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Research article

System dynamics model of taxi management in metropolises: Economic and environmental implications for Beijing

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ABSTRACT

Taxis are an important component of urban passenger transport. Research on the daily dispatching of taxis and the utility of governmental management is important for the improvement of passenger travel, taxi driver income and environmental impacts. However, urban taxi management is a complex and dynamic system that is affected by many factors, and positive/negative feedback relationships and nonlinear interactions exist between each subsystem and variable. Therefore, conventional research methods can hardly depict its characteristics comprehensively. To bridge this gap, this paper develops a system dynamics model of urban taxi management, in which the empty-loaded rate and total demand are selected as key factors affecting taxi dispatching, and the impacts of taxi fares on driver income and travel demand are taken into account. After the validation of the model, taxi operations data derived from a prior analysis of origin–destination data of Beijing taxis are used as input for the model to simulate the taxi market in Beijing. Finally, economic and environmental implications are provided for the government to optimise policies on taxi management.

1. Introduction

The development of public transport is an inevitable choice for metropolises to alleviate traffic-related and environmental problems such as traffic congestion and vehicle exhaust pollution. As a principal means of infrequent travel, taxi transport is a useful complement to public transport in a city. However, the efficiency of taxi use is always unsatisfactory, and the taxi empty-loaded rate remains high (e.g., over 38% in Beijing), which leads to a waste of taxi resources in many cities. In particular, the growing use of car-hailing service applications based on the internet such as Didi and Uber has made the situation worse in recent years. For example, if many empty taxi cars cruise around the road network this may increase traffic load, waste fuel energy and even increase greenhouse gas (GHG) emissions. Therefore, research on taxi travel characteristics and operational simulations are significant for the efficient management of urban taxis.

Taxi travel characteristics are usually divided into basic characteristics and the temporal and spatial distribution of travel, etc., which can be derived from origin–destination (OD) data. In practice, taxi OD data are mainly collected from the management information systems of taxi companies and cover the daily operational records of all operating taxis, which include information on car ID, pick-up points, drop-off points, pick-up times and drop-off times, etc. The analysis of taxi OD data can help reveal the basic situation of taxi operations. However, the current research question is a dynamic problem, namely, how is the efficiency of taxi services affected when taxi fare rates are adjusted? The main objective of this research is to investigate how taxi pricing mechanisms affect the efficiency of taxi services. Therefore, to comprehensively understand the development trends and existing problems of the urban taxi market, a systematic approach, i.e., system dynamics (SD) modelling, could be used for the simulation of taxi systems via the analysis of OD data.

SD is a quantitative approach to analysing causal relationships between various factors in a system and is designed to extract the internal causes and feedback mechanisms from complex phenomena (Anand et al., 2006; Shepherd, 2014). An urban taxi system is a multi-variable, multi-feedback and nonlinear complex traffic system that is restricted by many factors in terms of traffic, the economy and policy. Urban taxi operations can be simulated and predicted by building a dynamic model of a taxi system that considers all associated factors together. Besides, taxi-related research

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emerged decades ago, and its focus has shifted over time.

On the basis of an analysis of travel characteristics, this paper develops an SD model of taxi operations to simulate and predict the possible conditions of taxi operations under different scenarios so as to provide a quantitative reference and theoretical support for establishing more efficient and integrated taxi dispatching mechanisms in metropolises. Taxi dispatching is defined as guiding and moving taxi cars according to actual demand and supply. Taking Beijing city as a case study, the proposed model is used to run an SD simulation using taxi OD data for Beijing. The empty-loaded rate is used to represent the efficiency of taxi operations, and the efficiency of taxi management in Beijing is analysed and measured via the simulation. In addition, scenario simulations on changes in taxi fares are conducted to analyse a series of effects caused by the fare changes. Finally, the findings of this research can provide a scientific reference and recommendations for taxi operations and management in metropolises.

2. Related work

Taxi services have increasingly attracted researchers' attention in the field of urban transport, and many previous studies on urban taxi operations, dispatching and management have been conducted in recent years. For example, Rodriguez-Valencia (2014) investigated the differences in taxi operations between day and night in Bogotá, Colombia on the basis of surveys of drivers in the city. Wang et al. (2014) proposed a taxi dispatch policy comprising linking several taxi trips with demand time points to improve the existing systems used by taxi companies in Singapore. Conway et al. (2012) evaluated taxi dispatching procedures using kerbside data and interviews at a particular traffic hub, namely, JFK Airport in New York City. Furthermore, a few researchers have focused on simulations of taxi services in urban areas by modelling the environments of taxi operations as a whole to help decision-makers better manage the taxi market (Bischoff and Maciejewski, 2014; Grau and Maria, 2013; Grau and Romeu, 2015).

Taxi services were initially investigated from the perspective of economy, i.e., price (Arnott, 1996; Douglas, 1972), and regulating prices was recognised as an effective way to improve services and reduce waiting time. With the development of the taxi industry in many cities, researchers started to examine the industry from other points of view, including taxi demand and supply (Cooper and Faber, 2010), the performance of taxi operation systems (Chen and Zhao, 2011), evaluations of taxi-sharing systems (D'Orey et al., 2012) and urban taxis and air pollution (An et al., 2011). Because big data theory is widespread in current society, big traffic data have been widely used for the management and optimisation of transport. For instance, large-scale taxi OD data can be used not only to optimise taxi operations (Yang et al., 2015) but also to estimate urban link travel times (Zhan et al., 2013). In addition, the development of information and communications technology (ICT) has enabled people to manage taxi service operations more accurately and conveniently (Liao, 2011), and internet technology has also reshaped taxi service modes and the taxi industry (Anderson, 2014; Li, 2016).

