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Article

Dependence of Parking Pricing on Land Use and Time of Day

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Abstract: A key strategy of sustainable transportation, parking pricing can directly contribute to decreased greenhouse gas emissions and air pollution. This paper describes an optimal structure of parking rates in terms of parking locations and time of day. A two-level parking model based on game theory is established using parking survey data collected in Beijing in 2014. The model was estimated based on Stackelberg game and the Nash equilibrium. Using the two-level parking model, the optimal structure of parking rates for inside/outside business zones and during peak/off-peak hours was calculated. In addition, the relationship between the government (which represents the public benefit) and car users, as well as the relationships among car users in the parking system were investigated. The results indicate that equilibrium among all of the agents in the parking system can be obtained using the proposed parking rate structure. The findings provide a better understanding of parking behavior, and the two-level parking model presented in the paper can be used to determine the optimal parking rate to balance the temporal and spatial distribution of parking demand in urban areas. This research helps reduce car use and the parking-related cruising time and thus contributes to the reduction of carbon emissions and air pollution.

Keywords: parking rate; business zone; peak hours; game theory; Nash equilibrium; Stackelberg game

1. Introduction

In recent decades, China's increasing energy consumption and fast-increasing vehicle population have placed a heavy burden on the urban atmosphere. Urban air pollution is rapidly emerging as a major environmental issue. How to protect our environment while encouraging the development of a strong, clean-energy economy has become one of the most important questions facing the nation. The government has begun to investigate technical approaches to decreasing carbon dioxide emissions. Among these approaches, transportation solutions play a crucial role. To reduce carbon emissions, regional leaders have proposed "smart" transportation programs, and parking pricing has become a key component of sustainable transportation solutions. A well-designed parking pricing structure can help optimize the temporal and spatial distribution of parking demand in urban areas and partially solve the problem of traffic congestion. More importantly, by reducing car use and the parking-related cruising time, parking pricing directly contributes to decreased greenhouse gas (GHG) emissions and air pollution [1,2].

Previous studies have observed that the parking demand in the business zone of large cities has rapidly increased in recent years. In addition to the rapid increase in the automobile population, another major reason for the increased parking demand is the excessive concentration of its temporal and spatial distribution. Parking survey data for Beijing for 2014 indicate that the intensity of parking demand in business zones is substantially higher than outside the zones and that the parking pressure during peak hours is higher than that during off-peak hours [3]. The concentration of parking demand results in crowded parking facilities in the business zone during peak hours but idle parking facilities outside the business zone during off-peak hours. Consequently, the cruising time required to search for available parking and thus the traffic volume are increased. Shoup (2006) found that approximately 8%–74% of the traffic in central business districts consists of vehicles that are cruising for parking and that the average time spent searching for a parking space ranges from 3.50 min–14.00 min [4]. The concentration of parking demand also results in traffic congestion and other problems, such as increased fuel consumption and environmental pollution. Parking problems can even cause individuals to change their travel destination to a non-business district, which may hinder the economic development of the local economy. Therefore, it is crucial to resolve business-district parking problems.

Parking pricing is a means to manage parking demand whose effectiveness has been demonstrated by many previous studies. For example, Ison and Wall (2003) found that parking fees can be used to regulate the number of cars that are cruising in the road network [5]. Several studies indicate that the price of parking is possibly the single most important factor that influences car use and car-related behavior [6,7]. The structure of a given parking pricing policy in terms of the location of the pay-parking areas and the temporal structure of the charges has been considered an important issue with respect to establishing the reaction of users to parking charges [8]. Zhang *et al.* (2008) revealed that compared with road tolls, parking fees are relatively more efficient because the transaction entailed in fee payment generally does not impede traffic flow [9]. Thus road pricing has been implemented in only a small number of cities, whereas nearly all of the cities collect parking fees. In addition, compared with restrictions on the parking space supply, the parking fee has been demonstrated to be more appropriate with respect to temporal efficiency and inter-temporal efficiency arguments [10]. Using case studies on eight firms that complied with California's employer parking cash-out requirement, Shoup (1997) demonstrates that by eliminating free parking for employees, the benefits to commuters, employers, taxpayers, and the environment exceeded the program costs by at least three times [11]. Considering the useful effects of parking fees on adjusting parking demands, this study employs this policy to address the parking problems in the business zone of urban areas. We present a parking pricing structure based on parking zones and parking times. Specifically, different parking rates inside/outside the business zones during peak/non-peak hours are established to encourage car users to park outside the business zones and choose non-peak times to park.

