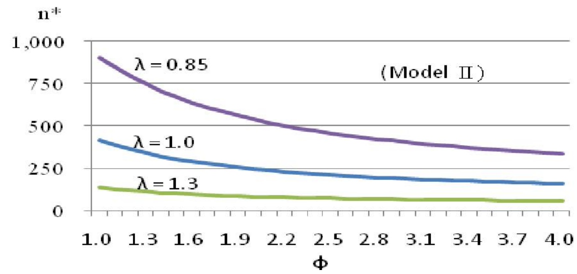

Figure 3. Effect of Tolerable Coefficient on Optimal Number of Taxi Stands

Figure 3 also depicts that as ϕ increases, the number of taxi stands decreases. By intuition, when passengers' tolerance for waiting is lower, the number of taxi stands should be larger in order to reach a better service level. However the outcome of this study shows the opposite effect. The reason for this is that as ϕ becomes higher, the actual taxi fare P is less. Due to the assumption of fixed demand, no matter how the operator changes the number of taxi stands, the demand in this region is still fixed. Based on this assumption, the total revenue is fixed to PLD. With the objective of maximum total profit, the operator tends to reduce the number of taxi stands to reduce operation and maintenance costs. If we assume elastic demand, there might be a different result in terms of the optimal number of taxi stands. This is worth further exploration.

However, there is a trade-off for passengers between ModelⅠ and ModelⅡ depending on passenger cost. If and only if the additional passenger cost is less than the waiting cost incurred in the traditional mode, passengers will select the innovative dispatching service mode. The decision model can be expressed as follows:

$$tW_2^{\phi} + u - tW_1^{\phi} \begin{cases} <0 & \text{model Ⅰ} \\ >0 & \text{model Ⅱ} \end{cases} \tag{23}$$

.

Figure 4(a) depicts the sensitivity of the dispatching time M and the communication cost μ. Given ϕ equals 2.5, it can be shown that passengers will be willing to pay more communication costs to book service as the dispatching time decreases. Beneath the curve shown in Figure 4(a), it is feasible to assume that passengers are likely to select the dispatching service mode.

Similarly, given that reasonable dispatching time is 1.5 minutes, the relationship of communication cost and the tolerable coefficient of waiting time is illustrated as Figure 4(b). If the cost of communication for each trip is fixed, the curve for dispatching time and the tolerable wait coefficient is depicted as Figure 4(c). In practical application, the tolerable coefficients for passengers might be different in various countries. Once the value of the tolerable coefficient is identified, the optimal communication cost and dispatching time can be estimated simultaneously. As the result, the optimal scale for the dispatching control center can also be obtained.

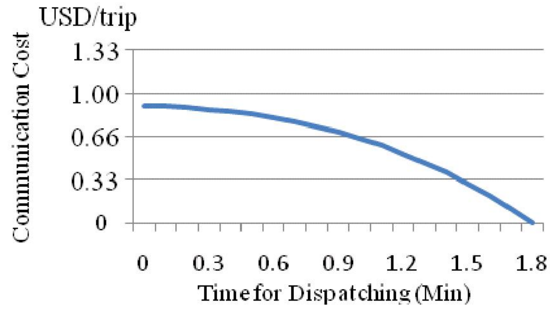

Figure 4(a). Communication Cost Versus Time for Dispatching

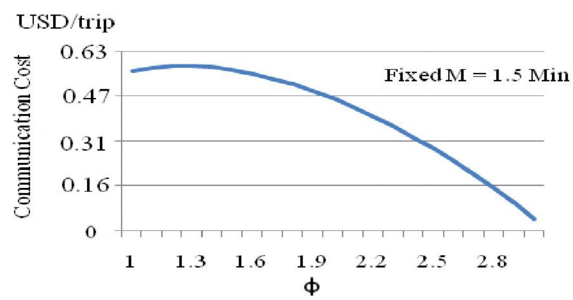

Figure 4(b) Effect of Tolerable Coefficient on Communication Cost (Fixed Dispatching Time)

Studies and evaluations have indicated that the vacancy rate is usually considered to be one part of service level and that a reasonable vacancy rate for Taipei is about 30~35% (Chang and Huang, 2003). However, the actual distant vacancy rate in Taipei is about 60%, which causes severe pollution.

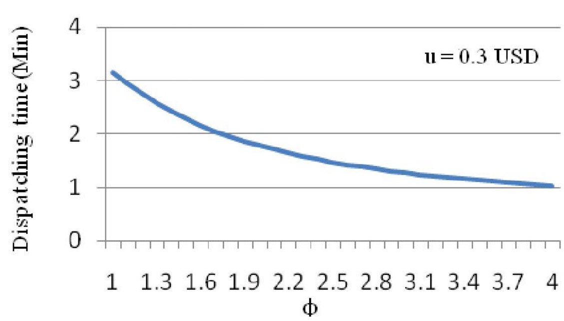

Figure 4(c). Effect of Tolerable Coefficient on Dispatching Time (Fixed Communication Cost)

In the following analysis for Model Ⅱ, the optimal fleet size of taxis in a service region N^* will be adopted as 29,627 in Taipei with assumptions of 0.9 of the marginal operating cost coefficient of taxi stands γ ; 47 km is assumed as the length and width of Taipei, and 1, 3 of geometric coefficient of road network e.

By computing the two different models, the internal cost can be estimated. However, what we are really interested in is the external savings between the two models. In general, the external cost includes air pollution cost, noise pollution cost, accident cost and congestion cost. Based on Chang and Guo (Chang and Guo, 2007), the external costs of taxies for each item are 0.254 NTD/vehicle-km, 0.043 NTD/vehicle-km, 0.84 NTD/vehicle-km and 3.19 NTD/vehicle-km, respectively, and the external effect can then be obtained by multiplying the total vacancy mileage V_T. Therefore, the total external costs of the two models can be calculated. The results for both internal cost and external cost of the conventional cruising model and the scheduled dispatching model are listed in Table 1. Compared with the conventional cruising market, the innovative dispatching model can avoid meaningless cruising and reduce total vacancy mileage so that the external cost can be reduced considerably (from 22 to 38 thousand USD per hour). Under an optimal situation, 0.5 million USD per day can be saved as contributed from the external effects in the Taipei metropolitan area. This impressive performance implies that environmental benefits are also one of the most important advantages of the innovative dispatching model. Moreover, the cost to passengers for waiting time decreases significantly by paying a slight additional cost for making phone reservations.

6. Conclusions

Different taxi operation models will lead to different consequences related to costs and service performance. This study formulates mathematical models of conventional cruising taxies and innovative dispatching taxi services to analyze both their internal and external costs. With the assumption of fixed demand and quantity of taxis in a given service region, we compared these two models on the same basis. It can be seen that the selection of conventional cruising or innovative dispatching models depends on the preference of passengers related to such things as their tolerance for or the value of wait time. Passenger decisions will have an influence on these coefficients and parameters and then will indirectly change the operational strategies of operators. It is concluded that an innovative dispatching model has a comparative advantage over a cruising model in terms of decreases in external cost and aspects related to environmental sustainability. Changing the operation type from a conventional cruising model to an innovative dispatching model can save 0.01 billion USD in both the internal and external total cost per day, which is about 4.35 billion USD of energy savings per year. Passenger costs and driving costs can also be reduced because of the adoption of this innovative dispatching model.

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