SD is a systematic and holistic approach based on the science of complexity that is suitable for dealing with complex interrelationships among various factors in complex systems and quantitatively simulating the future development of these systems (Liu et al., 2015a, 2015b). An urban traffic/transport system is a typical giant complex system, as so many constituent elements such as people, cars and roads are interrelated in the system. To probe such complex systems, SD modelling has been widely used in urban transport research (Shepherd, 2014). For instance, Haghani et al. (2003) attempted to use SD simulation modelling in the simultaneous treatment of land use and interactions in a transport system between a large number of physical, socioeconomic and policy variables. Cao and Menendez (2015) modelled the SD of urban traffic on the basis of parking-related states to evaluate the interactions between urban traffic and parking systems. Lewe et al. (2014) created an SD model of multimodal intercity transport that integrated socioeconomic factors, mode performance, aggregate demand and capacity. Similarly, Xia and Jiang (2014) established an SD model for the prediction of transport and socioeconomic factors that considered passenger transport capacity, cargo capacity, population, GDP and other major factors in the whole system. In addition, some researchers applied SD models to urban traffic congestion problems in different places (Jahed Shiran, 2014; Yang et al., 2013), and other researchers adopted an SD approach to analyse the effects of transport policies on energy consumption and GHG emissions (Liu et al., 2014, 2015b; Vafa-Arani et al., 2014). Although an SD approach has been employed to understand individual behaviour in mode choice between public transport and private cars in the context of a city (Bajracharya, 2016), few studies have focused on the problems of urban taxi operations from a holistic viewpoint using SD (Song, 2014), let alone systematic taxi dispatching and the empty-loaded rate.

Therefore, to bridge this research gap, this research employs an SD approach to model the holistic system of urban taxi operations and analyse taxi dispatching using the empty-loaded rate in different scenarios.

3. SD model

3.1. Description of taxi system

3.1.1. Aim of system modelling

With the rapid development of the urban economy, the urban taxi industry has grown progressively to make a significant contribution to the travel of residents and accounts for a large share of overall urban traffic. However, this rapidly growing industry has brought about great pressure on urban traffic, and inappropriate control measures proposed by some local governments have further worsened the situation. Phenomena referred to as ‘difficult to call a taxi’ and ‘empty-loaded cruising’, etc., have emerged in many cities, such as Beijing and Shenzhen, which indicates low efficiency and problems in taxi dispatching. Therefore, it is essential to examine the dispatching and control mechanisms of taxi systems. An overall taxi system is a complex system that includes not only taxis themselves but also other factors in terms of travel demand, taxi supply and taxi policies, which are directly or indirectly associated with taxis within the city. Research refers to the travel route arrangements of all taxis in a city during a working day as the taxi dispatching system, and the main factors that affect taxi routes are referred to as the dispatching mechanism. Because modern taxis are equipped with global positioning system (GPS) devices and unified voice communication platforms, taxi drivers can receive real-time information such as taxi high-demand areas and traffic jam areas, etc., in a timely manner and adjust their driving routes accordingly, which implies that supply and demand theory can be used to interpret taxi dispatching. In the urban taxi system modelled in this paper, the total taxi demand (demand) and empty-loaded rate (supply) are selected as the two key factors in taxi dispatching, on which the research on taxi dispatching and associated problems is based.

In addition, the management of the taxi market by governments mainly comprises macro-management, including quantity control and price control, etc., which is defined as taxi market regulation in this paper. In considering the conditions of balancing taxi supply and demand, this research develops an SD model of an urban taxi system to investigate the dispatching and control mechanisms. Specifically, the effects of relevant policies can be reflected by changes in total demand, the empty-loaded rate, and taxi income and can be analysed and tested using scenario simulations. The SD model consists of two sub-models, namely, a taxi dispatching model and a taxi pricing model, and the latter is developed with reference to the former. The specific objectives are listed as follows:

(1) To investigate the taxi dispatching mechanism using supply and demand theory, identify causal relationships between influencing factors such as the service level, empty-loaded rate, and total demand, etc., analyse problems in current taxi dispatching and propose corresponding suggestions.
(2) To examine the impact of regulatory policies imposed by the government on the taxi system from a macroscopic viewpoint and analyse changes in the distribution of benefit among the government, taxi drivers and passengers.
(3) To simulate future urban taxi operations on the basis of an analysis of urban taxi OD data and policies and planning for taxi development.
(4) To develop an SD model for the analysis of the effect of price regulation by the government and study its impact on the development of the taxi industry so as to provide the government with feasible proposals.

3.1.2. *System boundaries and model elements*

In the theory of SD, the driving force of the development of a system stems from factors within the system and results from interactions between internal elements, and the system boundary is defined as the minimum extent affected when the objectives of the system are achieved. Therefore, prior to the definition of an urban taxi system, the system boundary needs to be defined in accordance with the objectives of modelling and the feedback mechanism of the taxi system, and then endogenous and exogenous variables of the taxi system are identified. Following the principles of simplicity, purpose and effectiveness, this research defines the boundary of the urban taxi system to identify factors included in the system, and the details are given as follows:

(1) Traffic demand factors, which represent taxi demand and basic characteristics of taxi operations, etc.
   - Average daily distance travelled per taxi
   - Average daily carrying frequency per taxi
   - Taxi empty-loaded rate
   - Taxi fare
   - Taxi total demand
(2) Taxi supply factors, which represent taxi supply and road infrastructure, etc.
   - Number of taxis
   - Average waiting time
   - Average travel time
(3) Taxi policy factors, which represent management policies and tax policies, etc.
   - Regulatory policies on taxi fares
   - Limit of taxi quantity
   - Informatisation of taxi market

3.2. *Causal relationships*

The interrelationships between all the key factors in the system are described using a causal diagram, in which causal chains represent positive or negative influences. A plus sign indicates that the variable at the end of the arrow will increase (decrease) with an increase (decrease) in the variable at the start of the arrow, whereas a minus sign indicates the reverse relationship between the variables. This research develops two causal diagrams for different periods of a single day (Fig. 1) and one year (Fig. 2) in order to analyse the efficiency of urban taxi dispatching and the effectiveness of pricing mechanisms.

3.2.1. *Causal diagram of taxi dispatching for a single day*

The main causal feedback loops are as follows:

(1) Empty-loaded rate↑→Taxi dispatching based on empty-loaded rate↑→ Variation of carrying frequency↑→Daily carrying frequency per taxi↑→Empty-loaded rate↓
(2) Empty-loaded rate↑→Service level↓→Attraction coefficient↓→Potential demand↓→ Total demand↓→Taxi dispatching based on urban demand↓→ Variation of carrying frequency↑→Daily carrying frequency per taxi↑→Empty-loaded rate↓

These negative feedback loops show that efficiency improvements are possible via the taxi dispatching mechanism. Theoretically, the taxi empty-loaded rate can be maintained within an appropriate range by means of rational dispatching.

