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巡迴計程車市場衛星派遣車隊最適規模之研究
Optimal Fleet Size of GPS Taxi in a Cruising Taxi Market

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土 312, Aug. 2010

摘要

計程車由於其方便、迅速、及戶、私密、舒適、營業時間長及免停車等使用特性，在都會區之公共運輸系統中被定義為「副大眾運輸」，相較於一般大眾運輸系統，在經濟活動頻繁之都會地區廣為旅行者所歡迎。近年來，由於資訊與通訊科技的發展，臺北地區之衛星派遣計程車比例已攀升至16%，隨著日益增高的行車成本，以及日益普及的衛星定位技術，衛星派遣計程車已逐漸成為計程車市場的趨勢與潮流。

本研究藉由雙層規劃數學分析模式描述衛星派遣計程車在巡迴計程車市場的營運績效，並輔以臺北地區2008年營運情形調查資料，在「社會福利最大」以及使「計程車駕駛營收最大」的雙層目標下，推估最適衛星派遣計程車的車隊規模，並研析駕駛營運形式變化對使用衛星派遣服務乘客數量之影響。針對臺北地區實證分析之研究結果顯示，在每日營業八小時之假設下，以現況衛星派遣計程車比例為16%、使用衛星派遣服務乘客比例為8.96%的情境下，欲滿足尖峰小時的旅次需求，僅需31,359輛計程車即可達到社會福利最大化之目標；若將外部環境成本合理內部化後，最適之計程車車隊規模將降至30,743輛。相較於現況之54,747輛，本模式所推估計程車總量顯著低於現況的供給，亦證明衛星派遣計程車的營運確實更有效率。此外，根據營運情形的調查資料，本研究分析發現，當衛星派遣計程車的比例高於60 %時，使用衛星派遣的乘客可望增加為現況之1.5倍。本研究亦針對計程車之外部性加以考量，研究結果對於相關單位推動總量管制以及計程車創新服務等政策將有具體助益。

關鍵詞：衛星計程車、巡迴繞行計程車、派遣服務、雙層數學規劃、最佳化

Abstract

Taxi service is featured with convenience, speediness, door-to-door, privacy and comfort so that it has become a popular mode in urban area. With the rapid development of information and communications technologies, GPS-taxi has become a new trend since the distinguished operation performance especially when taxi operation costs increase rapidly. The current fleet size of taxi in Taipei Metropolitan Area has reached 54,747 vehicles while the ratio of GPS-taxi rose to only 16% by 2008.

However, most researches had established models to analyze the performance of cruising taxi market only. To realize the difference features and interactions between the cruising taxi and the GPS-taxi, this study aims to develop a mathematical model with a bi-level concept to explain the interaction of maximum profit objective for drivers and maximum social welfare objective for public sector, respectively. Furthermore, taxi market in Taipei Metropolitan Area is considered as a case study to verify the applicability of the model.

Numerical results showed that the optimal fleet size of taxi was 31,359 vehicles under the current market in which 8.96% of passengers use the dispatch service while 16% of taxis equipped with GPS. Meanwhile, with considering external effects, the optimal fleet size of taxi reduced to 30,743 vehicles. Comparing the existing fleet size of 54,747 in Taipei metropolitan, these optimal results of fleet size have shown an over-supply problem in taxi market. However, the efficiency of GPS-Taxi can also be verified. It was also shown that the ratio of dispatch-used passenger will be 11.18% when the ratio of GPS-taxi is about 60 percentages. In conclusion, the optimal fleet size of taxis estimated by this model might support the public sector to manage the quantity regulation.

Keywords: Cruising taxi, GPS-taxi, Dispatching Service, Bi-Level programming, Optimization

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Chapter Ⅰ Introduction

1.1 Background

Taxi is defined as the paratransit in urban public transportation systems and provides a seamless service for the general public. With the features of convenience, speediness, accessibility, door-to-door, privacy and comfort, taxis have become a popular transportation mode in urban area. For instant, in Taipei Metropolitans, it has a market share about 8-10% of the total ridership and the daily passenger trip is about 1.0-1.3 millions.

There are three major operation approaches of taxis in an urban area, including cruising, scheduling and dispatching as illustrated in Fig. 1-1. Taxi drivers cruising randomly around the city to search for passengers is the most common approach in Taipei Metropolitan Area. Because the drivers cannot predict when and where will come out a demand request, aimless cruising usually leads to an inefficient operation performance and huge meaningless energy consumption. To avoid blindly cruising on the road, scheduling and queuing at particular spots or taxi stands are efficient operation modes for taxi drivers. Currently, the technology of the satellite positioning system is well developed and has widely applied to taxi dispatch system. Since the application of taxi dispatch system shows a distinguishing advantage for both assignment efficiency and taxi drivers in terms of lower cost and higher revenue, the number of taxis embedded automatic dispatching devices, also known as the GPS-taxi, increases apparently.

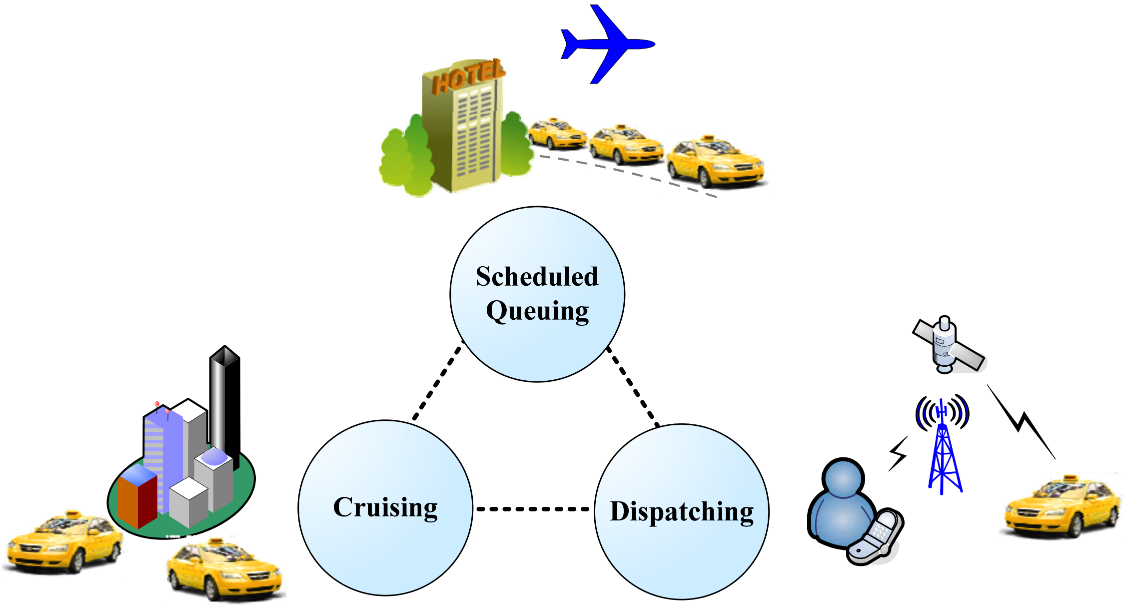

Fig. 1-1 Main operation approaches in a taxi market.

In recent years, over-supply and high vacancy rate have become two of the critical problems in the taxi industry. These problems result in some negative effects such as unhealthy competition between operator, law-breaking behaviors of drivers, and poor social image of taxi industry. In order to characterize the features of the taxi market, previous studies had formulated some mathematical models to provided recommendations of the optimal quantity of taxis and the reasonable vacancy rate.

Despite of quantity control, it is generally believed that the satellite technology could support a good fleet management, provide a better service for passengers, operate with a higher efficiency and decrease the vacant rate of taxis. Lee (2009) pointed out that the ratio of GPS-taxi has got a remarkable rising during a few years because GPS-taxi could provide a better service quality comparing with the conventional cruising taxis. Utilizing the dispatch technology has turned into a new trend in the taxi market. According to the survey conducted by Chang et al. (2008), up to the end of 2008, the number of registered taxis has almost reached to 56,000 vehicles in Taipei Metropolitan area while the ratio of GPS-taxi has reached to 16%.

However, most the mathematical models established by previous studies assumed that the operation model was unitary and all taxis cruised on the road. Since the ratio of satellite usage keeps rising, the dispatching operation model could not be ignored anymore. Huang (2001) suggested that a mixed operation models of taxi market should be considered in order to meet the reality condition more accurately. In addition, there was few research discuss on the external cost and environmental impact of the taxi industry. With a viewpoint of the mobility management, an environment issue could not be neglected.

1.2 Objective

This study aims to develop an analytic model to describe the multi-operation system in which the cruising model and the GPS-dispatch model are included in the taxi market at the same time. Not only the cost of taxi drivers, passengers, and dispatch center are incorporated into this model, but also the external environmental cost is imposed to evaluate the equilibrium results with consideration of both private sector and public sector. In this model, we developed a bi-level programming framework to analyze the interaction and competition between cruising and dispatch taxi models. Moreover, we can also apply the model to obtain the optimal fleet size and ratio of GPS-taxi.

1.3 Methodology

Eykhoff (1974) defined a mathematical model as “a representation of the essential aspects of an existing system (or a system to be constructed) which presents knowledge of that system in usable form.” When optimizing or analyzing a system, researchers often establish a descriptive model to represent the phenomenon in order to gain a better understanding and resolve the problems of the system. Bi-level Programming is one of the adequate approaches of the mathematical modeling when the system consists of two decision makers who make the decision upon different objective and these decision makers will influent other's decision process in the meantime.

In this study, we proposed a bi-level programming mathematical model to describe the taxi market based on two reasons. The first reason is that a mathematical model could provide an analytic result and available solution under basic assumptions when it is hard to simultaneously consider all variables having various influences on the performance of taxi market. The other reason is that the percentage of GPS-taxi and the number of taxis are decided by two different decision makers and objectives. The taxi drivers might change their operation model depending on the net profit they can get. Meanwhile, the Government also adjusts the control policy relying on the performance of the taxi market. Therefore, the approach of bi-level programming mathematical model is applied for this research.

1.4 Outline and Contents

This paper was organized as follows. In Chapter 2, vast previous research literatures were reviewed, including the characteristics and problems of the taxi firm, some weighty mathematical models and the algorithms of be-level resolution. Next, the modeling and formulating process were presented in Chapter 3. The limitations and assumptions were also defined in this section. After developing an analytical formulation, numerical results of a cast study were presented and discussed in Chapter 4. In Chapter 5, the sensitivity analyses of parametric factors were conducted. Finally, several significant remarks and key issues for further research were summarized in Chapter 6. A description of the data and parameters were provided in the Appendix. The flowchart of this study was presented in Fig. 1-2.

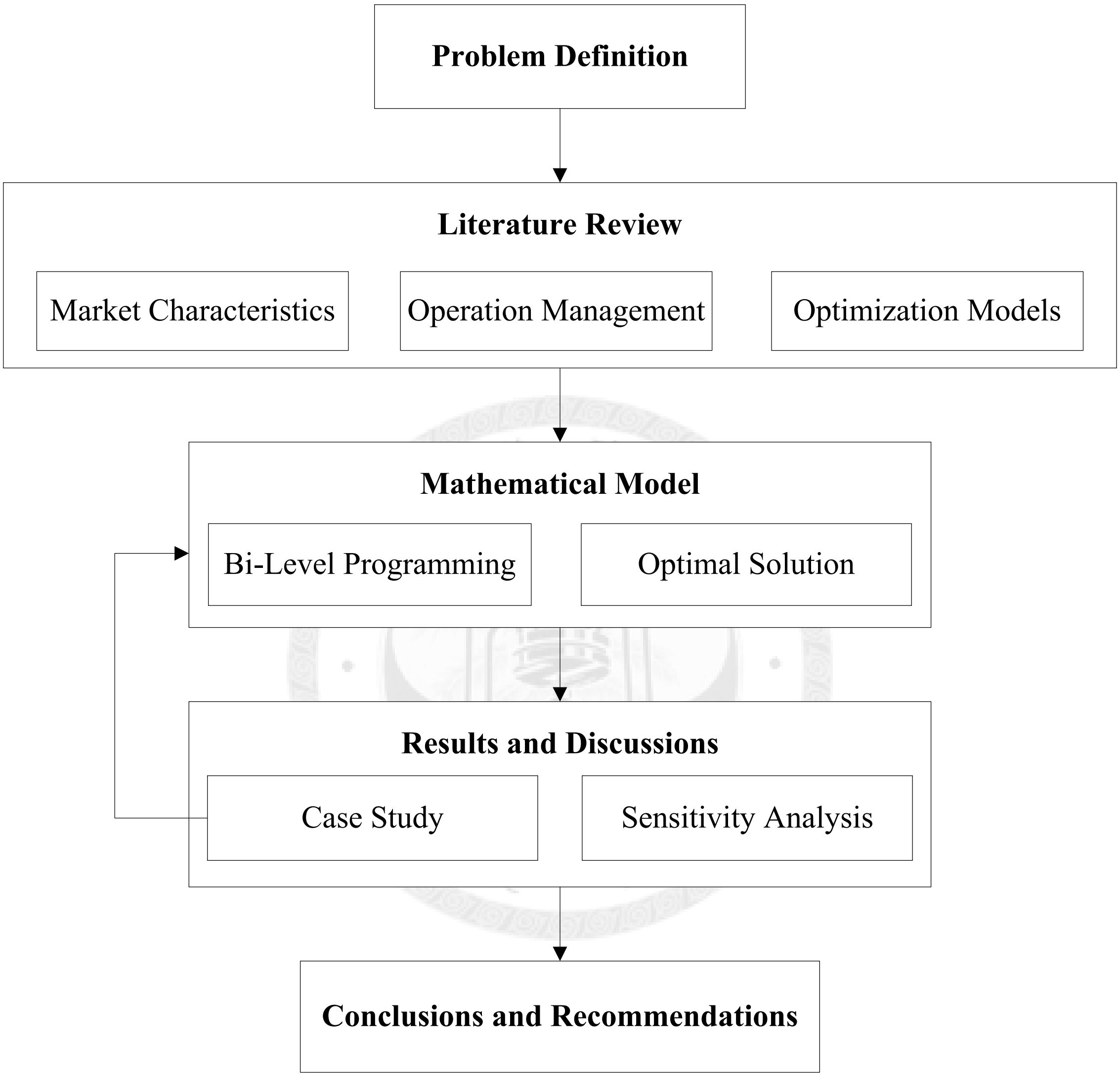

Fig. 1-2 Research flowchart

ChapterⅡ Literature Review

This chapter first conducts an intensive review of research literatures on both supply and demand characteristics in the taxi market and the regulation policies. In the second part, we concentrated on the pros and cons, management features and the future trend of different taxi operation models. Then, the relevant mathematical optimization models focused on the taxi market were reviewed.

2.1 Overview of the Taxi Industry

Operation Characteristics

Since not only providing flexible and convenient service as private transportation, but also fulfilling car pooling and car sharing as public transportation, taxis are defined as a paratransit in theory. Tseng (1989) analyzed the operation and management of taxis and compared taxis with private vehicle and public transportation. Main operation characteristics of taxis are summarized in Table 2-1.