The determination of the optimal structure of parking fees is a complex systematic problem because it involves interest conflicts among car users and between car users and the government. The government, which represents the public benefit, desires a parking pricing structure that is fair to the public (including not only car users but also non-car users) and that improves traffic conditions. In contrast, car users select their parking locations and parking periods according to their travel demands and the comparison of parking costs and benefits. In addition, one car user's personal parking behavior can affect the parking utility and parking behaviors of others because of the limits on parking and driving space. These complex relationships among the government and the car users enable the parking system to be viewed as a game. In this study, we describe these complex relationships employing the two-level game theory [12]. The game between the government and the car users is examined using the Level-1 model, whereas the game among the various car users is investigated using the Level-2 model. In this two-level parking model, the government seeks to maximize social benefits, whereas each car user seeks to maximize his or her benefit. By solving the two-level parking model, we can determine the equilibrium condition among all of the agents (including the government and the car users) in the system and thus the optimal parking rate structure.

The remainder of this paper is organized as follows. In Section 2, we present a general review of parking pricing studies. Section 3 presents the data that were used in the investigation. Then, in Section 4, the two-level parking model is described and solved. In Section 5, the parking utilities that emerge after the implementation of the parking rate structure are analyzed. The paper concludes by summarizing the key findings and identifying directions for future research.

2. Literature Review

Parking pricing analysis has been a popular topic in transportation research. A number of studies have addressed the parking-pricing problem based on a combined consideration of location and time-of-day information. For example, Ottosson *et al.*, (2013) calculated the price elasticity of on-street parking demand and the percentage change in block-level occupancy in response to a change in parking rate according to time of day and neighborhood characteristics [13]. The researchers also examined how parking pricing results in changes in parking turnover rates, parking duration and total revenue generated. Hensher and King (2001) investigated how parking pricing and supply by time of day affect the decision to drive and park in a central business district (CBD) [7]. The study revealed that appropriate parking pricing could divert parking not only beyond the business zone but also to non-peak hours.

A number of studies have specifically addressed parking pricing in the business zone. For example, in [14], the optimal price for curb parking in the CBD was calculated with respect to minimizing the social cost. Kelly and Clinch (2006) developed an ordered probit model of parking behavior with the parking fee as explanatory variable and set the optimal fee by considering the attraction of business in the CBD [15].

Migliorea *et al.* (2014) designed a parking pricing scheme for different zones in the CBD [16]. The optimal hourly charge was defined using an iterative maximization process of an objective function, which was subject to the constraint that the percentage of available parking in the various parking zones had to remain greater than 30%. Several researchers studied parking pricing by examining the effect of time-variable parking rates. Related studies include investigations on on-street price-elasticity that varies by day and time [15], time-variable parking charges [17], the effects of charging for parking by the minute [18], real-time dynamic pricing in parking [19], and time-variable parking fees for commuters [20].

Most of these studies have addressed parking pricing problem by examining the effectiveness of the parking rate on parking demand. The most frequently used method is to determine the optimal parking rate by maximizing the utility of the individual car user but omitting the public (including car users and non-car users) benefit. In addition, one car user's parking behavior is affected by the parking behavior of other car users. For example, if most other car users park in a business zone, a car user will choose to park outside the area because of the traffic congestion inside the area. This phenomenon can be viewed as a game among various car users. Most previous studies do not consider the public benefit or the competition between different car users in their investigations of parking rates. In this study, we determine the parking rate by examining the benefit not only of car users but also of the public. The interaction among different car users in the parking system is also considered.

Game theory has been widely used to examine the competition among different participants in a system, such as the relationships among the government (which represents the public benefit) and car users in the parking system. For example, a number of studies employed game theory in transport pricing by considering the competition among different participants, such as parking pricing [21,22], congestion tolls [23,24], time-variable road tolls, and public transport pricing [22]. Tsai and Chu (2006) investigated a parking pricing game between a government and a private firm [21]. In the Stackelberg three-stage game that was constructed in the study, the car user's choice of parking lot (which involved the parking fee and the search-time cost) was also examined. Proost and Sen (2006) examined a game between different government levels with respect to transport pricing in which the urban government controlled parking fees and the regional government controlled a cordon toll [22]. These studies reveal that game theory can be used to analyze the interactions among different participants in urban transport systems and to determine the optimal pricing scheme based on game analysis.