3.2.2. *Causal diagram of taxi price regulation mechanism*

(1) Positive feedback loop

Profit per taxi↑→Variation of carrying frequency↑→ Daily carrying frequency per taxi↑→Empty-loaded rate↓→Service level↑→Attraction coefficient↑→Potential demand↑→Total demand↑→Operating income↑→Profit per taxi↑

(2) Negative feedback loop

Profit per taxi↑→Variation of carrying frequency↑→Daily carrying frequency per taxi↑→ Monthly carrying frequency↑→Variable cost↑→Operating cost↑→Profit per taxi↓

In this research, the taxi control mechanism mainly focuses on price regulation. Taxi fares directly affect target demand and operating income and indirectly influence profit per taxi and the

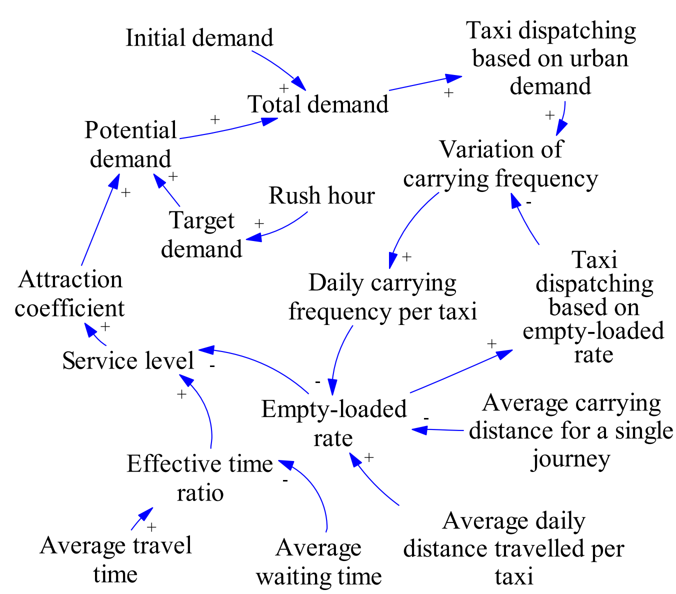

Fig. 1. Causal diagram of taxi dispatching.

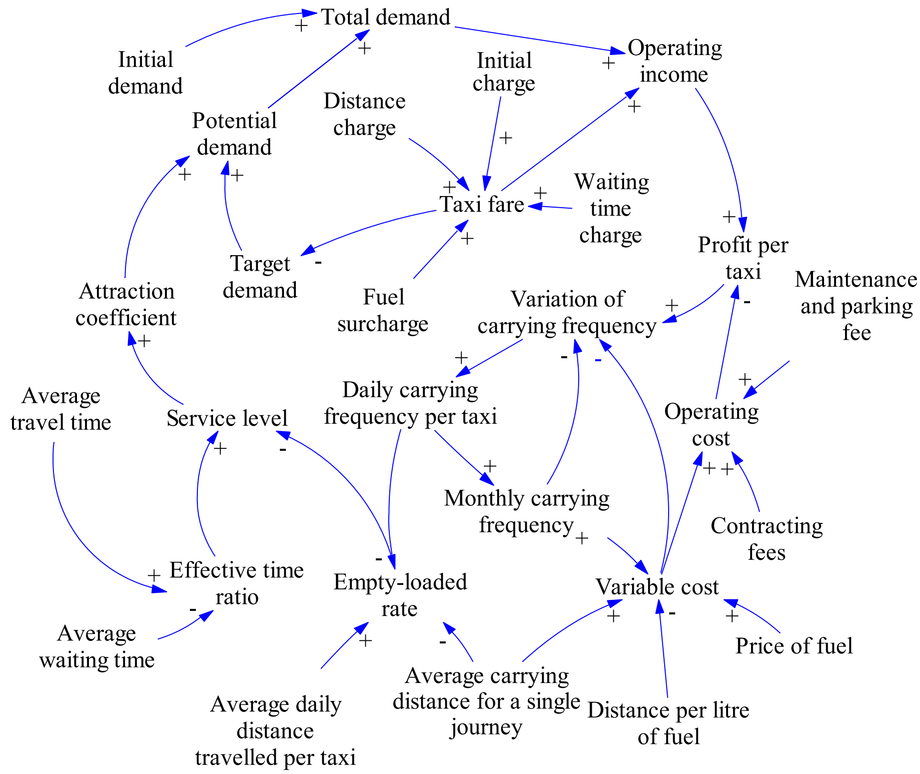

Fig. 2. Causal diagram of taxi price regulation.

empty-loaded rate indirectly.

3.3. SD flow diagram of taxi system

In this paper, an SD model of an urban taxi system is developed on the basis of supply and demand theory. Specifically, the economic development level and population density, etc., are regarded as exogenous variables of the taxi system, whereas the total number of urban taxis, average daily distance travelled per taxi, average carrying distance and average waiting time, etc., are considered as input variables of the system. From the causal diagrams of the taxi system presented in section 3.2, system flow diagrams are generated after a quantitative analysis.

3.3.1. Taxi dispatching over a single day

As shown in Fig. 3, the SD model of urban taxi dispatching includes two cumulative variables, namely, potential demand and variation of carrying frequency. A growth in potential demand depends on changes in the attraction coefficient: an increase in the attraction coefficient indicates that more passengers choose to travel by taxi instead of using other travel modes, which thereby makes demand increase. Variations in carrying frequency depend on taxi dispatching: on the one hand, taxi dispatching centres can increase taxi supply according to a growth in local demand; on the other hand, the dispatching centres can remove some taxis according to the local empty-loaded rate so as to keep an appropriate balance between the numbers of taxis and passengers and thus ensure the interests of both groups.

3.3.2. Taxi price regulation

As shown in Fig. 4, the SD model of urban taxi price regulation also includes the two cumulative variables, namely, potential demand and variation of carrying frequency. Variations in carrying frequency depend on the income and costs of taxi drivers: if the average income from an increase in taxi operations is greater than the costs, taxi drivers will increase their service time and carrying frequency as much as possible; if the reverse is the case, they will reduce their carrying frequency.

4. Case study – Beijing taxi operations

4.1. Analysis of taxi operations based on OD data

Taxi travel characteristics can be divided into basic characteristics and the temporal and spatial distribution of travel, etc., which can be derived from taxi OD data. In practice, taxi OD data are mainly collected from taxi companies' information systems, and the information covers the daily records of all operating taxis, which include car ID, pick-up points, drop-off points, pick-up times and drop-off times, etc.

4.1.1. Basic characteristics of travel

According to the principle of random sampling, this paper selected the OD data of 1000 taxis in Beijing for 2016 as the research sample and chose three operating dates, namely, March 4, March 5 and April 4, for comparative analysis. March 4 was a weekday, March 5 was on a weekend and April 4 was a holiday. Therefore, these three dates can basically represent all situations and comprehensively reflect the operational characteristics of Beijing taxis.