Table 2-1 Operation characteristics of taxis

Operation Characteristic	**Comparison**		
	Public Transit	Taxi	Private vehicle
Flexibility : Route/ Headway	×	○	◎
Parking/Maintenance	◎	◎	×
Transfer/Door to door	×	◎	◎
Driving/Operating speed	×	◎	◎
Privacy/Comfort	×	○	◎
Package carrying	×	○	◎
Accessibility: Waiting time	×	○	◎
Fare rate	◎	×	○

◎: Distinguishing advantage ○: Average ×: Disadvantage

Adapted from Tseng (1989)

Taking Taipei Metropolitan Area as an example, taxis started to operate in the city from 1959 and have become one of the vital modes after half of century. According to the survey of taxi operation in 2008 (Chang, 2008), there were 54,747 registered taxis operating in Taipei Metropolitan Area and the daily ridership of taxis in Taipei Metropolitan Area reached about 1 million, which was near to the total trip of mass rapid transit. This phenomenon indicates that taxis have more volumes and output values than most other public transportation. In terms of the operation revenue, Taipei taxi has an amount of total revenue 42 billion per year, which is about 4 times of the MRT system. Moreover, the Ministry of Transportation and Communications pointed out that the total trip of taxis per day in Taiwan is 1.85 million passengers, which is 4 times than Railway system (0.46 million passengers) and 1.8 times than the MRT system (1.1 million passengers). Thus, taxi has played an important role in the urban transportation system.

Supply and Demand Characteristics

With the operation advantages and the rapid development in economy, the registered taxi ownership increased sharply during 1968 to 1978. Since the end of 1978, the Ministry of Transportation and Communications announced a license control policy. With little effectiveness, there were more than 112 thousand registered taxis in Taipei City till 1998.

To figure out the operation performance of taxi, the vacancy rate is a common evaluation indicator which defined as the vacant mileage over total operation mileage. A reasonable vacancy rate presents a promising service level and the respected waiting time of passenger. In addition, the vacancy rate is also a critical factor to assess the fare rate of taxi. Chang and Huang (2003) analyzed the taxi operation performance in Taipei Metropolitan Area and suggested the reasonable vacancy rate is 33 %. Nevertheless, as shown in Fig. 2-1, which displayed the average vacancy rate cross the eight-year period from 2000, the current vacancy rate apparently surpasses the theoretical analysis.

Fig. 2-1 Average vacancy rate in Taipei Metropolitan Area.

Source: Chang (2008)

This very high percentage of vacancy rate is increasingly alarming, especially with a certain caution of environment and energy issues. Past studies found that the excess supply of taxi led to some negative effects. Lo and Huang (1983) indicated that the negative impacts such as the road occupancy, air pollution and fuel consumption of cruising taxis are 1.72 times than private vehicle. Chang (2008) declared that those vacant taxi vehicles cruising on the road cause a huge loss of fuel cost, more than 5 billion NTD, and may result in more than 280 thousand tons of CO2 emission.

At the end of 2008, the amount of taxis was down to 54,747 vehicles in Taipei, while still higher than the optimal quantity suggested by Chang and Chu (2008).To reduce the excess supply of taxi, the public sector usually adopted the policies such as quantity control and entry control to achieve the balance between the supply and demand in the taxi market.

Control Policies

Recently, increasingly significant problems regarding excessive supply of taxi service and the management of taxi fleet have emerged. Manski and Wright (1976) illustrated the relationship between supply and demand of taxi as in Fig. 2-2. The availability of taxis relies on both the number of taxis and the vacancy rate. This fundamental research also addressed that the control policies, as the entry restrictions and regulated fare structure, are common approaches for the public sector to manage the supply quantity of taxis.

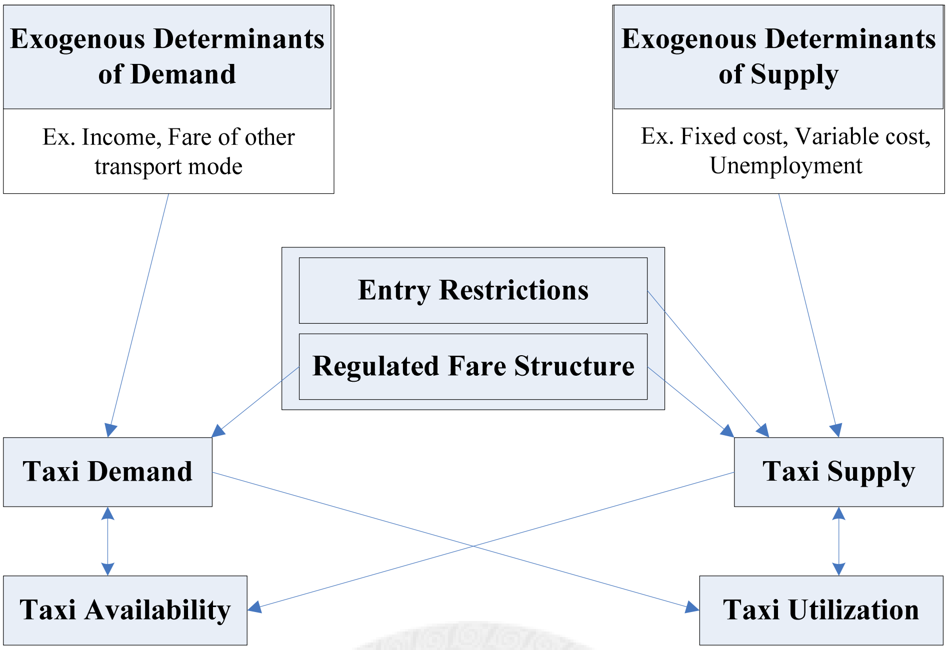

Fig. 2-2 Relations between taxi availability and taxi utilization.
Source: Manski and Wright (1976).

The control policies have been extensively studied in recent years. Shreiber (1975 and 1981) insisted that a regulation of taxi quantity is necessary to establish a competent level of taxi availability. Additionally, restriction on entry is essential in order to avoid undesirable cyclic fluctuations in the quantity of taxis.

In a research article in 1983, Pagano addressed principle indicators including the average cost in terms of per trip, per passenger-mileage, and per vehicle to determine if the taxi industry is economic scale. Taking Chicago city as an example, Pagano found some empirical evidence and mentioned that because the taxi industry was economic scale, properly release the regulation policy was benefit for the taxi market to the most efficient scale.

Unlike the viewpoint of Pagano, Teal (1987) had a contrast observation on the taxi market in America that the number of taxi increased hugely but the taxi fare went upward after the deregulation policy decreed. This phenomenon was due to the decrease income of taxi drivers caused by the oversupply and high vacancy rate. This case also supported that a deregulation may bring the negative effect on the productivity of taxi. In summary of above studies, whether put the quantity control into practice should depend on the social condition and operation performance of taxi market in each city.

Kang (1998) reviewed the control policies of taxi in the USA, the U.K, South Korea, Sweden, New Zealand, Japan, Australia, Ireland and the Netherlands. In this research, Kang reported that the public sector should apply the control policy of taxi quantity and taxi fare when the taxi market reaches some specific conditions. For instance, stringent regulations are necessary in order to ensure the high quality service and improve the safety in taxi market. On the other hand, a deregulation of entry coming with a flexible fare rate may turn out an optimal number of taxis by the market mechanism when the passenger demand is much more than the supply. Moreover, applying advance dispatching system is benefit to the quality of taxi services.

Huang (2003) had examined abundant literatures, including a serious of discussion by Shreiber (1975 and 1981), Coffman (1977) and Williams (1980), and concluded that control policies are more likely suitable for the cruising taxi market; otherwise, Huang propounded that the dispatching or scheduled taxi market might have better performances under the deregulation control.

Feng and Chia (1997) emphasized on the issue of quality management of taxi service which is contingent on the vehicles, drivers, the waiting time of passengers, and the travelling time of passengers. This article further remarked that the information of taxi services is asymmetric between drivers and passengers. With this feature, passengers hail taxis randomly. To guarantee a certain service quality, Chou (2002) established an inspection mechanism of taxi service including the discriminations of engine displacement and age.

2.2 Operation Models

Introduction

Taxis can be categorized by their different operation models. Chou (2002) defined four types of taxi operation model as cruising taxi, queuing taxi, scheduled taxi, and dispatching taxi. Cruising taxi, which also seems as the traditional service type, is majority and plurality in many cities, just like in New York City and Taipei. A cruising taxi goes around on the road without a fixed route and time table while the passenger waits on street. In contrast, queuing taxis usually wait for the passenger at particular points generating plenty taxi demand such as hotels, train stations, department stores or the airports. Queuing taxis are also encouraged for the purpose to control the traffic and reduce aimless cruising. A scheduled taxi, which is easily found in a suburb area, waits for passenger’s reservation or call. Mixed the features of cruising taxis and scheduled taxis, the dispatching taxis (also known as GPS-taxi), which embed radio paging systems or Global Positioning System (GPS) dispatching equipment, can drive around on the road and wait for assignments at the same time. The performance comparisons of various operation models are summarized in Table 2-2.

Table 2-2 Comparison of operation models of taxi

Models	Advantages	Disadvantages
Cruising	Convenience for passengers Operating flexibly with time/route	High traffic volume/ jam High fuel consumption and air/noise pollution Uncertainly waiting/searching time Low taxi utilization
Queuing	Provide safe place to pickup/get off Reduce consumption of fuel More rest for drivers	Lower accessibility Lack of taxi stands Long waiting time for drivers
Scheduled	Suitable for rural area Reduce consumption of fuel More rest for drivers	Lower accessibility Fewer revenue of drivers Long waiting time for drivers
Dispatching	Reduce vacancy rate and searching time Safe and security supervision Reliable fleet quality	High cost of GPS system installation and operation Insufficient supply at peak hour

Source: Chou (2002) and Xu (2005)

In spite of Chou (2002), Xu (2005) analyzed and classified the operation models of taxis based on the availability of location information. For instance, due to both the passengers and the cruising taxi cannot get the location information of each other, the operation model of cruising taxi also named as Random Searching Model. Queuing taxis is waiting for a passenger at a heavy traffic center or stop points so that the location of taxi is capable for passenger, but the location of arriving passenger is unknown for taxi drivers. Hence, this operation model is also called as Fixed-stop Model. On the other hand, there are two types of dispatching taxis classified by their application technology. One kind of the dispatching taxi is operation as Broadcasting Model. When receives a demand request, the control center applies the radio broadcast to notify all the taxi drivers and waits for their response of the relative location and willingness to take this case. Another, GPS-taxi installed the position device on the vehicle can be traced automatically by the dispatch center. Different from the

Broadcasting model, GPS-based Dispatching Model have full location information of both passenger and taxi driver. Therefore, the advance dispatch system is respected to provide a more reliable service and comprehensive supervision on taxi drivers. Table 2-3 shows these four taxi models respectively based on the availability of location information of passengers and taxis.

Table 2-3 Classification of taxi models

Location Information		**Passenger**	
		Unknown	**Known**
Taxi	**Unknown**	Random Searching Model	Broadcasting Model
	Known	Fixed Stop Model	GPS-based Dispatching Model

Source: Xu (2005)

GPS-based Dispatching Taxi

The traditional dispatch method which applied the Radio-paging system was the only mechanism for a taxi company to assign and manage the taxi fleet in the past. However, Xu (2005) has reported that it usually takes a receptionist more than 3 minutes for the dispatching center to identify an available taxi to respond to a passenger's request with radio-paging system. Furthermore, Xu found that about 70% of passengers feel dissatisfied on the noise generated by the broadcast.

In addition, the radio-paging systems could no longer serve such an enlarged consumer market when the demand of taxi services grew. After the Automatic Vehicle Location and Dispatch Systems (AVLDS) first brought up as an advance approach of taxi fleet management in Singapore, radio-paging systems had faded away gradually. The AVLDS consists of interactive voice responses (IVR), differential global positioning systems (DGPS), wireless data communications (WDC) and computerized dispatch systems (CDS). The most distinguished difference between radio-paging system and AVLDS system is if there is control center constructed for the data transmission between the dispatch manager sector and the taxis. By recording and tracing the real time information and location of all taxis, the control center is responsible for the management of the GPS-taxi fleet and assigns the dispatch case to each taxi drivers. The dispatching mechanism has illustrated in Fig. 2-3. Once receiving a demand requirement, the control center would position the location of the passenger by GIS map. Once upon the control center match the GPS-based taxi and passenger successfully by a dispatching algorism, the taxi's registration number and its expected arrival time would be notified to customers.

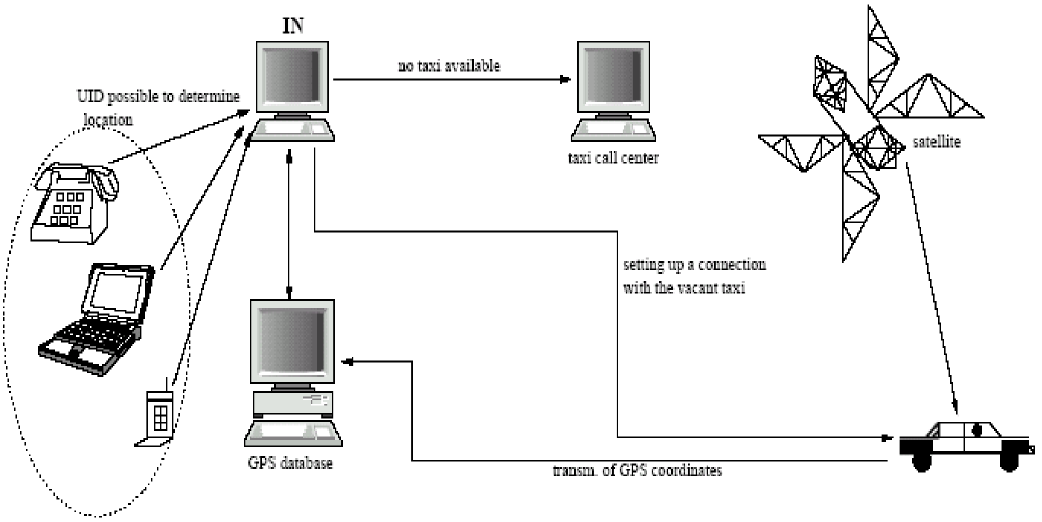

Fig. 2-3 Intelligent dispatching taxi system
Source: Silva and Mateus (2003)

The implement of the Global Satellite Position System (GPS), the Geographic Information System (GIS) and the General Packet Radio Service (GPRS) has radically changed the traditional approach of taxi fleet management. Since GPS-based system could provide a safer supervision and a higher service quality than traditional radio paging taxis, the market share of dispatching taxi is ascending recently.

Liao (2001) investigated three taxi companies in Singapore in terms of the implementation of AVLDS and then explored a plenty of managerial issues associated the taxi dispatching technology. In comparison to the radio-paging systems used previously, the GPS-based dispatch system has considerably enhanced the communications, accuracy, and productivity of taxi operations.

Hshieh (2008) stated that intelligent transportation system just as advanced satellite dispatch technology could reduce the cost of low taxi loading rate, increase the operation efficiency, and gain more income. Therefore, the development of intelligent transportation system in commercial transportation of taxi has become a major direction in near years. To assess the customer influence under this trend, Lee (2009) performed a survey on taxi passengers who had utilized the GPS-based dispatching service. This work emphasized on the investigation of customer needs, decision criterions, and experience of taking taxi dispatching service and then identified the key strategies to fulfill customers' satisfaction and proposed an innovative taxi dispatching services.