Previous studies indicate that a parking pricing study that combines an analysis of the interactions between the government and car users and among different car users is urgently required. In this study, we use a game-based analysis to describe the relationship between car users and the government and the relationship among car users in a parking system. Using parking rates based on parking periods and locations as the decision variable in the model, the optimal parking rates for inside/outside the business zone and during peak/off-peak hours parks in Beijing were determined.

3. Data and Study Area

This study takes advantage of parking information collected in Beijing in 2014. The survey sampled approximately 0.64% of the residing population and gathered data by means of a home visit interview. The survey area was 16,410 square kilometers (covering all the 18 districts of Beijing, shown in Figure 1) and the residing population of the study was approximately 11.8 million people. In this survey, for each car trip, questions were asked regarding the parking information (parking starting time, number of passengers, walking distance and walking time to the destination, park leaving time, mode of payment, parking fee, and parking location). With records containing missing values eliminated, our final sample consisted of 46,874 parking records of 138,480 respondents from 54,398 households [25].

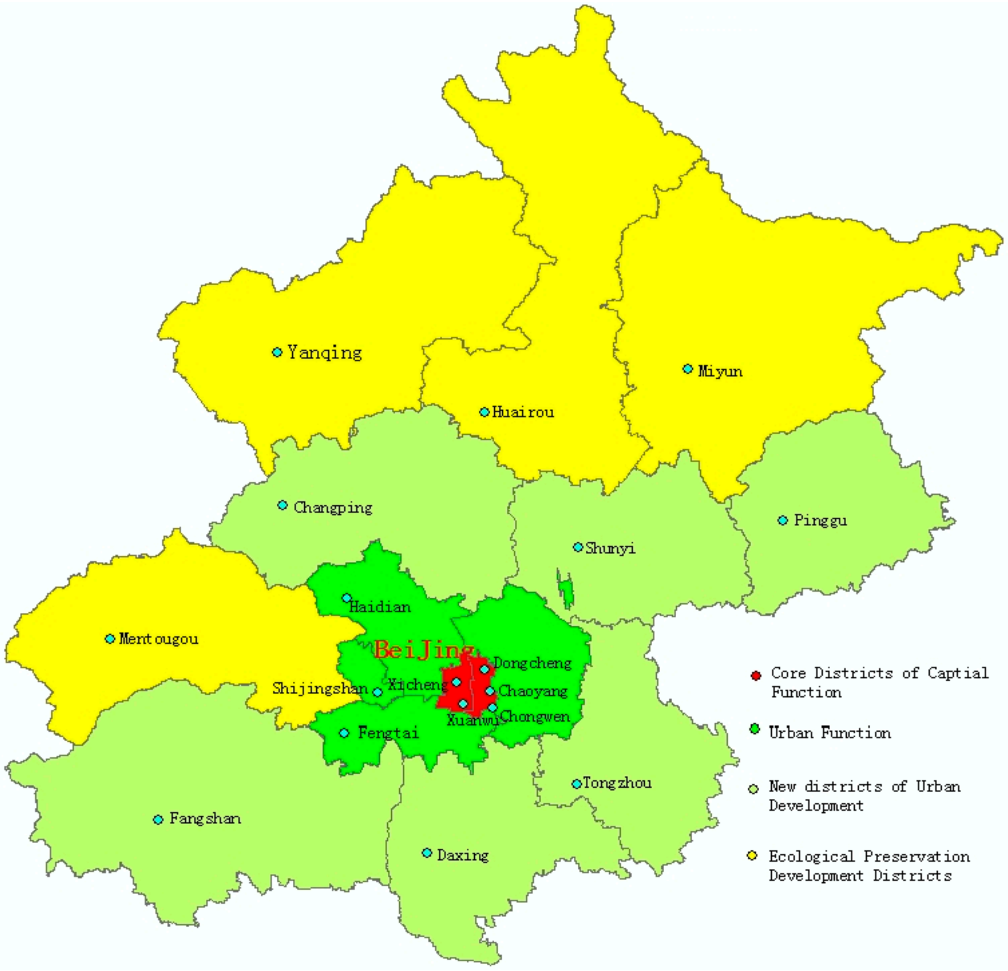


Figure 1. Administrative division for Beijing for 2014.