To reduce errors and make the statistics more accurate, some invalid records, in which the data format did not correspond to that of the other records or the carrying distance was less than 100 metres, were deleted. The weightings of single-shift and double-shift taxis per day were considered and set at 0.6 and 0.4, respectively, in accordance with the proportions of the two types of taxi. An Access database and Excel data editing and calculations were used to calculate detailed statistical indicators as follows, e.g., the

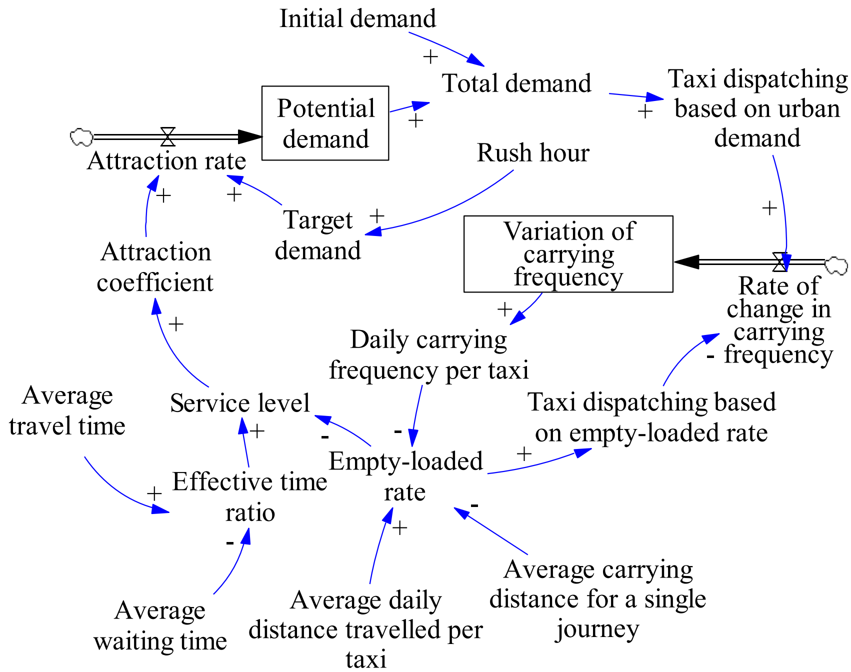

Fig. 3. SD flow chart of taxi dispatching.

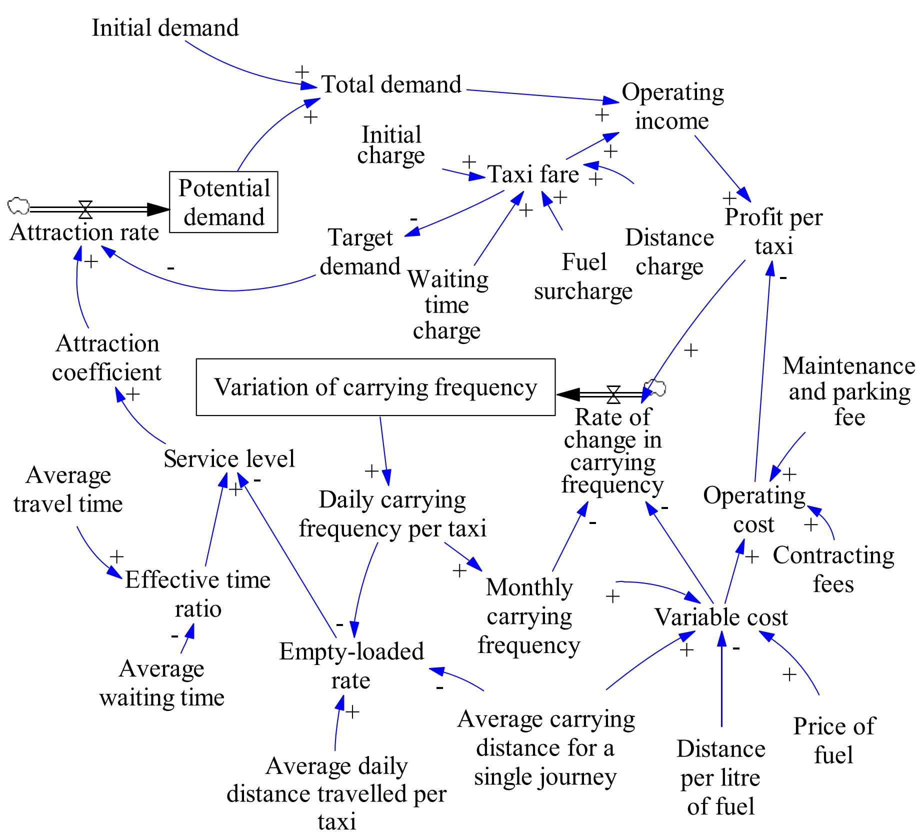

Fig. 4. SD flow chart of taxi price regulation.

weighted average daily operating time of a Beijing taxi is 16 h.

(1) Comparison of average carrying frequency per taxi, average carrying distance and average operating income per taxi

From Table 1, data for these three indicators on a weekend and holiday were lower than on a weekday. The average carrying frequency and average carrying distance per taxi on a holiday were also slightly lower than on an ordinary weekend. In comparison with a weekday such as March 4, these three indicators decreased

Table 1
Basic operational statistics of Beijing taxis.

Indicator	Date		
	March 4	March 5	April 4
Daily total carrying frequency (rounds)	5548.0	4253.0	3262.0
Average carrying frequency per taxi (rounds)	22.6	21.9	20.5
Carrying time (min)	583.0	565.0	433.1
Empty-loaded time (min)	377.0	395.0	526.9
Daily operating time (h)	16.0	16.0	16.0
Proportion of empty-loaded time (percent)	39.3	41.1	54.9
Daily total carrying distance (km)	32100.0	23817.0	18050.0
Average carrying distance (km)	130.5	122.8	113.5
Daily total operating income (yuan)	162577.0	121489.0	92259.0
Average operating income per taxi (yuan)	660.9	626.2	580.3

Data source: OD data from the information management system of Beijing taxis.

by 2.8%, 5.9% and 5.2%, respectively, on March 5, and the decrease grew to 9.0%, 13.0% and 12.2%, respectively, on April 4, which indicates that the demand for taxi travel decreases on weekends and holidays.