Chen and Chang (2004) summarized the merits contributed by applying the intelligent dispatching system. A professional and advance technology could not only erect a better brand image of companies, but also help companies to manage and trace the vehicles accurately. Besides, the more efficient dispatch and real time information of traffic benefit the taxi utilization. The reduction of vacancy rate also has positive effect on decreasing traffic congestion and air pollution. As the intelligent taxi fleet size reaches a certain scale, the delivery speed in GPS model is remarkable better than the traditional radio-paging system as 15 times.

Chang et al. (2007) observed that the operation performance of intelligent dispatching model is more effective than of the traditional cruising model. Furthermore, the GPS-taxis show greater predominance in terms of the efficiency, equity, and capacity than the broadcasting taxis. Some further comparisons between radio-paging system and GPS-based system listed in Table 2-3.

Table 2-4 Comparison of dispatching systems

Function	**Radio-Paging System**	**GPS-based System**
Equipment	Wireless radio page system	GPS/GIS system
Noise	Loud	Quiet
Layout	Broadcast; make mistake easily	Scream; display digitally
Equity	Compete unfairly of drivers	Automatic/computerized dispatch
Interference	Next-channel Interference	Interference-free
Supervision	Driver's behavior w/o surveillance	Location information controlled
Security	Users information unknown	Satellite position
Capacity	300~400 vehicles	10,000 vehicles
Dealing time	2~5 minutes	0.5~1 minute

Source: Chen and Chang (2004) and www.e-cab.com

2.3 Review on Mathematical Models

In general, the relationship of the supply and demand in a taxi market could be represented by taxi availability and taxi utilization (Manski and Wright, 1976), as showed in Fig. 2-2. Founded on this concept, there are two kinds of variables that are usually concerned when formulating theoretical models. One kind of the variables is endogenous like the waiting time for a meeting between a passenger and a driver, the vacancy rate or the demand of taxis. Another is exogenous just as the consumer index, the number of registered taxis, the population, or the taxi fare. Most of the following studies developed their analytic models and assessment on this frame assumption.

Many researchers have applied mathematical models to analyze the taxi industry features, including demand function and supply function. Some diagrammatic and economics analysis of the cruising taxi service have been observed by existing studies.

Douglas (1972) demonstrated a pioneering model based on a log-linear function to explain the demand function of taxis. Because the demand of taxis varies with the fare rate, the waiting time of passengers and the service quality, Douglas regarded the waiting time of passenger as a key factor index of service level. The result of this paper claimed that the operation cost of taxis contributed by the vacancy mileage might lead to the deficit of drivers along with the condition of the first-best solution, also known as the marginal cost pricing rule.

A diagrammatic approach was used by Ferna´ndez et al. (2006) to analyze the characteristics of a cruising taxi market to fulfill the free market equilibrium, social optimum and second best solution. It was presented that a unique equilibrium existed for a deregulated industry and it corresponds to a monopolistic competition under short-run and long-run conditions.

Yang et al. (1998, 2001, 2002, and 2005) reported a series of articles to investigate the operation performance of taxis by a network simulation modeling. A following discussion about taxi service with a bilateral taxi-customer searching and meeting function was then conducted in 2010. Remained consistent with previous evaluations, taxi service should be subsidized at social optimum if there are increasing returns to scale in taxi market. Besides, Yang stated that the service quality and profit of taxi can would never occur the simultaneously rise with taxi fleet size if the meeting function exhibits constant or decreasing returns to scale.

Lo (2004) extended an economic model on the basis of the research of Yang and Wang (1998) to reach two objectives as maximum social welfare and break-even condition. An essential result of this study showed that the existing vacant taxi rate will not sustain the drivers' reasonable wage even with a higher price. Although the waiting time for customers is rather short, it is hardly to reach an optimal equilibrium.

Chang and Schonfeld (1991) observed that there are numerous differences between peak hour and off-peak hour in terms of the demand quantity and the traffic condition. But the excess vacant vehicles meaninglessly cruise on the road, especially during off-peak hour, and thus contribute to a huge social welfare loss. Similarly, Chang and Sun (1997) indicated that single pricing scheme is an unreasonable strategy for taxi market and suggested that the different features between peak hour and off-peak hour should be considered when formulating a pricing strategy.

To analyze the characteristics of cost and benefit between different time periods, Shen (2008) developed a multiple period model which divided 24 hours into 3 intervals, such as peak hour, off-peak hour, and midnight to evaluate the operation cost in each time interval. This work proposed an analysis of the operation features of multiple periods and optimized the fare structure of taxi market in Taipei.

Over-supply and high vacancy rate are two of the critical problems for the taxi industry and usually cause inefficient operation performance. These demerits result in negative effects such as poor service, unhealthy competition, and law-breaking behaviors. Several authors have applied the mathematical model to explain taxi industry features. Chang and Huang (2003) identified that the reasonable vacancy rate associated with operation hours is 33% in Taipei Metropolitan Area. Chang and Chu (2008) explored a model with the objective of maximum social welfare and external effects. With a break-even constraint, an optimal fleet size was obtained. The authors concluded that the existing taxi fleet size in Taipei was almost 40% over-supplied.

Although these works have explored the optimal fleet size of the taxi industry, they mostly focused on the cruising model and neglect the dispatching system. Opposite to Shreiber (1975), Williams (1980) mentioned that the demand function of fixed stop model or dispatching model may differ from the random research model. Based on the presumption of Williams, price competition works because the generation behavior of demand is not random any more. For example, half of passengers in Melbourne took taxis at fixed stop, one third of the passengers made phone calls and only one sixth of the passengers hailed on the street. In this case, the fare rate would decrease along with the market competition and finally achieve an optimal level after deregulation of price been executed. Additionally, some conclusions coinciding with previous literatures showed that if it is given perfect adaptation of dispatch technology, the taxi occupant rate of GPS-based taxis would increase. The declaration of the benefits in terms of safety by dispatching system has also been verified.

However, seldom researchers discuss the difference of operation performance between cruising and dispatching taxis. Likewise, there are few researches quantifying the impact of the externality between these two operation models. A recent study conducted by Chang et al. (2009) evaluated the environmental benefits of the GPS-based taxi compared with the conventional cruising taxi. In this paper, two models in view of different operation mechanisms were progressed. In order to overcome the obstacle to deal with the uncertainty of both demand and supply functions, Chang et al. (2009) assumed that the operation model in a taxi market is unitary, all cruising or all dispatching model, and then compared the optimal fleet size and the environmental benefits saving by adopting all dispatching systems. As the major limitation of the study by Chang et al. (2009), the scenario of “all dispatching model” is an ideal and virtual operation condition which still far from the reality.

2.4 Summary of Literature Review

From the first part of literature review, the quantity regulation of registered taxi is an inevitable issue because of the unbalance between supply and demand of taxi. Additionally, as claimed in the second part, the application of advance satellite technology to taxis is a notable trend but the optimization model been proposed in the past put less emphasis on this operation model.

Therefore, this study attempts to establish a mathematical model to analyze the multi-operation models of taxi market by categorizing the taxi market into two operation models, the randomly cruising model and the advanced dispatching model. In addition to the cost of drivers, passengers and dispatch companies, the cost of external environment effect was also included in the mathematical model. .

ChapterⅢ Model Formulation

3.1 Basic Idea of Bi-level Programming Model

A mathematical model could provide an analytic result and available solution under the assumptions especially when there are too many variables but it is hard to consider all simultaneously. Bi-level Programming is a feasible approach for mathematical modeling when the system consists of two decision makers who make the decisions upon different objective.

For a taxi market, the public sector controls the total number of taxi to supervise the performance and service level of taxis. Meanwhile, the taxi drivers enter the taxi farm responding to the control policy of the Government. Concluding the above phenomenon, it is suitable to represent this interaction relationship by a bi-level programming model.

Basically, the bi-level programming model consists of two sub-models, (U0) is defined as an upper level problem and (L0) is a lower level. A simple example is taken as following equations (1) and (2) (Sun, 2008):

$$\text{(U0)}\ max_x\, F(x,y) \tag{1}$$
$$\text{s.t.}\ f(x,y) \leq 0$$

Where $\mathrm{y} = \mathrm{y(x)}$ is implicityly defined by

$$\text{(L0)}\ min_y\, G(x,y) \tag{2}$$

$$\text{s.t.}\ g(x,y) \leq 0$$

$\boldsymbol{F(x,y)}$ is the objective function of upper-level decision-makers or system managers, and x is the decision vector of the upper-level decision-makers; $\boldsymbol{G(x,y)}$ is the objective function of lower-level decision-makers; y is the decision vector of the lower-level decision-makers. $\boldsymbol{f}(\boldsymbol{x},\boldsymbol{y})$ and $\boldsymbol{g}(\boldsymbol{x},\boldsymbol{y})$ are the constraint sets of the each decision vector; $\boldsymbol{y}=\boldsymbol{y}(\boldsymbol{x})$ is usually called reaction or response function. The key for solving the bi-level programming model is to obtain the response function through solving the lower-level problem and replace the variable **y** in the upper-level problem with the relationship between **x** and **y**. Sun (2008) mentioned some main advantages of bi-level programming models compared with traditional single-level programming model as (a) the bi-level programming can be utilized to analyze two different or even conflict objectives at the same time in a decision-making process; (b) the multiple criteria decision making methods of bi-level programming reflect the practical problem better; (c) the bi-level programming methods can explicitly represent the mutual-action between the system leaders and the followers.

Although the issue of optimal quantity of taxi has been studied broadly, very little attention has been given to formulate the operation model shift of taxi drivers. In fact, the public sector adjusts the strategy to manage the performance of taxi market based on not only the passenger demand but also the operation efficiency of drivers; and at the same time, different control policies and passenger preference would also affect taxi drivers' operation model. Due to the dispatching usage ratio of taxi drivers and the optimal amount of taxis are decided by two different decision makers and objectives, applying a bi-level programming mathematical model to describe the taxi market is suitable.

In this paper, we assume the upper level of the bi-level model represents the decision management process of the planner/leader, namely the public sector, for maximizing the social welfare. As the followers, taxi drivers can freely shift their operation model from traditional cruising model to advanced dispatching model depending on the net profit of taxi driver. Namely, the lower level is to determine the equilibrium point that the net profit of both cruising taxi driver and GPS-taxi driver are equal. The relationship between upper level and lower level are synchronously associated. Once the public sector announces to control the taxi quantity, the taxi drivers may adjust their operation strategy, such as work hour or operation model, to meet a new balance of taxi market. These responses of taxi drivers also influence to the further policy of the public sector. This concept was illustrated as Fig. 3-1.

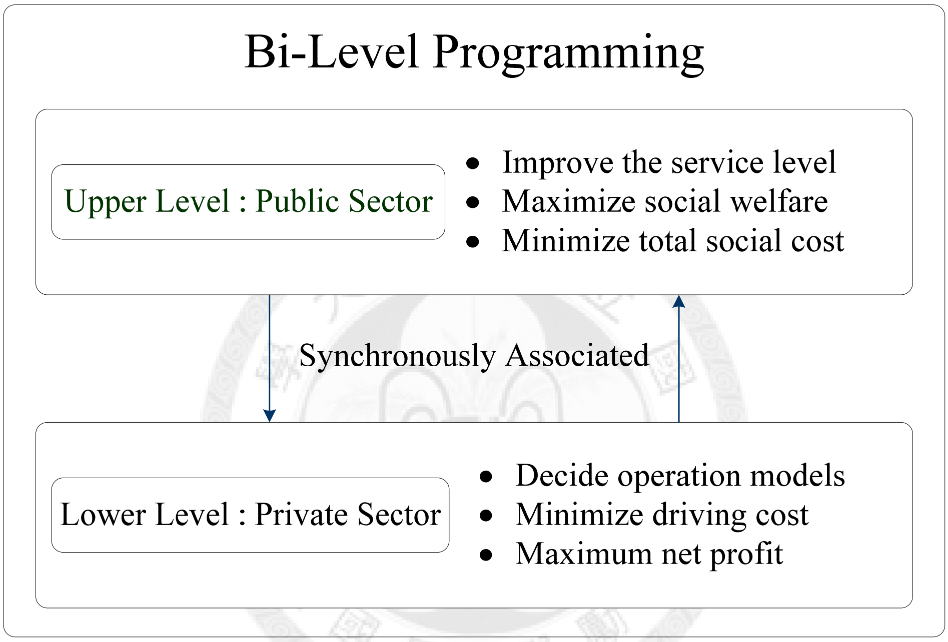

Fig. 3-1 Basic construct of bi-level programming model.

For the fundamental construct of the bi-level mathematical model, we build a bi-level programming as equations (3) and (4):

$$\text{(U)} \quad max_N \ SW \tag{3}$$

$$\text{(L)} \quad \pi(C) = \pi(G) \tag{4}$$

Where **N** is the quantity of taxis vehicle; $\boldsymbol{\pi}(\mathbf{C})$ and $\boldsymbol{\pi}(\mathbf{G})$ are the net profit of taxi driver of cruising taxi and GPS-taxi. The definitions of each notation are addressed in the proceeding section.

Upper level

The upper level is to determine the optimal total number of taxi (**N**) to maximum the social welfare (**SW**). Based on the research of Chang and Schonfeld (1991), when fixed demand is assumed, the optimization objective is maximum social welfare, then the analytic result shows coincidence with the objective to minimize total system cost, which including operator cost and user cost. In this model, with a fixed demand assumption, we can replace this objective function (3) by minimizing total cost of taxi market as equation (5):

$$\text{(U)} \quad min_N \ TC \tag{5}$$

In general, there are four cost functions involve in a taxi market such as driver cost, passenger cost, control center cost, and external environmental cost. This study set two different objectives of upper level. One of the objective functions considered three cost functions as equation (6), including driver cost, passenger cost, and control center cost. Another objective function included the external environmental cost into the total cost function as shown in equation (7).

$$\text{(U1)} \quad min_N \ TC = C_D + C_P + C_O \tag{6}$$

$$\text{(U2)} \quad min_N \ TC = C_D + C_P + C_O + C_E \tag{7}$$

Lower level

The lower level model intends to basically formulate the choice behavior of taxi drivers on the operation model decision. To determine the ratio of GPS taxi ($\boldsymbol{\alpha}$) which represents a competition balance among different operation models, the objective function is to find the equilibrium condition of the net profit for taxi driver.

3.2 Model Assumptions

As can be seen in Fig. 1-1, the operation type in a taxi market is basically classified into three main operation models: dispatching taxi, cruising taxi, and scheduled/queuing taxi. To simply the characteristics of taxi market, this thesis assumes that a multi-operation taxi market is composed of both cruising taxi and dispatching taxi and not concerned here with the scheduled/queuing taxi. Some assumptions are made to clarify the study scope of this research as below.

(1) There are only two kinds of operation models of taxis: the cruising taxi and the dispatching taxi.

(2) A cruising taxi always drives the vacant vehicle on the road to randomly search for passengers. A dispatching taxi embedded the GPS device finds the passengers on the road and waits for the dispatch assignment at the same time.

(3) The total demand of passengers is fixed. The customers can pick the taxis as their own preference as long as they use dispatch technology to book a service.