According to the survey data, the characteristics of the major parking behaviors and parking demands in Beijing are presented in Table 1. Concerning Beijing's parking rate, the major reason for most (60.96%) of the total number of parking records being free parking is that parking in the residential areas is free in most cases. Based on the survey data, for most of the public parking facilities, the parking rate is 5–10 yuan/h. Currently, there is no different setting of parking rate for parking in business zones/non-business zones or during peak/off-peak hours.

Table 1. Statistics summary of major parking behaviors and demands in Beijing in 2014.

Variable	Level	Percentage (%)	Variable	Level	Percentage (%)
Parking period [a]	peak period	56.71	Vehicle ownership	Private [c]	14.46
	non-peak period	43.29		none-private	85.54
Parking duration (hour)	≤3	17.29	Number of passengers	0	78.32
	3–12	35.30		1–3	21.40
	>12	47.40		>3	0.27
Trip purpose	work	53.47	Walking time (min)	≤2	47.23
	maintenance	16.83		2–5	46.66
	entertainment	21.78		5–10	5.64
	other	7.92		>10	0.47
Parking rate (yuan/h [b])	0	60.96	Parking location	temporary stop	7.07
	0–1	0.48		on-street parking	3.38
	1–3	1.90		illegal parking	8.81
	3–5	3.48		off-street parking	9.44
	5–10	20.20		residential zone parking	50.63
	>10	12.97		Employer-sponsored parking	20.45
				other	0.21

Note: [a] Peak hours refer to parking starts between 7 AM and 9 AM or between 5 PM and 7 PM, and off-peak hours refer to parking starts at the rest of the day; [b] The yuan is a Chinese monetary unit. One yuan is approximately equal to 0.16 U.S. dollars. [c] Private refers to the private car, while none-private means the employer-provided car.

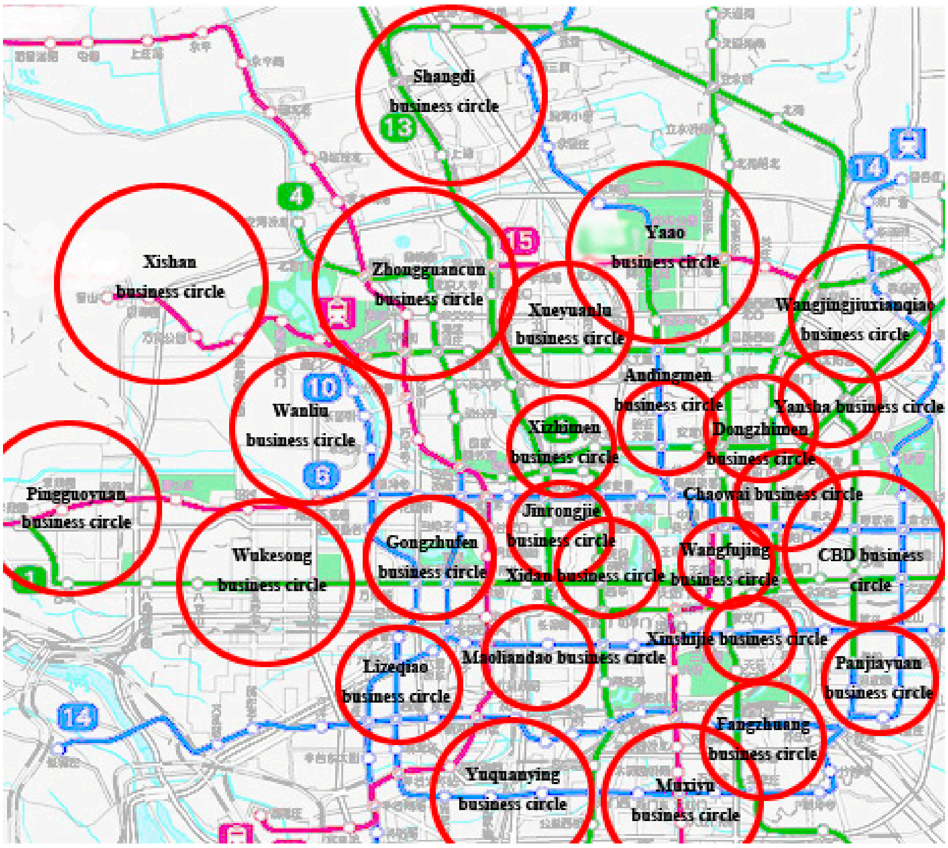
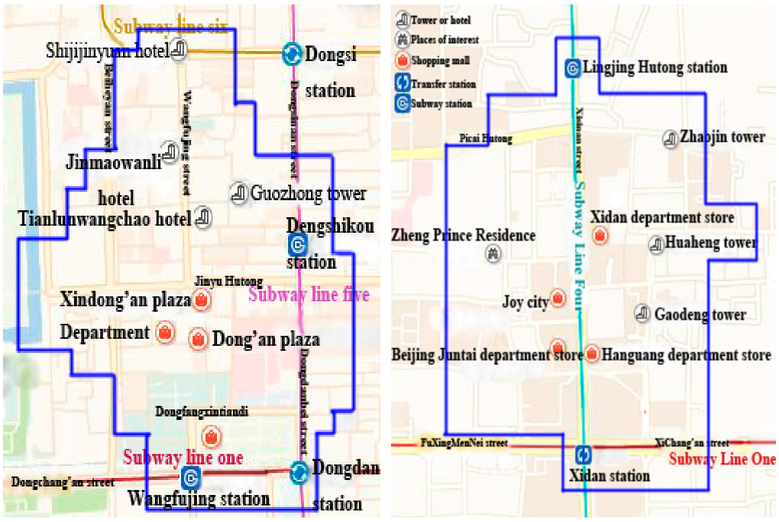