(2) Comparison of empty-loaded rate and empty-loaded time

Conversely, the empty-loaded rate and empty-loaded time on weekends and holidays were much higher than on weekdays, and these indicators on holidays were also higher than on weekends. Moreover, the proportions of empty-loaded time on all three dates were over 39%, which suggests a severe waste of resources. Therefore, rational taxi dispatching or operational measures need to be formulated to reduce the empty-loaded rate and improve the operational efficiency of taxis.

4.1.2. Analysis of travel time

(1) Changing trends in carrying time and distance over time

The changes in average carrying time per taxi over time is shown in Fig. 1 in Supplementary Materials (Appendix A). A trough period extends from 9 p.m. to 4 a.m., during which people travel less and a large percentage of taxis are in the empty-loaded state, which is prominently reflected in the diagram of changing trends in the empty-loaded time over time. In Beijing, there are always taxis in operation 24 h a day, and the operating hours are continuous. The changes in average carrying time per taxi over time have similar peak and trough hours to general motor vehicles. As shown in Fig. 1 in Supplementary Materials, the average carrying time per taxi has two peak periods on weekdays (e.g., March 4), which are 7–9 am and 5–7 pm and correspond to the rush hours on working days. The peak periods on weekends and holidays occur one hour earlier than on weekdays, and the curve fluctuations on weekdays (e.g., March 4) are greater than on weekends (e.g., March 5) and holidays (e.g., April 4), which is consistent with people's elastic travel characteristics on weekends and holidays.

The frequency distribution of the single-journey time is shown in Fig. 2 in Supplementary Materials (Appendix A). The single-journey time of Beijing taxis is mostly around 10–15 min, and single journeys account for 45% of total journeys. Journeys with durations of less than 40 min account for 95% of total journeys, which indicates that most taxi journeys are short trips and is fully reflected in the changing trends in travel frequency with travel distance.

The distribution of the journey distance of Beijing taxis is shown in Fig. 3 in Supplementary Materials (Appendix A). Journeys with distances of less than 6 km account for nearly 65% of total journeys, and over half of these are within 3 km, which indicates that the majority are short trips.

(2) Changing trends in average carrying distance over time

The changes in average carrying distance over time is shown in Fig. 4 in Supplementary Materials (Appendix A). The trends are significantly different on weekends/holidays and weekdays. Specifically, the fluctuations over time on weekdays (e.g., March 4) are more significant, with an obvious peak and trough in the early morning, and the peak between 5 a.m. and 7 a.m. is consistent with the early peak period on weekdays. However, the fluctuations are relatively gentle on weekends and holidays (e.g., March 5 and April 4), which is in accordance with the flexibility of travel on non-working days.

(3) Changing trends in empty-loaded time over time

The changes in average empty-loaded time over one day is shown in Fig. 5 in Supplementary Materials (Appendix A). In general, the trends are similar on weekends (e.g., March 5), holidays (e.g., April 4) and weekdays (e.g., March 4), but the curve for weekdays is lower, which indicates that the carrying time is longer and the efficiency is therefore higher. In contrast, the curves for weekends and holidays are smoother, and the changes over each time period are slight.

The average empty-loaded time determined for the entire research sample of 1000 taxis is shown in Fig. 6 in Supplementary Materials (Appendix A). As the average empty-loaded time per hour is greater than 25 min, the efficiency of Beijing taxis is relatively low and the taxi resources are not fully exploited. In other words, under ideal circumstances, over half of the existing taxis are idle and can be removed, which indicates that reducing the empty-loaded rate of Beijing taxis is necessary and essential for economic efficiency.

4.2. Estimation of model parameters

The data used in the SD model in this research were mainly obtained from the analysis of Beijing taxi OD data for the period from March to June 2016, the 2016 Beijing Statistical Yearbook and survey data of taxi operations in Beijing. Besides, the empty-loaded rate used here is given in terms of distance.

4.2.1. Basic parameters of taxi operations

With reference to the analysis of OD data in section 4.1 and Beijing Transport Institute (2016), related statistical data for taxi operations in Beijing (shown in Table 2) can be obtained and used in the SD model. By a Vensim PLE simulation, trends in each variable

Table 2
Basic parameters of taxi operations in daytime.

Parameter	Value
Initial charge (yuan)	13.0
Distance charge (yuan)	2.3
Empty-loaded rate (percent)	41.9
Daily carrying frequency per taxi (rounds)	23.0
Average daily distance travelled per taxi (km)	236.7
Average carrying distance for a single journey (km)	6.2
Average travel time (min)	19.6
Average waiting time (min)	5.0
Contracting fees (yuan)	6417.0
(Vehicle) Maintenance and parking fee (yuan)	695.3
Price of fuel (92#) (yuan)	6.0
Distance per litre of fuel (km)	11.4

Data sources: OD data from Beijing taxi information management system, 2016 annual report on Beijing traffic development.

in the taxi system and its subsystems can also be determined.

4.2.2. Level models

(1) Single-day taxi dispatch

The total demand for taxis and the supply of taxis are cumulative variables. Changes in the total demand for taxis depend on the potential demand, whereas increases in the supply of taxis depend on increases in carrying frequency. Equations (1) and (2) relate potential demand and increases in carrying frequency, in which the variable DT means a time step, which can be assigned different values in the two models. J represents the previous value and K represents the last value. PD represents potential demand, AR is the attraction rate, VCF is the variation in carrying frequency and FIR is the rate of increase in frequency.

$$PD_K = PD_J + DT \times AR \quad (1)$$

$$VCF_K = VOF_J + DT \times FIR \quad (2)$$

(2) Taxi management mechanism

The total demand for taxis and the daily carrying frequency per taxi are cumulative variables. Changes in the total demand for taxis depend on the potential demand, whereas the daily carrying frequency per taxi depends on increases in carrying frequency. The equations that relate potential demand and increases in carrying frequency are the same as Equations (1) and (2) given above.