According to the survey of taxi operation in Taipei Metropolitan Area, which is demonstrated by Chang et al. in 2008, the current number of taxi was about 54 thousand vehicles. In addition, there were about 20 thousand passenger trips using the dispatch technology. Based on this information, we can then determine an optimal fleet size of GPS taxi for existing taxi market by the proposed mathematical model.

3.3 Cost Function

Driver Cost

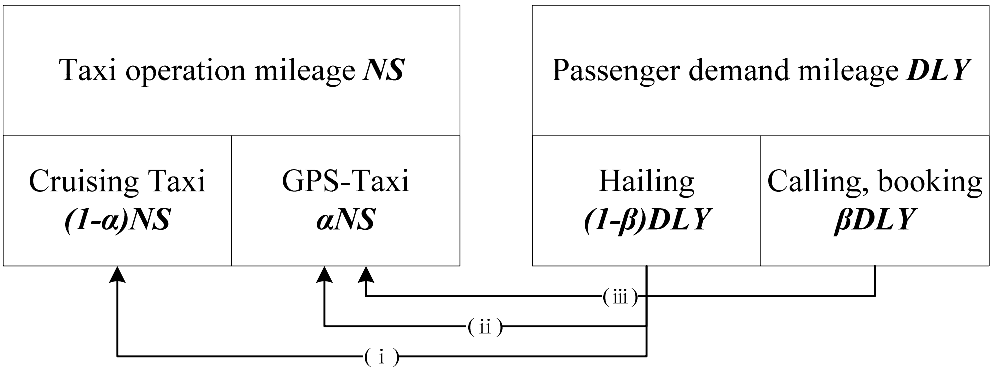

Fig. 3-2 Trip assignments of different taxi operation models.

The fixed demand of the passenger is assumed, so the occupant mileage of the cruising model (cruising taxi) and the advanced dispatching model (GPS-taxi) is expressed as equation (8):

$$T(G) + T(C) = DLY \tag{8}$$

Where,

$T(G)$ is the total occupant mileage of the GPS-taxis (km/hr);

$T(C)$ is the total occupant mileage of the cruising taxis (km/hr);

Y is the average length of per passenger trip (km/trip);

D is the generation density of demand in a taxi market (trip/km-hr);

L is the length of road network in a taxi market (km).

The total amount of taxi drivers is **N** vehicles per hour and the passenger demand is **DL** trips/hr. The passengers hailing taxis at the road side would randomly allocate to a cruising taxi or GPS-taxi. On the other hand, the passengers who make a phone call to book a taxi service only can be assigned to the GPS-taxi rather than a cruising taxi. The passenger trip distribution functions in a taxi market can be written as (9) and (10), where (ⅰ) (ⅱ) (ⅲ) is schematized as Fig. 3-2:

$$T(C) = \text{Random case}\left(\text{ⅰ}\right) \tag{9}$$

$$T(G) = \text{Random case}\left(\text{ⅱ}\right) + \text{Assignment case}\left(\text{ⅲ}\right) \tag{10}$$

As can be seen in Fig. 3-2, **α** is the market share ratio of dispatching taxi and **β** is the proportion of passengers who tend to use the advanced dispatch technology to reserve taxi service. The value of both **α** and **β** are in the range from 0 to 1. Based on above assumptions, the total mileage of GPS-taxis assigned with dispatch cases is equal to $\boldsymbol{\beta DLY}$, which is the total trip length of the passengers booking taxi service by calling to dispatch center. The number of available vacant mileage is conducted by total operation mileage of taxis (**NS)** minus the requirement of dispatching service (**$\boldsymbol{\beta DLY}$)**. Besides, a discount coefficient is considered for the failure dispatch assignment. Sometimes the product of mileage waste due to the unsuccessful dispatch assignments. Thus the improvement of the service reliability and technology efficiency of dispatch system contributes to a smaller discount coefficient. The passenger trip distribution functions are given as follow:

$$T(G) = \beta DLY + \frac{(1-\beta)DLY}{NS-\beta DLY}(\alpha NS - \varepsilon\beta DLY) \tag{11}$$

$$T(C) = DLY - T(G) \tag{12}$$

$$0 \le \alpha \le 1$$

$$0 \le \beta \le 1$$

Where,

α is the ratio of the GPS-taxis;

β is the ratio of dispatch-used passenger;

N is the total number of available taxis (veh./hr);

S is the average operation speed of taxi (km/hr);

ε is the discount coefficient of GPS-taxi.

Additionally, different driver costs of various operation models are concerned in our model. To determine the driving cost of each operation model, $\boldsymbol{C_D(C)}$ and $\boldsymbol{C_D(G)}$ are introduced in equations (13) to represent the driver cost of traditional cruising taxi and advance GPS-taxi. Equation (14) addresses that the driving cost of cruising taxi is directly related with the total operation mileage. As can be seen in Equation (15), the driving cost of GPS-taxi consists of the fixed cost ($\boldsymbol{\lambda^k}$), the cost for cruising mileage ($\mathbf{c_c}$) and the cost for dispatching mileage ($\mathbf{c_d}$). The fixed cost includes all the expense related without mileage such as the miscellaneous expenses, management fee, the rental, the equipment maintenance charges or any other unquantifiable personal factors. The dispatching cost, which as presented in equation (16), is composed of the dispatch fee paid for each assignment case and the driving cost for occupant mileage.

$$C_D = C_D(C) + C_D(G) \tag{13}$$

$$C_D(C) = \mathrm{c_c}(1-\alpha)NS \tag{14}$$

$$C_D(G) = \alpha N\lambda^k + \mathrm{c_c}(\alpha NS - Y\beta DL) + \mathrm{c_d}Y\beta DL \tag{15}$$

$$\mathrm{c_d} = \mathrm{c_c} + \frac{\mathrm{A}}{\alpha \mathrm{NY}} \tag{16}$$

Where,

C_D is the total driver cost of the taxi market (NTD/hr);

$C_D(C)$ is the aggregate driver cost for traditional cruising taxi (NTD/hr);

$C_D(G)$ is the aggregate driver cost for advance GPS-taxi (NTD/hr);

c_c is the average operation cost for cruising per kilometer (NTD/veh.-km);

c_d is the average operation cost for dispatching per kilometer (NTD/veh.-km);

A is the fee paid by driver for each dispatch case (NTD/call);

λ is the fixed cost paid by GPS-taxi driver (NTD/veh.-hr);

k is the coefficient of the fixed cost.

Net profit can be calculated by total operation cost minus the revenue of taxi driver. Hence, substituted by (11), (12), (14) and (15), the functions of net profit of taxi driver can be conducted by (17) and (18).

$$\pi(C) = [P \cdot T(C) - C_D(C)]/(1-\alpha)N \tag{17}$$

$$\pi(G) = [P \cdot T(G) - C_D(G)]/\alpha N \tag{18}$$

Passenger Trip Cost

Passengers decide whether to apply the dispatching technology or not depending on their individual cost or personal preference of passenger such as the tolerance or value of waiting time. These coefficients and parameters will influence passengers' decision and the technology reliance. The individual cost of passenger generally consists of four components:

A. taxi fare,

B. value of waiting time,

C. value of traveling time,

D. Communication fee.

Taxi fare is also regarded as "transfer payment" in one transportation system, so we can dispose this component from our model. Besides, according to the research of Yang (2010), the value of traveling time, which is also known as the time within the taxi, is constant. The passenger cost is given by equation (19) and (20):

$$\overline{C_P}(C) = \qquad \tau Y + t_C W_C \tag{19}$$

$$\overline{C_P}(G) = u + \tau Y + t_G W_G \tag{20}$$

Where,

$\overline{C_P}(C)$ is the cost of per passenger trip hailing taxis on the street (NTD/person);

$\overline{C_P}(G)$ is the cost of per passenger trip using dispatch system (NTD/person);

τ is the value of travel time for passengers sitting in a taxi (NTD/min);

u is the communication fee for calling to dispatch center (NTD/trip);

t_C is the value of time for passengers hailing taxis on the street (NTD/min);

t_G is the value of time for passengers using dispatch system (NTD/min);

W_C is the waiting time for passengers hailing taxis on the street (min);

W_G is the waiting time for passengers using dispatch system (min).

In addition, Yang (2010) claimed that the waiting time should be decided by both the un-served passengers and the vacant taxis. We can assume that:

$$\text{W(waiting time of passenger)} \propto \frac{\text{D(un-served demand)}}{\text{N(available taxi)}}$$

Then, the waiting time of passenger could be obtained by (21) and (22):

$$W(G) = \omega \frac{\beta DL}{\alpha N} \tag{21}$$

$$W(C) = \omega \frac{(1-\beta)DL}{N-\beta DL} \tag{22}$$

$$\omega = \text{constant}$$

Under the assumption that both the passengers and drivers are uniform distribution, we only consider the maximum pickup distance in terms of the drivers, which is equal to $\frac{L}{2N}$, and if the distance of one taxi and passenger is longer than $\frac{L}{2N}$, another taxi cab will pick up the passenger instead. We replace ω into (21) and (22) by $\frac{L}{2NS}$, then get (23) and (24):

$$\overline{C_P}(C) = \qquad \tau Y + t_C \frac{L}{2NS} \frac{(1-\beta)DL}{N-\beta DL} \tag{23}$$

$$\overline{C_P}(G) = u + \tau Y + t_G \frac{L}{2NS} \frac{\beta DL}{\alpha N} \tag{24}$$

To confirm if there exists an obvious threshold for passengers between randomly hailing a taxi and booking a taxi in advance, we can firstly presume that if and only if the additional passenger cost is less than the waiting cost of traditional model, passengers would like to choose the dispatching service model. That is to say, when the average passenger cost of using advance technology $\overline{\boldsymbol{C_P}}(\boldsymbol{G})$ is less than of hailing on the road $\overline{\boldsymbol{C_P}}(\boldsymbol{C})$, passengers tend to apply the dispatching technology rather than hailing taxis on the street. Until this system meets a balance condition, for the general model in the long run, the individual cost of passenger would be the same, $\overline{\boldsymbol{C_P}}(\boldsymbol{G}) = \overline{\boldsymbol{C_P}}(\boldsymbol{C})$, then we can get the distribution percentage of these two kinds passenger.

After verifying by simple numerical test, we found that as $\boldsymbol{\beta}$ increasing, $\overline{\boldsymbol{C_P}}(\boldsymbol{G})$ also rises while $\overline{\boldsymbol{C_P}}(\boldsymbol{C})$ decrease slightly. This result present that the cost of passenger varied with $\boldsymbol{\alpha}$ or $\boldsymbol{\beta}$ is neither significant nor sensitive. Therefore, we assume the ratio of $\boldsymbol{\beta}$ is not directly decided by the cost of passenger.

In fact, the waiting time of the passenger is not the only essential factor when the passengers decide if they would attend the dispatch technology or not. Convenience, safety and security, fare discount, service quality and brand praise are might influence the preference/habit of passengers. In many cases, the passengers take taxis without sufficient information. For example, most of passengers cannot define the quality of the taxi driver and the vehicle before riding in taxis especially the brand praise of the dispatch company did not establish yet. It is reasonable to infer that the incentive of passenger to accept a dispatching technology is not just the quantitative cost. Hence, this study assumed in the optimizing process that the ratio of dispatch-used passenger is fixed no matter the change of the ratio of GPS-taxi or the fleet size.

Control Center Cost

Chang (2009) proposed a control center cost function to evaluate the cost of the dispatch company. The control center cost is direct changed with the number of dispatch center, so the incremental operating cost coefficient of control center is $\boldsymbol{\gamma}$, which shows that the cost of taxi stands is non-linear. Since the marginal operating cost decreasing with the number of control centers, namely the more taxis join the dispatch system, the less management cost would the control center pay, the value of $\boldsymbol{\gamma}$ must be between 0 and 1. The management operation cost is $\boldsymbol{b}$ NTD per vehicle-hour. Modified the cost function of Chang, we then obtained the cost item shown as (25):

$$C_O = (b \cdot \alpha N)^{\gamma} \tag{25}$$

$$0 \leq \gamma \leq 1$$

Where,

C_O is the cost of the control center (NTD/hr);

b is the management cost of the control center (NTD/veh.-hr);

γ is the coefficient of marginal management cost of the control center.

External Environmental Cost

The growth of the number of commercial vehicle such as taxi has increased the intensity of movement that leads to the increase of traffic delays and the raised charge of fuel. The frequent stops and congestions of cars on crossroads both contribute to the raised pollution. Many researchers have been conscious of the environmental subject and expanded a range of analytic work on the social cost issue. Social costs refer to the costs imposed on society from transportation activities but not belong to the direct financial transactions. The common approach to evaluate the social costs is to quantify and monetize the impacts of transportation activities. The external impacts and the cause-effect chart are illustrated as Fig. 3-3.

In general, four social costs are considered as the external cost including air pollution, noise, accidents and road congestion. Thus, the external environmental cost represented as (26):

$$C_E = \left(C_{air} + C_{noise} + C_{accident} + C_{congestion}\right)NS \qquad (26)$$

As a result demonstrated by Chang and Guo (2007), the external costs in terms of taxi is 0.254 NTD/vehicle-km of air pollution, 0.043 NTD/vehicle-km of noise pollution, 0.84 NTD/vehicle-km of accident cost and 3.19 NTD/vehicle-km of congestion cost.

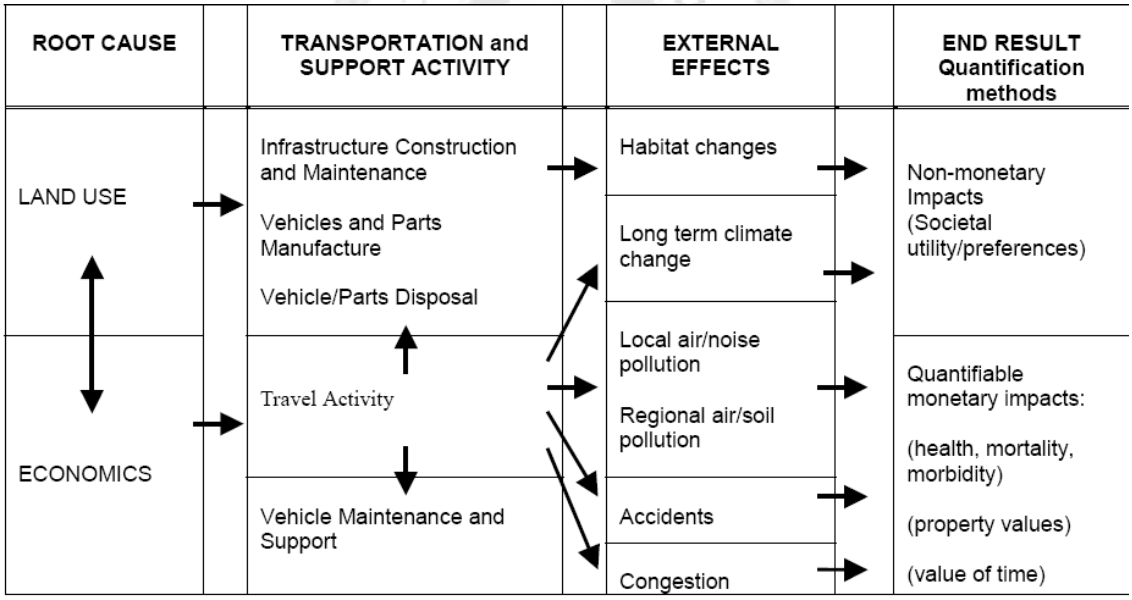

Fig. 3-3 Transportation externality cause and effects

Source: English (2000).