Figure 2. Major business zones in Beijing.



Wang Fujing Xi Dan

Figure 3. Maps of traditional business zones in Beijing.

By the end of year 2014, Beijing metropolitan area covered 16,410 km^2 (square kilometers) and had a permanent registered population of 21.52 million. It consisted of 16 urban and suburban districts and two rural districts. These 18 administrative districts were divided into four functional areas: The Core Districts of Capital Function, Extended Areas for Urban Function, New Districts of Urban Development, and Ecological Preservation Development Districts (Figure 1).

There are more than 30 business zones in the urban area of Beijing city, among which the best known are, Wang Fujing and Xi Dan. The spatial distribution of the major business zones in Beijing is shown in Figure 2. As shown in Figure 3, there are many shopping malls, office buildings, subway stations, and transfer stations within a traditional Beijing business zone. The average radius of a business zone is approximately 1 km.

4. Two-Level Parking Model

4.1. Model Construction

In this paper, game theory, which is a widely used method to study strategic decision making, is employed to construct a parking pricing model. Game theory is the study of mathematical models of conflict and cooperation between intelligent rational decision makers [26]. A two-level game [27] is used to describe the decision-making processes of the government and the car users in the parking system. The Level-1 game is a game between the government and car users, whereas the Level-2 game is a game among various car users.

There are many types of game. For example, games can be classified into simultaneous or sequential games. A simultaneous game is one in which the players move simultaneously, or if they do not move simultaneously, later players are unaware of the actions of earlier players (which makes these actions effectively simultaneous). A sequential (or dynamic) game is a game in which later players have a certain degree of knowledge regarding earlier actions. There are also games with perfect (as opposed to imperfect) information. A game has perfect information if all of the players are acquainted with the previous moves of all of the other players. Thus, only sequential games can be games with perfect information because players in simultaneous games are not aware of the actions of the other players. For the Level-1 game developed in this study, because the government sets the parking rates first, and the behavior of the car users is based on their knowledge of the basic information in the game, the game is a sequential game with perfect information. In contrast, the car users in the Level-2 game undertake parking actions based on imperfect information regarding the other car users. Therefore, the Level-2 game can be classified as a simultaneous game with imperfect information.

To be fully defined, a game must specify the following elements: the players of the game (*i.e.*, the participants), the strategies and the actions available to each player at each decision point and the payoff for each outcome (*i.e.*, the utility, which represents the satisfaction experienced by the players). The major elements in the two-level parking model are shown in Table 2. Typically, a game theorist uses these elements and a solution concept selected by the theorist to deduce a set of equilibrium strategies for each player such that when these strategies are employed no player can profit by unilaterally deviating from his or her strategy. These equilibrium strategies provide the game with equilibrium, *i.e.*, a stable state in which one outcome occurs or a set of outcomes occurs with a known probability.