4.2.3. Rate models

(1) Single-day taxi dispatch

The attraction rate and rate of change in carrying frequency are the rate variables in the model. The attraction rate depends on the attraction coefficient. If the attraction rate is too low (the critical point can be set at 0.3 on the basis of the findings from the modification and validation of the model in Section 4.4), the customer will choose other transport. The rate of change in carrying frequency is related to taxi dispatching based on travel demand and taxi dispatching based on the empty-loaded rate, as the dispatch of taxis mainly relies on the local empty-loaded rate and demand, as shown in Equations (3) and (4). Here, AR is the attraction rate, TD is the target demand, AC is the attraction coefficient, TRCCF is the rate of change in carrying frequency, TDBER represents taxi dispatching based on the empty-loaded rate, and TDBTD represents taxi dispatching based on travel demand.

$$AR = TD \times (AC - 0.3) \quad (3)$$

$$TRCCF = TDBER - TDBTD \quad (4)$$

(2) Taxi management mechanism

The attraction rate depends on the attraction coefficient and target demand, whereas the rate of increase in frequency depends on the profit per taxi, as demonstrated by Equations (5) and (6). Here, PPT represents the profit per taxi, VC represents variable cost and MCF represents the monthly carrying frequency.

$$AR = TD \times AC \quad (5)$$

$$TRCCF = PPT/(VC \times MCF) \quad (6)$$

4.2.4. Auxiliary models

(1) Single-day taxi dispatch

In this research, taxi speed and effective time ratio were used as standards to measure the level of taxi service, and the impact of increasing demand in peak periods was also taken into account. Although taxi companies in Beijing all have access to an electronic dispatch platform, in the absence of a unified platform in Beijing information cannot be shared between the various dispatch centres. Therefore, each platform can only judge on the basis of partial information and hence tends to dispatch a large number of taxis to a certain region that exceeds demand, which will cause a waste of resources. The lack of information sharing also makes the overall dispatch of taxis awkward, and the previous operation level tends to be maintained (there is no strong external interference, such as adjustments to taxi prices). See the following equations in which definitions of variables can be found in Table 3, in particular Equations (10) and (11), for details:

$$A = B + C \quad (7)$$

$$D = 23 + E \quad (8)$$

$$F = 0.6 \times G + 0.4 \times (1 - H) \quad (9)$$

$$I = 23 - (1 - H) \times 236.7/6.16 \quad (10)$$

$$J = 16 \times MAX(A - 367, 0)/1000 \quad (11)$$

$$H = (K - D \times M)/K \quad (12)$$

$$G = N/(N + O) \quad (13)$$

Constants in Equations (8) and (10) are used to equalise the dimensions and can be found in Table 2. Values 0.6 and 0.4 in Equation (9) represent impacts of effective time ratio and empty-loaded rate on taxi service level respectively. In Equation (11), 367 is initial demand, i.e., average operating taxis per hour in total sample size 1000.

(2) Taxi management mechanism

For reasons of quantity control, Beijing taxi operations employ contract management mode, and the means most commonly used by the government to control the taxi market is price control. Changes in taxi fares will affect the income of taxi drivers and thus affect the service level, the operation of vehicles and the daily carrying frequency. The specific auxiliary equations are as follows, in addition to the abovementioned Equations (7), (9) and (13):

$$P = Q \times A \quad (14)$$

$$R = S + T + U \quad (15)$$

$$S = (W \times M \times Z)/Y \quad (16)$$

$$H = (K - D \times M)/K \quad (17)$$

Table 3
Definitions of variables in the above equations.

Variable	Definition	Variable	Definition
A	Total demand	B	Initial demand
C	Potential demand	D	Daily carrying frequency per taxi
E	Variation of carrying frequency	F	Service level
G	Effective time ratio	H	Empty-loaded rate
I	Taxi dispatching based on empty-loaded rate	J	Taxi dispatching based on travel demand
K	Average daily distance travelled per taxi	N	Average travel time
M	Average carrying distance for a single journey	P	Operating income
O	Average waiting time	R	Operating cost
Q	Taxi fare	T	Contracting fees
S	Variable cost	W	Monthly carrying frequency
U	Maintenance and parking fee	Y	Distance per litre of fuel
X	Profit per taxi	Z	Price of fuel

$$X = P/1000 - R \tag{18}$$

4.3. Model modification and validity analysis

Both the adjustment of the parameters and the use of a set of different weightings in the SD model of taxi operations will affect the final result of a simulation. Thus, it is important to test the validity of the model using reliable historical data before performing an example analysis. A test simulation was conducted on the basis of the data for March 1 to 10, 2016 (for single-day taxi dispatch) and the data for four months, namely, March to June 2016 (for the taxi management mechanism). According to a comparison between the searched information and the actual historical data for single-day dispatch, when the attraction coefficient is less than 0.3, some customers will choose other modes of transport, which leads to a local decrease in taxi demand. Two tests, namely, a dimensional consistency test and a goodness-of-fit test, were used to verify the validity and rationality of the model.

4.3.1. Dimensional consistency test

The SD model requires that the units of the variables on both sides of an equation must be consistent. In this research, auxiliary variables were used to ensure that the dimensions on both sides of the equations remained consistent, and the model passed the dimensional consistency test.

4.3.2. Goodness-of-fit test

The goodness-of-fit test can verify the rationality and correctness of simulation results by comparing the difference between the simulated and true values. In this research, representative indicators were selected from the two major systems to calculate the rate of deviation between the simulated and true values. Details are shown in Tables 4 and 5.

(1) Single-day taxi dispatch
(2) Taxi management mechanism

As shown in the simulation results, the forecast deviation for each indicator is less than±10%, which means that the validity is high. As a result, this SD model of taxi operations can be used for simulations and analyses.

4.4. Scenario simulation of Beijing taxi operations

4.4.1. Single-day taxi dispatch

Using average situation of supply and demand in Beijing on June 23, 2016 as the basis input, the initial demand is 367 (an average of 367 customers per 1000 taxis in this period). The remaining input parameters are shown in Table 2. On this basis, the SD model was used to simulate scenarios of Beijing taxi services for a period of 5 days. The simulation results are shown in Table 1 in Supplementary Materials (Appendix A) and Fig. 5.

As shown in Table 1 in Supplementary Materials and Fig. 5, the efficiency of spontaneous taxi dispatch that relies on the market is not high, and the attraction coefficient, daily carrying frequency per taxi and service level are low. The empty-loaded rate is about 41%, which is much higher than the international standard of 25% and implies a great waste of resources. A further study found that total demand increased when the carrying frequency decreased and the empty-loaded rate increased during the peak periods of the day (7–9 am and 5–7 pm). This is because in the absence of a unified dispatch centre and scheduling platform, although each platform has timely access to a variety of operational information, it cannot receive information from the other platforms, which results in the overall situation that taxi dispatch causes too many vehicles to be sent to some areas in comparison with not enough vehicles in other

Table 4
Comparison of SD simulation results with actual data for single-day taxi dispatch.