3.4 Multi-Operation Model

The external cost was little considered in the past when decision makers evaluating the optimization for transportation system. This study presumes two decision principles of the public sector: (1) total cost is composed of three cost functions, as the driver cost, the passenger cost, and the control center cost; (2) total cost is composed of four cost functions, like the driver cost, the passenger cost, the control center cost and the external environmental cost. In a word, we can summarize this chapter and rewrite the multi-operation model as equations (27)-(30).

$$\text{(U1)}\quad min_N\ C_D + C_P + C_O \tag{27}$$

$$\text{(L)}\quad \pi(C) = \pi(G) \tag{28}$$

and

$$\text{(U2)}\quad min_N\ C_D + C_P + C_O + C_E \tag{29}$$

$$\text{(L)}\quad \pi(C) = \pi(G) \tag{30}$$

To perform mathematical calculations, this paper followed the solving procedure as below: Firstly, the number of taxi ($\mathbf{N_0}$) and the ratio of dispatch-used passenger ($\boldsymbol{\beta}$) are input into the lower level. To meet the objective function of lower level, the ratio of GPS-taxi ($\boldsymbol{\alpha}$) is conduct. Secondly, $\boldsymbol{\alpha}$ is input into the upper level to perform the objective function of the public sector and then conduct an optimal total number of taxi ($\mathbf{N}$). Then, the lower level is calculated again with a new input of $\mathbf{N}$ and get new distribution of $\boldsymbol{\alpha}$. The computing procedure repeats until the solutions of $\boldsymbol{\alpha}$ and $\mathbf{N}$ are convergent. Finally, while the optimal result $\boldsymbol{\alpha}^*$ and $\mathbf{N}^*$are obtained, $\boldsymbol{\beta}^*$ could be estimated based on $\boldsymbol{\alpha}^*$. The flow charts of solving procedure of multi-operation model are sketched as Fig. 3-4 and Fig. 3-5.

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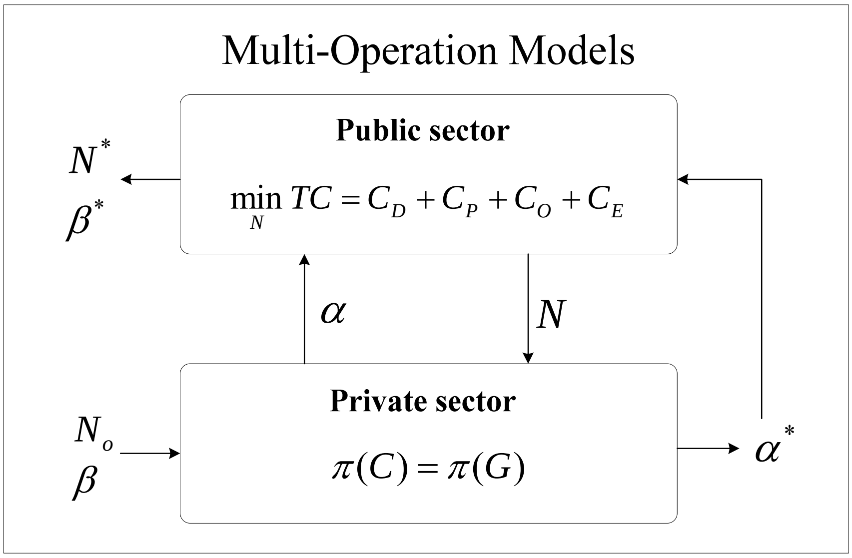

Fig. 3-4 Solving procedure of multi-operation model.

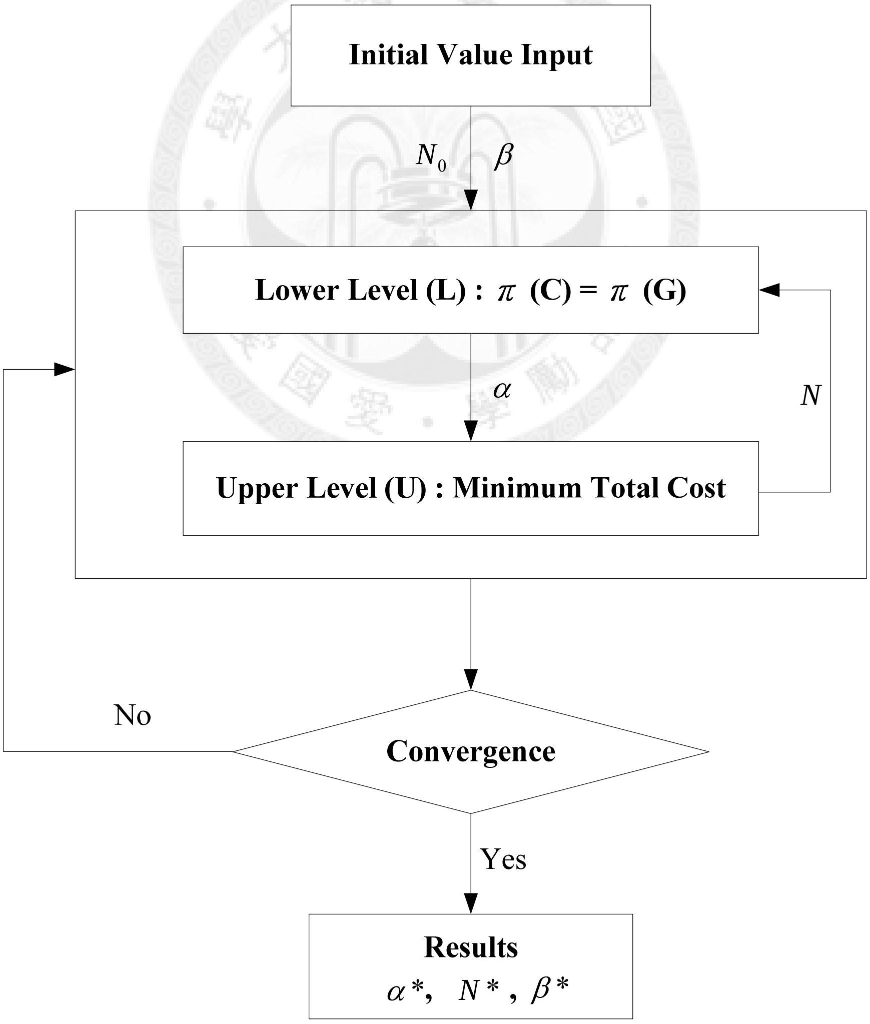

Fig. 3-5 Detailed solving procedure of multi-operation model.

ChapterⅣ Results and Discussions

In Chapter Ⅲ, the concept of the mathematical model of taxi market was developed. To examine the feasibility of the model proposed for the multiple operation models, a numerical example was presented in this section. This paper directly adopted Excel Solver tool to perform the algorithm process. Because the solving procedure is repeatedly performing the same actions, a macro is created in Excel by the Macro editor. All the parameter of the numerical example, which had been identified based on the survey of actual behaviors observation of taxi market, were input into the bi-level model.

4.1 Parameters setting

The parameters involved in this numerical analysis, such as the length of road network, the trip generation density of taxi demand, the average trip length of each taxi service, the average fare rate of each taxi trip, were set by the survey of Chang in 2008. The value of time of passengers on/off the taxi followed the setting in Chang and Chu's study (2008) as 4.77 NTD/min. The communication fee for calling to dispatch center was determined by the current communication fare rate as 6 NTD/call. The management cost of the control center, and the coefficient of marginal management cost were set according to the study of Chang et al. in 2009. Otherwise, some baseline value of the parameters estimated by this study were analyzed the sensitivity and reasonability in Chapter Ⅴ. All the baseline value of the parameters set in the numerical analysis were listed in Table 4-1.

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Table 4-1 Parameters' baseline setting for the numerical analysis

Parameter		**Unit**	**Baseline Value**
Length of road network	L	Km	2732
Average trip generation density of taxi demand	D	Trips/km-hr	9.23
Average length of taxi trip	Y	Km/trip	4.95
Average fare rate of each taxi trip	P	NTD/trip	178.87
Value of time of passengers off vehicle	t_c	NTD/hr	286.2
Value of time of passengers in vehicle	τ	NTD/hr	286.2
Communication fee calling to control center	u	NTD/call	6
Operation speed of taxi	S	Km/hr	23.38
Dispatch fee paid by driver for each case	A	NTD/case	10
Management cost of control center	b	NTD/veh.	10
Coefficient of marginal management cost	γ	-	0.9
Average operation cost for cruising	c_c	NTD/veh.-km	30.88
Fixed cost of GPS-taxi	λ	NTD/veh.-hr	15
Coefficient of the fixed cost	k	-	1.5
Discount coefficient of GPS-taxi	ε	-	1.2

By substituting the parameters setting in Table 4-1 into the multi-operation model developed in this study and then following the solving process stated in section 3.4, the solutions of each solving stage could be conducted. The first stage demonstrated the ratio of GPS-taxi ($\boldsymbol{\alpha}$) by setting a baseline value of the number of available taxi per hour ($\mathbf{N_0}$). $\mathbf{N_0}$ is simply conducted by the following equation:

$$N_0 = \frac{\text{Total number of taxi fleet size (veh.)} \times \text{average operation hours (hr/day)}}{24\ \text{(hr/day)}}$$

According to the report of Chang et al. (2008), the total number of registered taxi is 54,747 vehicles and the average operation hours are 12.17 hours. Thus the initial value $\mathbf{N_0}$ was set as 27,761 veh./hr. After substituting $\mathbf{N_0}$ into the lower level, the results with each different objective functions could be found in the next sections.

4.2 Optimization Solutions

There are about 600,000 taxi trips per day in Taipei Metropolitan Area in 2008. Among this, the population of passengers who utilizing the dispatch technology to book taxi services is nearly 8.96% in 2009 (Lee, 2009). According to the survey (Chang, 2008), the average driving cost for taxi driver ($\mathbf{C_c}$) was 30.38 NTD/veh.-km and the average trip generation density of taxi demand was 9.23 trips/km-hr. Therefore, the initial value of the ratio of dispatch-used passenger ($\boldsymbol{\beta}$) was input as 8.96% and the number of available taxi ($\mathbf{N_0}$) was input as 27,761 veh./hr .

Based on these assumptions, the equilibrium condition that the net profit of cruising taxi is equal to the net profit of GPS-taxi was fulfill in lower level. As a result, the ratio of GPS-taxi was 79.93%. Secondly, inputting this result into the upper level, we got the optimal number of taxi was 4,249 veh./hr without the consideration of external effect and got 4,144 veh./hr with the consideration of external effect. Subsequently, input the quantity of taxi into lower level by 4,249 veh./hr and 4,144 veh./hr, the ratio of GPS-taxi could be conducted again. By repeating this solving procedure, we then finally got convergent solutions as presented in Table 4-2. As the trip generation density of taxi demand is 9.23 trip/km-hr and with the consideration of external effect, the first solution of number of taxi is 4,144 veh./hr and the second solution of number of taxi is 4,157 veh./hr. The change between these two solutions is less than 1% and can be thought as convergent. Hence, the second solution is regarded as the optimal result for the given scenario.

Table 4-2 Convergence of the results in terms of the number of taxi ($\beta = 8.96\%$)

Demand density (trip/km-hr)	**Without external cost**			**With external cost**		
	Number of taxi (veh./hr)	**Optimal number (veh./hr)**	**Difference**	**Number of taxi (veh./hr)**	**Optimal number (veh./hr)**	**Difference**
4.615	2,480	2,480	-0.00%	2,410	2,410	-0.02%
9.230	4,249	4,264	+0.35%	4,144	4,157	+0.29%
27.69	10,454	10,453	-0.01%	10,248	10,248	-0.01%

With different trip generation density of taxi demand inputting, the model can conduct the optimal fleet size respectively. That is, we could evaluate the optimal number of taxi for different taxi demand by this model. With the basic knowledge, a high trip generation density of taxi demand is usually happened during the peak hour and rainy day, or occurs around the shopping district and transfer station. Moreover, the prosperity business climate may also increase the demand of taxi service.

Since the taxi service is wildly believed as the paratransit, the reasonable vacancy rate for operation is required to provide a well level of service. Therefore, the peak hour demand should be take into account. For instance, as the trip generation density of taxi demand is 9.23 trip/km-hr, which is equal to the daily average demand density, the optimal fleet size of taxi is 12,791 veh./hr. While the peak hour demand is triple than the average one, which is equal to 27.69 trip/km-hr, the optimal fleet size rises to 31,359 vehicles. Moreover, if the external cost is concerned, the optimal fleet size would cut down to 30,743.

Table 4-3 Optimization results ($\beta = 8.96\%$)

Demand density (trip/km-hr)	**Without external cost**			**With external cost**		
	Number of taxi (veh./hr)	**Fleet size (veh.)**	**Optimal ratio of GPS-taxi**	**Number of taxi (veh./hr)**	**Fleet size (veh.)**	**Optimal ratio of GPS-taxi**
4.615	2,480	7,440	54.11%	2,410	7,229	55.32%
9.230	4,264	12,791	59.29%	4,157	12,470	59.89%
27.69	10,453	31,359	63.03%	10,248	30,743	63.31%

Table 4-3 reported the results with different trip generation density of taxi demand. These results showed that when the trip generation density of taxi demand rises, both the optimal fleet size and the ratio of GPS-taxi are increasing as well. In addition, Fig. 4-1 illustrated the trend of optimal ratio of GPS-taxi against the density of taxi demand. This trend might suggest that when the demand of taxi service is fewer than average, GPS-taxi can provide an obvious efficiency on operation performance so that more taxi drivers would shift their operation model toward dispatch model. On the other hand, when the demand of taxi service is higher than average, but the available taxi fleet size is limited, cruising taxi can easily find the passenger by the roadside. As a consequence, the advantage of GPS-taxi is unapparent when the demand density increasing gradually.

Moreover, comparing the results with the external effect consideration to the results without external effect consideration, the optimal fleet size of taxi slightly decreased whereas the ratio of GPS-taxi increased as sketched in Fig. 4-1. This difference between with and without external cost consideration could lead to a presumption that in the view of the internalization of the external cost into taxi drivers may promote for the advance dispatch technology and effectively amend the taxi industry.

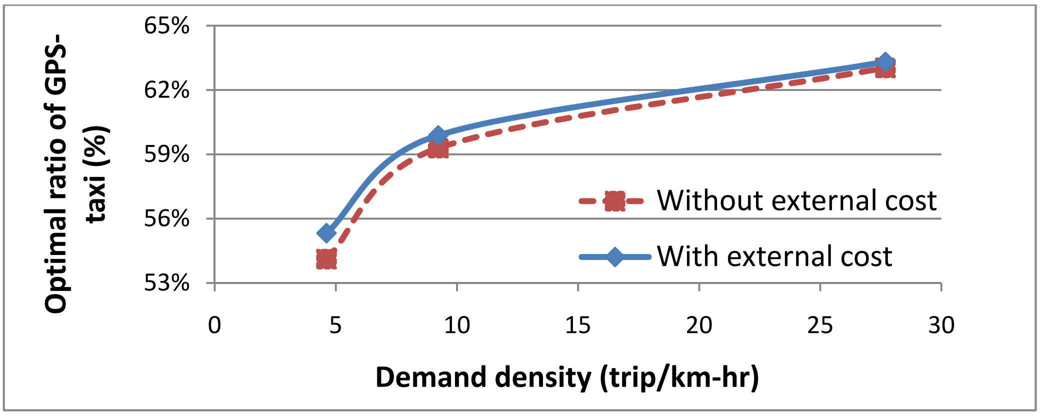

Fig. 4-1Comparison of the ratio of GPS-taxi with different objectives.

Fig. 4-2 and Fig. 4-3 depicted the change of total cost against the number of taxi. The total cost decreases at first until reach the lowest point, which is also regarded as the optimal number of available taxi, and then the total cost rises along with the number of taxi increasing. These results provided evidence that the optimal number of taxi estimated by the model would cost less expense indeed.

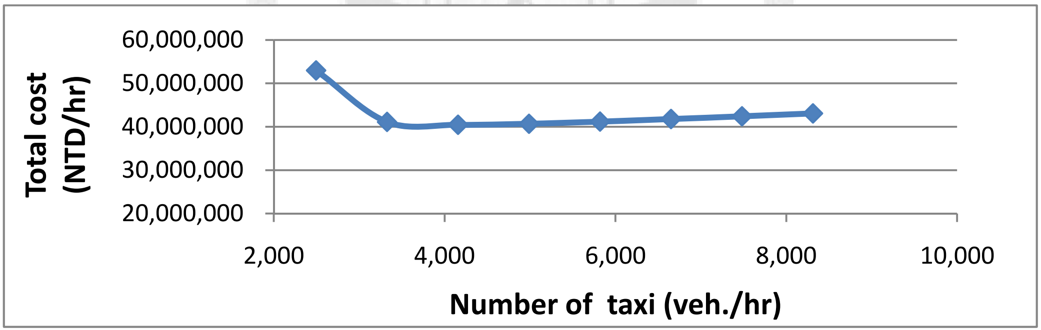

Fig. 4-2 Total cost against the number of taxi as D=9.23 trip/km-hr.

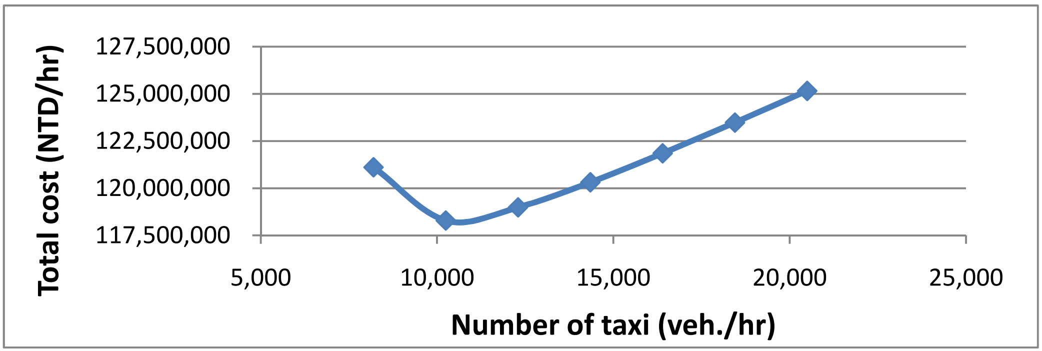

Fig. 4-3 Total cost against the number of taxi as D=27.69 trip/km-hr.

4.3 Performance Evaluation

Preference of Passenger

The preference behavior change of passengers is influenced by the successful implementation of advance dispatch system. As Liao (2001) claimed, the use of GPS-based taxi dispatching provides customers with great convenience. Customers benefit from the technological change because they no longer face the frustration of having to wait a long period of time before a confirmation of a taxi assignment.

Hwang and Jain (2006) identified primary factors that affect consumer preference on using the advance dispatch taxi service in Taichung City, Taiwan, by analyzing consumer responses from a survey conducted in that city. Four key factors such as comfort, convenience, reliability, and safety were then proposed. Nevertheless, as a research on the choice intention of customers by Hwang and Lai (2008), the intention to choose a GPS-taxi over a traditional one usually varied and showed variable priority of these factors in terms of different cities.

It is hard to accurately formulate the ratio of dispatch-used passenger; otherwise, the regression analysis could be applied to simply demonstrate the relationship between the ratio of GPS-taxi and the ratio of dispatch-used passenger. Lee (2009) has investigated the development history and operation performance of GPS dispatching system in Taiwan and Singapore over the years. Based on the data reported in Table 4-4 and Fig. 4-4, the following equations (25) and (26) were proposed.

Table 4-4 Survey of the usage of dispatch system

	Taiwan					**Singapore**
Date	2001	2004	2004	2006	2009	2009
Registered taxi	63,258	59,046	59,046	57,185	54,747	24,288
Fleet size of GPS-taxi	1,690	600	1,400	6,000	9,000	23,852
Ratio of GPS-taxi (α)	2.67%	1.02%	2.37%	10.49%	16.44%	98.20%
Daily total trip of taxi	803,092	848,263	848,263	716,541	669,592	588,632
Dispatch-used* (β)	1.25%	0.12%	0.71%	4.19%	8.96%	13.61%

*Dispatch-used (β): the ratio of passenger booking taxi service by dispatch technology.

Source: Lee (2009) and Chang (2008).

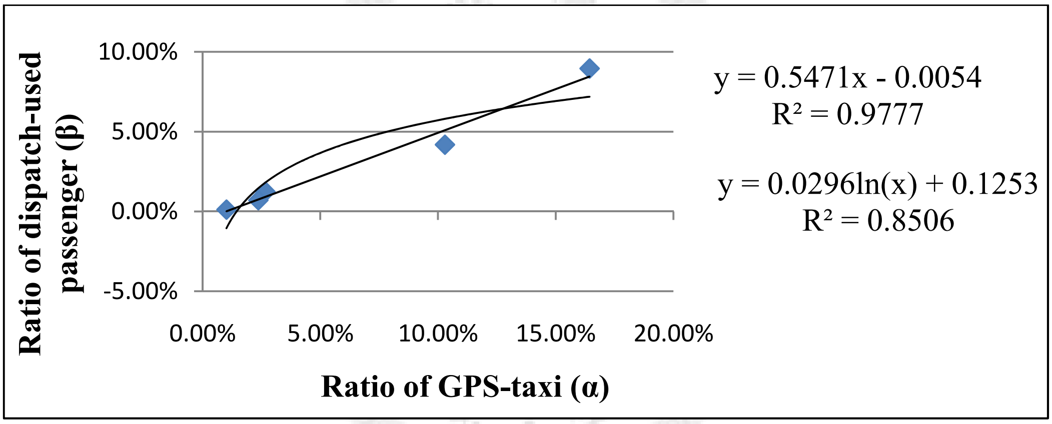

Fig. 4-4 Regression diagram of the preference on dispatch using of passenger.

$$\beta = o.5471\alpha - 0.0054 \tag{31}$$

$$R^2 = 0.9777$$

$$\beta = o.0296\ln\alpha + 0.1253 \tag{32}$$

$$R^2 = 0.8506$$

The current operation performance in Singapore was examined to verify the preference on the dispatch service usage of passenger. As estimated by the linear regression model as shown in (31), the ratio of dispatch-used passenger was about 55.89%. In terms of the log-linear regression model (32), the ratio of dispatch-used passenger was about 13.89%. Though the log-linear regression model provide an estimation similar to the reality, the performance of the ratio of dispatch-used passenger in the taxi market was evaluated by both linear and log-linear regression models since the limitation with the finite data in reality.

As a result, while the ratio of GPS-taxi is near to 63%, the ratio of dispatch-used passenger would be estimated as 33% by the linear regression model (31) and as 11% by the log linear regression model (32). Table 4-5 summarized the estimations of the ratio of dispatch-used passenger by both the linear and log linear regression model.

Table 4-5 Estimation of the ratio of dispatch-used passenger

	Fleet size of GPS-taxi (veh.)	**Ratio of GPS-taxi (%)**	**Ratio of dispatch-used passenger**	
			Log linear	Linear
Existing	9,000	16.44	7.19%	8.45%
No externality	19,767	63.03	11.16%	33.95%
With externality	19,464	63.31	11.18%	34.10%

Waiting time of passenger

There are plenty of reasons for passengers to choose a service type, and one of them is the waiting time of passenger. The waiting time is reasonably taken regard as an index of level of service and might influence the portion of dispatch-used passenger. Although the waiting time is not the only key factors for passenger when the passenger makes the ridership decision, it is still an important indicator to evaluate the performance of taxi service. The effect of the ratio of GPS-taxi on the waiting time of passenger was examined here. The ratio of GPS-taxi obtained in this chapter was input to the equation (21), (22) and (31) to fulfill Fig. 4-5. This diagram expresses the relationship between the waiting time of passenger and the ratio of GPS-taxi while the ratio of dispatch-used passenger was estimated by the log-linear regression model. As can be seen, the waiting time of dispatch-used passenger is apparently lower than the passenger randomly hailing on the street.

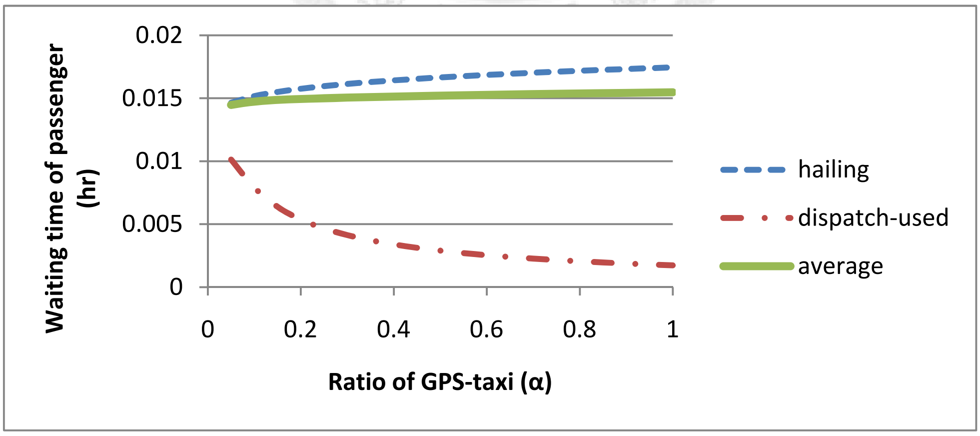

Fig. 4-5 Effect of ratio of GPS-taxi on waiting time of passenger.

4.4 Discussions of Results

In conclusion, this study eliminated the effect on personal preference of passenger for decision making to simply evaluate the likeable tendency of the optimal number of taxi and the optimal ratio of GPS-taxi by the numerical result. Besides, the validation of multi-operation model of taxi market was examined. With the assumption of a flat ratio of dispatch-used passenger, after inputting the initial ratio of dispatch-used passenger as 8.96% and the existing available taxi supply as 27,761 veh./hr, the optimal fleet size of taxi conducted by this model is 31,359 vehicles if the operation hours equal to 8 hours per day.

Considering the external effect, the size of taxi fleet would slightly cut down to 30,743 vehicles when the ratio of dispatch-used passenger kept as 8.96%. This outcome declared that the total number of taxi should be reduced by 2.08% while the fleet size of GPS-taxi increased by 5.02% when the external effect was taken. Therefore, a reasonable inference is proposed that the internalization of the external cost of taxi drivers and reduce the fleet size of taxi while promoting the advance dispatch technology might effectively amend the taxi industry.

Furthermore, comparing with the optimal fleet size in a cruising taxi market estimated by Chang and Chu (2008), the fleet size would decrease by 11,036 vehicles when the implement of advance dispatch system is more broadly. These comparisons showed the benefit and advantage of applying advance dispatch system in the taxi market once more. In terms of the vacancy rate with distance-based, the performance of the multi-operation model is significantly less than the existing status. However, due to the assumption of the operation model is still cruising around the city, the average vacancy rate still higher than 33%, which is regard to the reasonable vacancy rate. In reality, the GPS-taxi could get the dispatch case even without cruising on the road; as a result, the actual operation mileage should noticeable less than the conventional cruising taxi. Thought we might a little overestimate the vacancy rate, this model still could provide a basic comparison with the existing status. Table 4-6 listed some related studies which also took the Taipei Metropolitan Area as a numerical example and presented several basic comparisons in terms of the fleet size and the vacancy rate.

Table 4-6 Comparisons with previous studies and existing status

		Fleet Size		**Vacancy Rate**	**α**[1]	**β**[2]
Existing Status		54,747	-43.85%	70.04%	16.44%	8.96%
Chang & Huang	2003	52,142	-41.04%	33.33%	-	-
Chang & Chu	2008	41,779	-26.42%	13.98%	-	-
Shen	2008	39,728	-22.62%	36.65%	-	-
Chang et al.	2009	29,627	3.77%	30.69%	100%	-
Lin (this study)	2010	30,953	-	52.54%	67.48%	11.37%

1. α : Ratio of GPS taxi
2. β : Ratio of dispatch-used passenger

Table 4-7 summarized the results of the optimization model for multi-operation models and compared these results with the existing performance of the cruising taxi market in Taipei Metropolitan Area.

Table 4-7 Results of the optimization model for multi-operation models

Variables		**Existing**	**Without external**	**With external**
			β=8.96%	**β=8.96%**
Number of available taxi (veh./hr)	Ave.[1]	6,446	4,264	4,157
	Peak[2]	16,530	10,453	10,248
Taxi fleet size (veh.)		54,747	31,359	30,743
Ratio of GPS-taxi (α)	Ave.	16.00%	59.29%	59.89%
	Peak	16.00%	63.03%	63.31%
Vacancy rate (distance-based)[3]	Ave.	59.70%	58.26%	57.19%
	Peak	56.90%	48.93%	47.90%
Average passenger's waiting time (hr)	Ave.	0.0218	0.0846	0.0914
	Peak	0.0143	0.0553	0.0596
Total cost (NTD/hr)	Ave.	40,663,361	40,010,788	40,438,207
	Peak	119,519,014	117,239,161	118,287,906
Net profit of taxi driver (NTD/hr)	Ave.	-71,618	19,117,577	19,197,397
	Peak	798,450	59,099,299	59,253,414

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[1] Duration at which the trip generation density of taxi demand is equal to the average, D=9.23.

[2] Peak hour duration, at which the trip generation density of taxi demand is equal to 27.69.

[3] Vacancy rate (distance-based): the ratio of vacant mileage per hour over the operation mileage per hour.

Chapter Ⅴ Sensitivity Analysis

In order to clarify the impact on the optimal number of taxi and the ratio of GPS-taxi by different parameters setting, the sensitivity analyses were implemented in this chapter. By applying incremental change in the parameters and coefficients of bi-level model, the degree of sensitivity and the effect on the output value could be obtained. At each analysis paragraph, the parameters were set as the baseline values at Section 4.1 except for the target factor. The influence diagrams in terms of the demand side parameters and the supply side parameters were discussed in the following paragraphs.