Date	Empty-loaded rate (percent)			Daily carrying frequency per taxi (rounds)		
	Simulation results	Actual data	Rate of deviation (percent)	Simulation results	Actual data	Rate of deviation (percent)
March 1	41.79	40.78	2.48	23.70	23.93	−0.96
March 2	41.78	41.60	0.42	23.71	22.15	7.02
March 3	41.76	40.04	4.30	23.71	25.42	−6.72
March 4	41.74	43.70	−4.47	23.72	23.08	2.77
March 5	41.75	46.33	−9.89	23.72	22.35	6.13
March 6	41.70	42.95	−2.90	23.73	22.48	5.58
March 7	41.68	43.94	−5.14	23.74	23.22	2.26
March 8	41.66	43.56	−4.37	23.75	21.60	9.97
March 9	41.63	40.41	3.01	23.77	22.39	6.15
March 10	41.59	40.44	2.85	23.78	22.07	7.75

Table 5
Comparison of SD simulation results with actual data for the taxi management mechanism.

Month	Empty-loaded rate (percent)			Monthly carrying frequency (rounds)		
	Simulation results	Actual data	Rate of deviation (percent)	Simulation results	Actual data	Rate of deviation (percent)
March	43.10	43.06	0.08	687.05	687.02	0.00
April	43.09	44.19	−2.48	687.10	656.61	4.64
May	43.09	42.98	0.26	687.14	667.81	2.90
June	43.07	41.39	4.06	687.38	670.31	2.55

areas. This may explain why the 'hard to taxi' and 'taxi drivers sweep road' problems happen at the same time in Beijing. In addition, whereas the exogenous conditions in the system do not change with the passage of time, the empty-loaded rate increases slowly, which indicates that self-regulation ability is lacking and inefficient consumption cannot be reduced spontaneously, which needs the involvement of external forces.

Therefore, daily dispatch requires the intervention of the government or other regulatory agencies with the intention of allocating resources more reasonably. Taxis should be managed uniformly over the whole city and dispatched according to complete supply and demand information. It is necessary to allocate taxis to other areas whenever it is found that a region is attracting too many vehicles and the demand there is insufficient, especially during the peak commuting hours, which is the key to efficient dispatching.

4.4.2. Taxi management mechanism

(1) Basic scenario simulation

The OD data for June 2016 in Beijing were used as the input parameters. The average carrying distance is about 6.16 km, and the average taxi fare for once service is around 27 yuan in consideration of fare increase caused by driving at a low speed/waiting (speed less than 12 km/h) and driving at night (from 11 p.m. to 5 a.m.) (BMCDR, 2017). The simulation was run for a period of 60 months, and the results are shown in Fig. 6.

With the development of the economy, the travel demand of urban residents has increased year on year. However, if the government does not adjust taxi fares, the empty-loaded rate will decrease slowly and remain above 35% in the long term, which will eventually cause a great waste of resources.

(2) Scenario simulation for price control

Governmental regulations for taxi management mainly fall into three categories, namely, price control, quantity restriction and taxes. As the quantity of taxis in Beijing is almost unchanged and few tax measures have been adopted, the government mainly relies on price control. Taxi fares may include the initial charge, distance charge and fuel surcharge. Price changes were divided into three cases: an increase of 1 yuan in the initial charge, an increase of 1 yuan in the fuel surcharge and increases of 1 yuan in both the initial charge and the fuel surcharge. The simulation results for total demand, the empty-loaded rate, and the monthly profit per taxi under three different scenarios are shown in Tables 2, 3 and 4 in Supplementary Materials (Appendix A).

From the above simulation results, a rise in prices will reduce the empty-loaded rate, but decrease the rate of decline in the empty-loaded rate. Meanwhile, a rise in prices will also reduce both total demand and its rate of increase, even leading to a negative growth in demand, which is because the price increase will reduce target demand and some existing customers may be diverted to other modes of transport due to excessive taxi price. Last but not least, from the point of view of a taxi driver a rise in prices, although at the start it will lead to a significant increase in the driver's income, will finally reduce the rate of growth of their income. Furthermore, it is likely that there will be negative growth when prices are too high, on the grounds that price increases will decrease the probability that urban residents will choose to travel by taxi. In this case, both demand and the empty-loaded rate may be reduced. Therefore, price adjustment needs to be investigated. The appropriate price range should be selected so as to neither increase the difficulty of taking a taxi for urban residents nor damage the interests of taxi drivers, in order to improve the efficiency of taxi operations.

5. Policy implications for the development of the taxi industry in Beijing

On the basis of the above analysis, the following suggestions are provided for the future development and improvement of the efficiency of the taxi industry in Beijing.

(1) The government should get involved in taxi dispatching platforms, as it can control dispatching in a central place to enable information sharing among different platforms. Governmental involvement in the daily dispatching of taxis can not only monitor the condition of the taxi market in general to allocate resources more reasonably, but also dispatch a large number of taxis to areas with a high demand for taxis efficiently, which is a win-win situation that gives passengers more convenience and increases taxi drivers' income.

(2) There should be an emphasis on dispatching during both morning and evening rush hours. The simulation results of the SD model used in this research indicate that the morning and evening rush hours are the key periods for dispatching taxis, and attention should be paid to them. People can be encouraged to travel avoiding the rush hours, and taxis can be concentrated at densely frequented locations, such as subway/metro stations, in advance to alleviate traffic pressure and improve transport efficiency.

(3) Fares should be regulated properly. Appropriate fare control helps to increase the income of taxi drivers and decrease the empty-loaded rate, which conduces to improving the efficiency of taxi operations and reducing unnecessary energy consumption. In 2013, the government effectively tackled the problem that it was difficult to take a taxi during rush hours by raising the initial charge and fuel surcharge of Beijing taxis. However, an excessive fare increase may damage the interests of urban residents and even taxi drivers.