The parameters involved in this numerical analysis can be basically classified as demand side parameters and supply side parameters. In the first part, the parameters of supply side, such as driving cost of taxi driver, operating speed of taxi, the fixed cost paid by GPS-taxi driver, the discount coefficient, the coefficient of the fixed cost, the coefficient of marginal management cost of the control center, the length of road network, the management cost of the control center and the fee paid by driver for each dispatch case were examined. In another part, the sensitivity analysis of the parameters of demand side, such as length of taxi trip, communication fee calling to control center, the value of time of passengers in vehicle, the value of time of passengers off vehicle, fare rate of each taxi trip, trip generation density of taxi demand and the ratio of dispatch-used passenger were conducted.

5.1 Effect of Supply Side Parameters

Driving cost of taxi driver (C_c)

Fig. 5-1 and Fig. 5-2 present the influence upon the ratio of GPS-taxi and the number of taxi as the driving cost of taxi driver changing. When the driving cost of taxi driver is rising, which might caused by the rising price of fuel or inefficient operation, there was an increase of ratio of GPS-taxi and a drop of the number of taxi. In terms of different demand condition, as can be seen in Fig. 5-1, the ratio of GPS-taxi is more sensitive, while the slope is higher, under the average demand condition (D = 9.23 trip/km-hr) than under the peak demand condition (D = 27.32 trip/km-hr). This trend could provide an indication that the GPS-taxi operates efficiently so that more taxi shift the operation model from conventional cruising to advance dispatching model when the loading of the driving cost for taxi drivers inflate. In contrast, the number of taxi is more sensitive under the peak demand condition than under the average demand condition as depicted in Fig. 5-2. But both of them have the same trend that the number of taxi decreasing as the driving cost rising. This result give an inference that as the driving cost remarkably rising, fuel price rising as an example, the GPS-taxi might have a comparatively advantage.

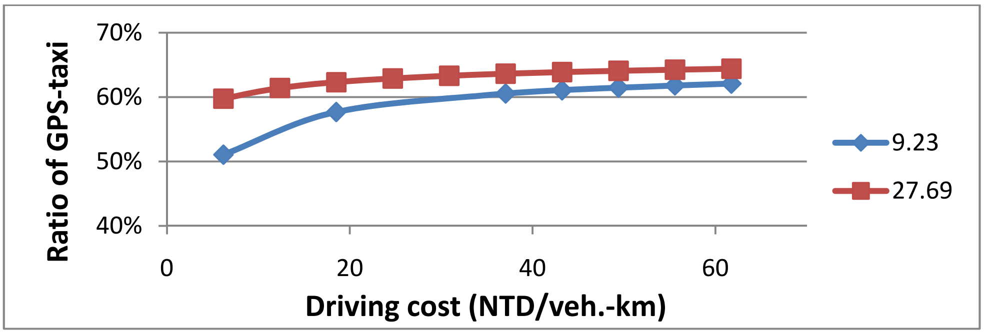

Fig. 5-1 Effect of driving cost on the ratio of GPS-taxi.

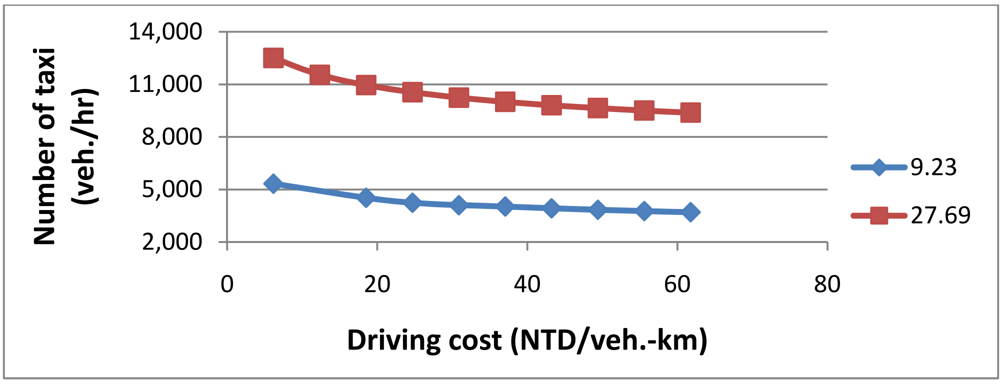

Fig. 5-2 Effect of driving cost on the optimal number of taxi.

Operating speed (S)

Fig. 5-3 displays the influence on the number of taxi as the average operation speed of taxi driver changing. When the operation speed rises, the number of taxi could be reduced but still supply the same operation mileage to customers. In terms of different demand condition, as can be seen in Fig. 5-3, the number of taxi is more sensitive under the peak demand condition (D = 27.69 trip/km-hr) than under the average demand condition (D = 9.23 trip/km-hr). This outcome suggested that the release of traffic congestion might do a significant benefit to reduce the quantity of taxi especially during the peak hour. On the other hand, less taxi aimlessly cruising on the street contributes to a smoother traffic flow which performs a higher operation speed as well.

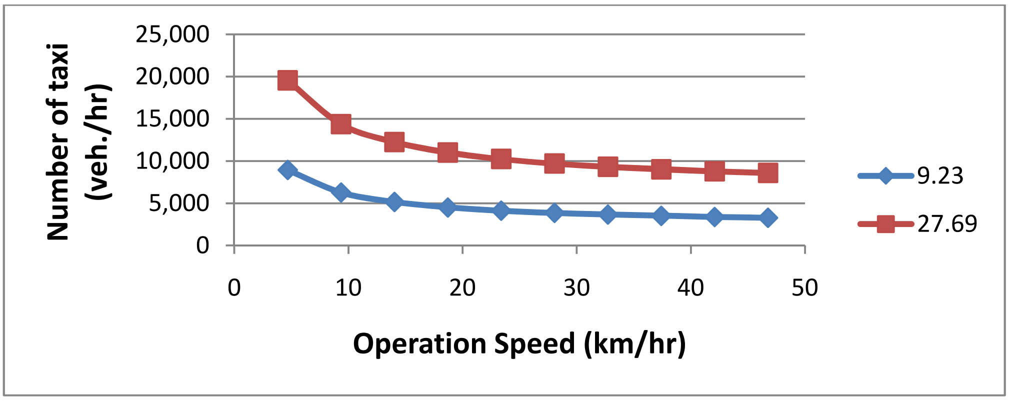

Fig. 5-3 Effect of operation speed on the number of taxi.

Fixed cost (λ) and coefficient of fixed cost (k)

Fig. 5-4 shows the influence on the number of taxi as the fixed cost paid by GPS-taxi driver changing. When the fixed cost paid by GPS-taxi driver rises, that is, the cost to join the dispatch fleet is more; the willingness of drivers to shift the operation model is less so that the ratio of GPS-taxi reduces. In terms of different demand condition, the ratio of GPS-taxi is more sensitive under the average demand condition (D = 9.23 trip/km-hr) than under the peak demand condition (D = 27.69 trip/km-hr). This outcome suggested that the lower fixed cost, such as the cost of device installation and maintenance or the tax and toll for the dispatch service, could help the growth of GPS-taxi fleet size especially during the average demand condition. When the coefficient of the fixed cost (**k**) increases, as shown in Fig. 5-5, the number of taxi goes down as well. Concluding by these results, the appropriate subsidy for the implement of GPS device can effectively encourage the drivers to apply the dispatch technology.

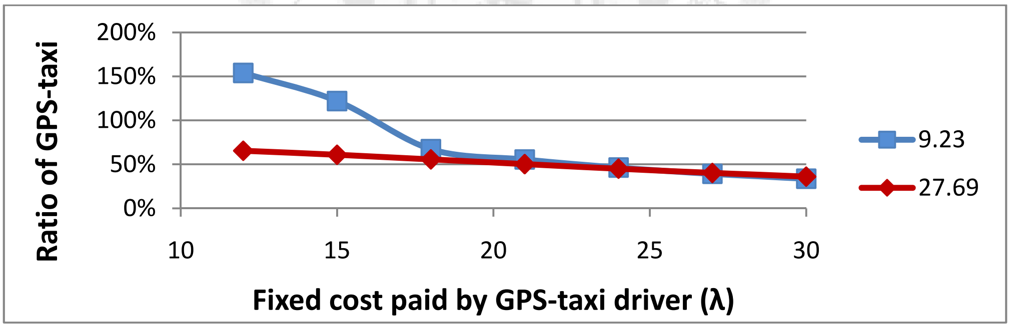

Fig. 5-4 Effect of fixed cost paid by GPS-taxi driver on the ratio of taxi.

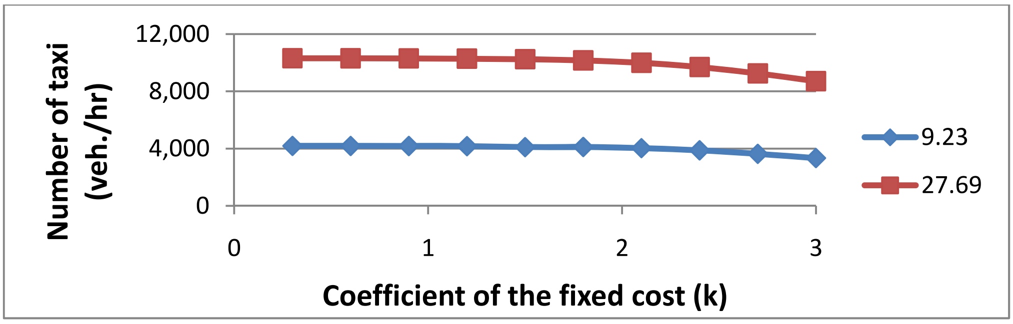

Fig. 5-5 Effect of coefficient of the fixed cost on the number of taxi.

Length of road network (L)

Fig. 5-6 presents the influence on the number of taxi as the length of road network changing. The road network is also regarded as the service region of a taxi market. When the length of road network rises, the quantity of taxi number intuitionally increases in order to afford more demand of taxi service. In terms of different demand condition, the number of taxi is more sensitive under the peak demand condition (D = 27.69 trip/km-hr) than under the average demand condition (D = 9.23 trip/km-hr). This difference claims that in a small service area, it requires the similar quantity of taxi supply. On the contrary, in a large service area, the quantity of taxi rises sharply with a higher demand. Additionally, in a large service area, the taxi supply should paid more attention on the allocation due to the demand of passenger is quite different in the peak or off-peak hour. But for a small service area, it should always keep a certain supply to avoid the huge consumer surplus loss due to a long waiting.

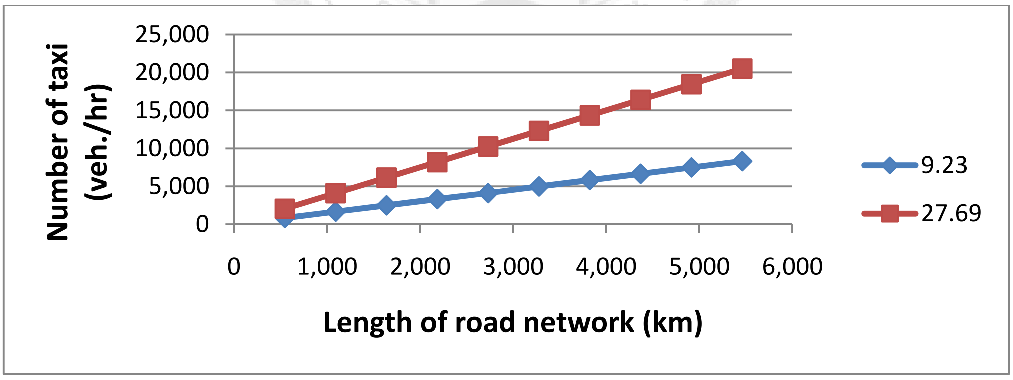

Fig. 5-6 Effect of length of road network on the number of taxi.

5.2 Effect of Demand Side Parameters

Length of taxi trip (Y)

Fig. 5-7 illustrates the influence on the ratio of GPS-taxi as the length of taxi trip changing. When the length of taxi trip is less than 3 kilometer per trip, the ratio of GPS-taxi decreases along with the length of taxi trip rises. Then, as the length is more that 3 kilometer per trip, the ratio of GPS-taxi increases with the rising length of taxi trip. This outcome suggests that for the short distance of taxi trip, the dispatch system shows little significant for operation efficiency. The time waiting for the dispatch and assignment is not much benefit for the net profit of taxi drivers. In terms of different demand condition, when the length of taxi trip is more than 3 kilometers, the ratio of GPS-taxi is keep the same level under the peak demand condition (D = 27.69 trip/km-hr) and the average demand condition (D = 9.23 trip/km-hr) and show comparatively advantage than the conventional cruising taxi.

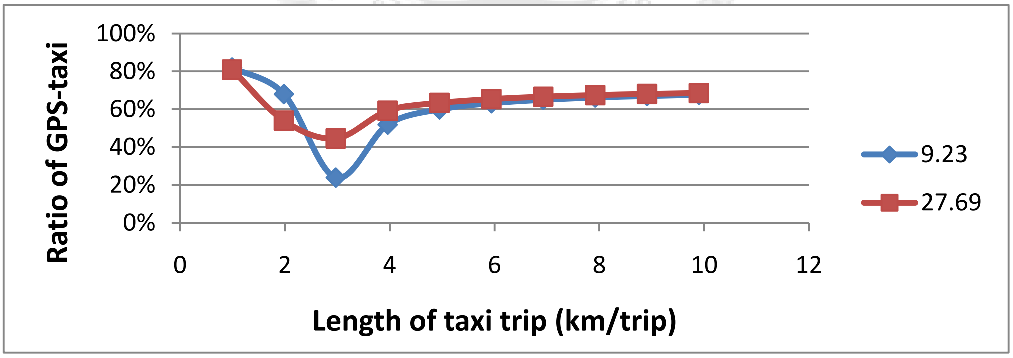

Fig. 5-7 Effect of length of taxi trip on the ratio of GPS-taxi.

Value of time of passengers off vehicle (t_c)

Fig. 5-8 depicts the influence on the number of taxi as the value of waiting time of passenger off vehicle changing. The number of taxi increases when the value of waiting time of passenger rising. Besides, in terms of different demand conditions, the number of taxi is more sensitive under the peak demand condition (D = 27.69 trip/km-hr) than under the average demand condition (D = 9.23 trip/km-hr). The result implies that the value of waiting time, which could be regarded as the preference of passenger, would influent the decision processes of both the taxi driver and the public sector. When the passenger could not endure to wait, the fleet size of taxi should properly extend to satisfy the demand of passengers especially during the peak hour.

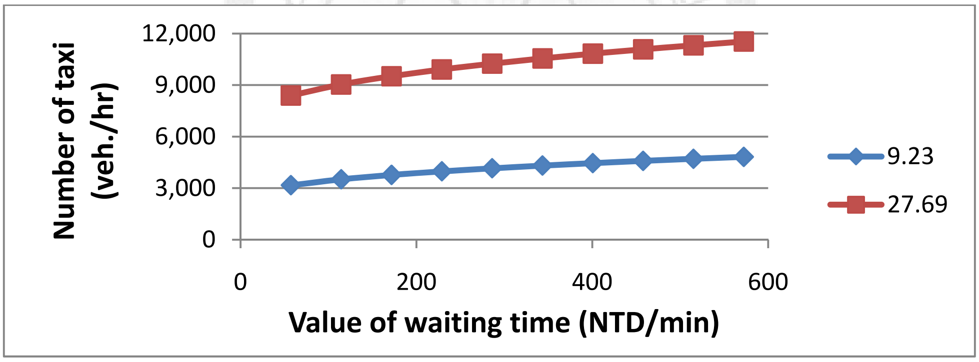

Fig. 5-8 Effect of value of waiting time on the number of taxi.

Fare rate (P)

Fig. 5-9 sketches the influence upon the ratio of GPS-taxi as the taxi fare rate changing. When the taxi fare rate increases, the ratio of GPS-taxi also increases slightly. In terms of different demand condition, the ratio of GPS-taxi is more sensitive under the average demand condition (D = 9.23 trip/km-hr) than under the peak demand condition (D = 27.69 trip/km-hr). Nevertheless, the ratio of GPS-taxi at peak hour is always beyond the ratio at off-peak hour. The outcome shows that the dispatch system application is not sensitive on the rising fare rate. It is also implies that the price-hike hardly contribute to the quantity amendment.

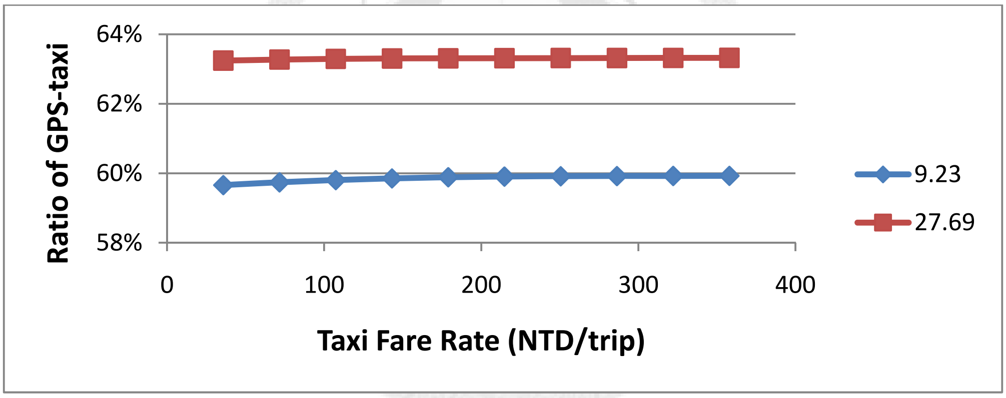

Fig. 5-9 Effect of taxi fare rate on the ratio of GPS-taxi.

Trip generation density of taxi demand (D)

Fig. 5-10 and Fig. 5-11 draw the influence on the ratio of GPS-taxi and the number of taxi as the trip generation density of taxi demand changing. For the ratio of GPS-taxi, the percentage grows along with the trip generation density of taxi demand increasing. In addition, the increment sharply rises when the density is less than the average demand, and increases gradually with a high demand density. For the number of taxi, intuitionally, the quantity of taxi rises as the demand density increasing. In terms of different dispatch-used ratio of passengers (β = 8.96% and β = 3.33%), as shown in Fig. 5-10, the ratio of GPS-taxi is sensitive for both preferences of passenger. Moreover, the number of taxi is more sensitive with a high dispatch-used ratio of passenger than with a lower ratio as depicted in Fig. 5-11. This result may state that a little growth on the ratio of passengers who applying the dispatch service bring great attraction for the taxi drivers shift their operation model from cruising on the road to utilizing the advanced dispatch system.

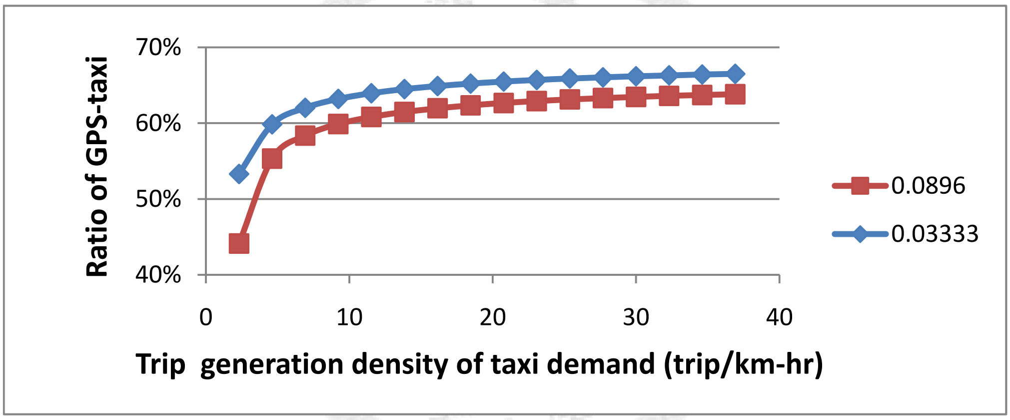

Fig. 5-10 Effect of trip generation density on the ratio of GPS-taxi.

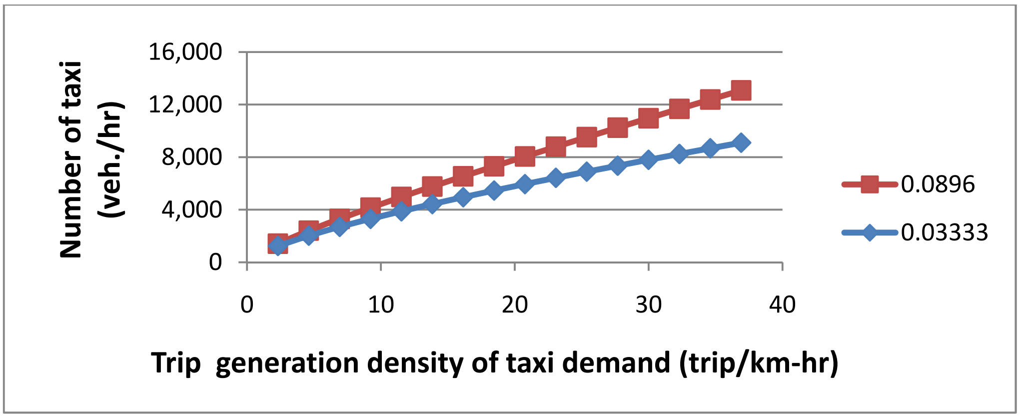

Fig. 5-11 Effect of trip generation density on the optimal number of taxi.

Ratio of dispatch-used passenger (β)

Fig. 5-12 shows the influence on the ratio of GPS-taxi as the ratio of dispatch-used passenger changing. For the fixed taxi fleet, in which the available taxi is 27,761 vehicles per hour, the ratio of GPS-taxi grows along with the ratio of dispatch-used passenger increasing. In addition, the increment rapidly rises when the ratio of dispatch-used passenger is less than 20%, and then slightly increases as the dispatch technology usage has popularized. In terms of different demand condition, the ratio of GPS-taxi is more sensitive under the average demand condition (D = 9.23 trip/km-hr) than under the peak demand condition (D = 27.69 trip/km-hr). This outcome also suggests that the GPS-taxi could take advantage mainly during off-peak hour than the peak hour. Since the taxi driver could easily find the passengers on the road during the peak hour, so that the advantage of GPS-taxi is undistinguished.

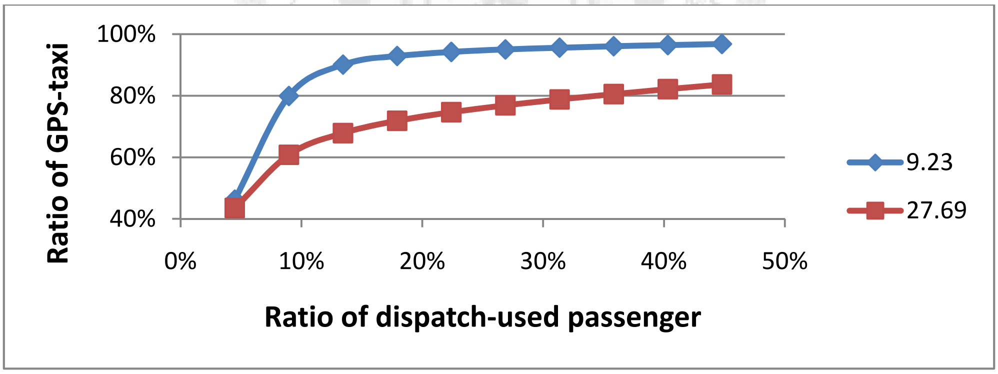

Fig. 5-12 Effect of ratio of dispatch-used passenger on the ratio of GPS-taxi.

5.3 Summary of Sensitivity analysis

Specific parameter values may influence the appearance of the multi-operation model of the taxi market. But significant changes in behavior do not occur for all parameters changing. As have been examined, most of the supply side parameters were in inverse proportion to the number of taxi but the demand side parameters were directly. Table 5-1 briefly summarized the effect of each parameter on the ratio of GPS-taxi and the number of taxi.

Table 5-1 Summary of the effect of parameters

Parameters		**Ratio of GPS-taxi (α)**	**Number of taxi (N)**
Driving cost	C_c	Directly	Inversely
Operation speed	S	Inversely	Inversely
Fixed cost	λ	Directly	-*
Coefficient of fixed cost	k	-	Inversely
Length of road network	L	-	Directly
Length of taxi trip	Y	Conversely	-
Value of waiting time	t_c	Inversely	Directly
Taxi fare rate	P	Directly	-
Demand density	D	Directly	Directly
Dispatch-used passenger	β	Conversely	Directly

*Unapparent impact on the decision variables.

Some conclusions are led to by a series of sensitivity analysis. First, when the driving cost remarkably rising, fuel price rising as an example, the GPS-taxi might have a comparatively advantage. In addition, the lower fixed cost, such as the cost of device installation or tax for the dispatch system, could help the growth of GPS-taxi fleet size.

Thus, the appropriate subsidy for the implement of GPS device can effectively encourage the drivers to apply the dispatch technology. But the price-hike hardly contributes to the application promotion for dispatch system.

Second, the release of traffic congestion might do a significant benefit to reduce the quantity of taxi; meanwhile, less taxi aimlessly cruising on the street contributes to a smoother traffic flow which performs a higher operation speed. Third, in a large service area, the taxi supply should paid more attention on the allocation due to the demand of passenger is quite different in the peak or off-peak hour.

Besides, the dispatch system shows much significant for operation efficiency when the average distance of taxi trip is longer. Moreover, when the passenger could not endure to wait, which represented by the value of time in the model, the fleet size of taxi should properly extend to satisfy the demand of passengers. Finally, this study also found that a little growth on the ratio of passengers who applying the dispatch service might bring great attraction for the taxi drivers shift their operation model from cruising on the road to utilizing the advanced dispatch system.

These findings could put forward some suggestions to benefit the taxi industry. Despite of the quantity control policy, the installation subsidy and internalization of the external cost are also the feasible financial strategies. Additionally, the allocation of operation time period or the supervision of working hour is practicable transportation management solutions. By applying the more efficient operation model, the fleet size of taxi could considerable go down and decline the total system cost.

Chapter Ⅵ Conclusions and Recommendations

6.1 Conclusions

This study aims to explore the optimal fleet size of GPS-taxi in a cruising taxi market. A mathematical model with a bi-level programming framework was developed to describe the multi-operation model in the taxi market and used to solve the optimization problem. The bi-level mathematical model considers both the social welfare objective and profit of taxi driver objective while the external effects were also included. An empirical example was applied to demonstrate the feasible and advantage of this model.

The numerical analysis results of Taipei Metropolitan Area showed that the optimal fleet size of taxi was 31,359 vehicles for the 2008 taxi market where the ratio of GPS-taxi was 16% and the ratio of dispatch-used passenger was 8.96%,. Once the external environmental effect was taken into consideration, the optimal fleet size of taxi was reduced to 30,743 vehicles. These results draw on a conclusion that optimization of the fleet size of taxis is distinguished less than the current supply of taxi (54,747 vehicles) and also indirectly prove that the GPS-dispatch system could provide a more efficient performance. Meanwhile, considering the operation cost of taxi driver grows up year by year, the dispatch system could enhance the operation performance by the efficient assignment and matching technology.

Despite of the quantity control policy, the subsidy for GPS Facility installation and internalization of the external cost are also feasible financial strategies. The optimal fleet size under the consideration of external effect was significantly less than that without concerning the external cost. Thus, internalization of the external cost of taxi system, reduction of the fleet size of taxi and promotion of the advance dispatch technology shall effectively enhance the taxi industry.

Furthermore, the allocation of operation time period or the supervision of working hour is practicable transportation management solutions. As the demand of taxi fluctuating with time, the optimal fleet size of taxi would be different as well. This change indicates that the improvement in the allocation of taxi service could help of a successful implement of quantity control.

Consequently, results of this research shall support the public authority to implement not only the policy of quantity regulation but also the application of innovative technologies in taxi industry. The widespread promotion of advance GPS dispatching taxi service will contribute to the change of passenger's preference and then attracts more taxi drivers to adopt the GPS dispatching system.

Nevertheless, the difficulty encountered in the implementation of the GPS dispatching system is the acceptance of taxi drivers. Initially, they were reluctant to accept the innovation, as they were used to the conventional cruising mode. Basically, they do not aware that the change to the new system could bring about more assignment opportunities and revenue. Accordingly, the recommendations are made that the development of the advance dispatch technology and the telematics application deserved more assistance by the public sectors. The innovations of taxi service are also encouraged to refresh the negative social image of the taxi industry and to provide a more attractive service for passengers.

6.2 Future Research

The bi-level programming model was developed on the basis of the assumptions that the operation models consist of two types: cruising taxi and dispatching taxi while the scheduled model is eliminated. Inclusion of the scheduled taxi in the mathematical model is worth further study.

Besides, a more comprehensive consideration of driving cost of taxi driver in a taxi market is deserved to work on to describe the characteristic of the taxi industry more accurately.

Furthermore, there may be obvious limitation in this study for which the ratio of passengers utilize the dispatch taxi service has been assumed fixed in the model. The exploratory observation and analysis of the relationship between the preference of passengers and the amount of GPS-taxi would be worth further research.

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Appendix

Parameter		Unit	Default Value
Number of available taxi	N	Veh./hr	
Ratio of GPS-taxi	α	-	
Ratio of dispatch-used passenger	β	-	
Average operation cost for cruising	C_c	NTD/veh.-km	30.88
Average operation cost for dispatching	C_d	NTD/veh.-km	
Coefficient of waiting time of passenger	ω	-	$L/2N$
Length of road network	L	Km	2732
Average trip generation density of taxi demand	D	Trips/km-hr	9.23
Average length of taxi trip	Y	Km/trip	4.95
Average fare rate of each taxi trip	P	NTD/trip	178.87
Value of time of passengers off vehicle	t_c	NTD/hr	286.2
Value of time of passengers in vehicle	τ	NTD/hr	286.2
Communication fee calling to control center	u	NTD/call	6
Operation speed of taxi	S	Km/hr	23.38
Dispatch fee paid by driver for each case	A	NTD/case	10
Management cost of control center	b	NTD/veh.	10
Coefficient of marginal management cost	γ	-	0.9
Fixed cost paid by GPS-taxi driver	λ	NTD/veh.-hr	15
Coefficient of the fixed cost	k	-	1.5
Discount coefficient of GPS-taxi	ε	-	1.2

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