(4) The contract fee should be reduced. The fare that a passenger pays is in exchange for the service provided by a taxi driver, and taxi drivers play the most direct key role in creating the value of taxis. However, the profit of taxi drivers has been reduced, because the taxi contract fee in Beijing is quite high

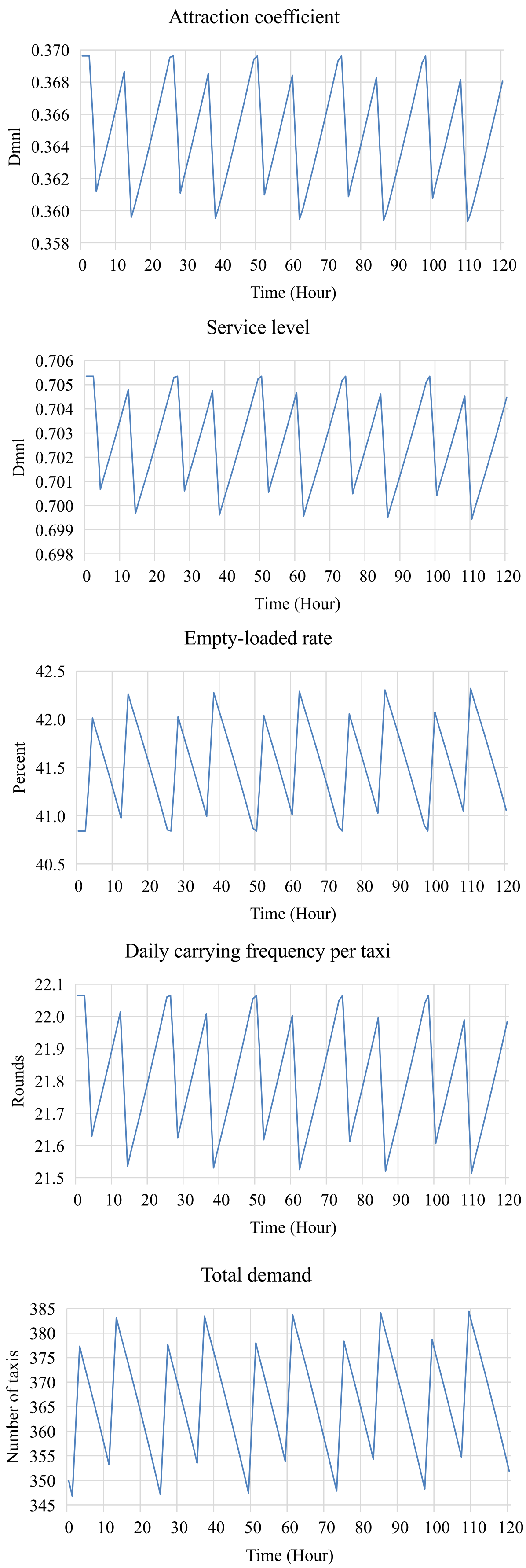

Fig. 5. Scenario simulation of Beijing taxi operations (Dmnl = dimensionless).

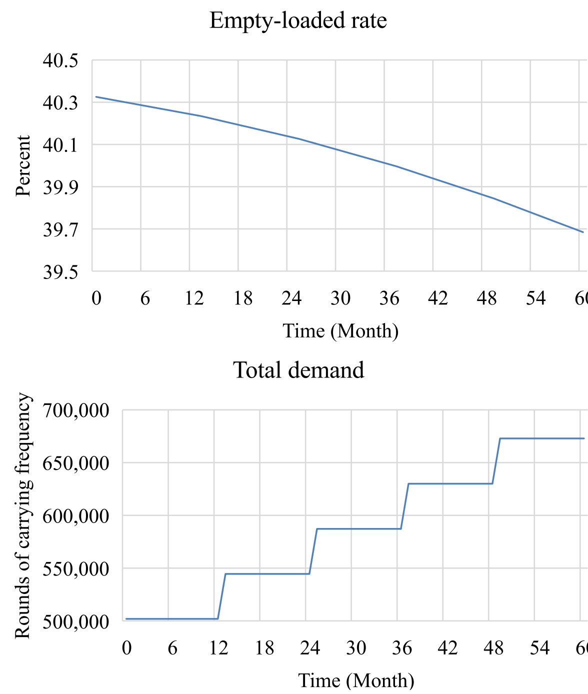

Fig. 6. Basic scenario simulation of taxi management.

and a large part of taxi drivers' income is paid to taxi companies. With the rise in the price of goods, an appropriate reduction in the contract fee could make taxi drivers happy, which would help to boost the working enthusiasm of taxi drivers and improve the quality of their service.

(5) The regulations governing the industry should be loosened. Prompted by economic and social development, traffic demand has grown continuously and regularly in Beijing, and the demand for taxi travel has increased rapidly. Meanwhile, the number of taxis has hardly increased in Beijing for years, as the government has set a limit to the number of taxis. Thus, the relaxation of quantity restrictions may be an effective way to satisfy the demand for taxi travel in Beijing in the long term.

(6) Environmental impacts brought by urban taxis should not be overlooked. Taxi empty-loaded rate in Beijing has been at a high level for years, that means more useless travelled distance, more fuel consumption, and more exhaust emissions. As we know, exhaust emissions may probably be a major contributor to smog in large cities. If the empty-loaded rate for all taxis in operation can be decreased, a large amount of fuel can be saved and the exhaust emission (GHG emissions mainly) can be reduced significantly. For example, average daily distance travelled per taxi is about 300 kilometres, equivalent to about 110,000 kilometres per year. As fuel consumption per 100 kilometres is about 10 litres in urban areas, the fuel consumption per taxi is about 11,000 litres per year. Calculating at the rate of 2.3 kilogrammes of CO_2 emissions per litre petrol, CO_2 emissions from a taxi per year can be nearly 25 tons. Beijing has about 65,000 fuel taxis, therefore, total CO_2 emissions from all fuel taxis in the city will be about 1.6 million tons per year. If the empty-loaded rate can be decreased by 10–15%, the CO_2 emissions will be reduced by around 0.2 million tons per year. The reduction of carbon emissions for taxis is much beneficial to environmental protection and energy/resource saving. In addition, as

adopted by an increasing number of cities, more traditional fuel vehicles can be replaced by electrical vehicles in urban taxis that could be an effective policy measure to reduce air pollution caused by taxis.

6. Conclusions

Urban taxi operations play a key role in the transport service provided by a metropolis, and taxi management has become a prominent problem in urban resource utilisation in terms of traffic administration, economic efficiency and environmental protection. To investigate this problem in an entire complex urban system, this paper develops an SD model of urban taxi management to simulate and predict possible taxi operations under different scenarios. Taking Beijing city as a case study, taxi operations data derived from a prior analysis of the OD data of Beijing taxis are input into the model to simulate the taxi market in Beijing and generate results of scenario simulations. On the basis of the simulation results, economic and environmental implications are provided for the government to improve relevant policies on the optimisation of taxi resources. Therefore, the findings of this research can serve as a scientific reference and suggestions for efficient taxi management in metropolises.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.02.026.

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