Table 2. The two-level parking model setting.

	Players	**Government**	**Car Users**
Level-1: Game between government and car users	Strategies	To establish parking rates according to the overall performance of the parking system to maximize social benefit	To choose parking strategy according to parking cost and benefit to maximize personal benefit
	Actions	To determine parking rate p for different parking locations and starting times	To choose parking strategy s_i: parking inside/outside a business zone and parking during peak/off-peak hours
	Utility function	$\pi_g(S^*(p), p) = \sum_{i=1}^{n}\pi_i + \sum_{i=1}^{n} p_i \times t_i$	$\pi_i(s_i(p), s_{-i}(p), p) = \pi_i^0 - C_i$
	Expected outcome	To obtain the optimal parking rate p^*	To park according to the most satisfying strategy $S^*(p)$
Level-2: Game among car users	Players	Car users	
	Strategies	To choose the optimal parking strategy under the influence of the parking rate to maximize individual parking utility	
	Actions	Car user i chooses parking strategy s_i according to parking rate p, whereas the strategies of the others are $s_{-i} = (s_1, \ldots, s_{i-1}, s_{i+1}, \ldots, s_n)$	
	Utility function	$\pi_i(s_i(p), s_{-i}(p), p) = \pi_i^0 - C_i$	

The variables in Table 2 are defined as follows:

π_g is the utility of the government, which is calculated as the sum of the total parking utility of all of the car users and the parking pricing income. The parking benefit of non-car users is not represented in the government's utility function because non-car users do not have a parking demand and do not need to pay a parking fee either. Superficially, their parking benefit in the parking system is zero. However, being a kind of public resource, parking facilities or the income collected from a parking system should be shared by not only car users but also non-car users. The usual practice is to utilize the parking pricing income ($\sum_{i=1}^{n} p_i \times t_i$) collected from the car users to support investment in public projects, particularly transport investment [22,23]. This fact demonstrates that the government represents the benefit of the public, *i.e.*, not only of car users but also of non-car users. Thus, we can also state that π_g represents a consideration of the benefit of non-car users.

p is the parking rate that is established by the government. Specifically, $p_{bz\&p}$ is the rate to park in business zones during peak hours, $p_{bz\&n\text{-}p}$ is the rate to park in business zones during non-peak hours, $p_{n\text{-}bz\&p}$ denotes the rate to park outside business zones during peak hours, and $p_{n\text{-}bz\&n\text{-}p}$ designates the rate to park outside business zones during non-peak hours. For most of the public parking facilities in Beijing, the current parking rate is 5–10 yuan/h. Considering the rapidly increasing commodity prices in China, we set the basic parking rate for parking outside business zones and during off-peak hours as 10 yuan/h: $p_{n\text{-}bz\&n\text{-}p}$ = 10 yuan/h. The values of $p_{bz\&p}$, $p_{bz\&n\text{-}p}$ and $p_{n\text{-}bz\&p}$ are calculated using the parking model.

π_i is car user *i*'s parking utility, *i* = (1,…, *n*), and *n* is the total number of car users in the parking system.

t_i is car user *i*'s parking duration. According to the results of a correlation analysis of t_i and other variables, we select parking rate p_i as the independent variable and establish a linear regression model for t_i [28,29]:

$$t_i = a + b \times p_i \pi_i^0 \tag{1}$$

where *a* and *b* are the coefficients to be estimated.

Then, the model is solved using the parking survey data for Beijing for 2014. The estimation results are shown in Table 3.

Table 3. Estimation results of the parking duration model.

Variable	Coef.	Standard Error	*t*-Stat.	Sig.
a	5.283	0.521	10.140	0.000
b	−0.046	0.013	−3.538	0.000

Note: *R* = 0.924.

π_i^0 is car user *i*'s total benefits for each instance of parking, which refers to the sum of car user *i*'s parking utility and parking cost. To simplify the model and enhance the calculation efficiency, we assume that π_i^0 is of the same value for different trip purposes and different types of car user. Then, π_i^0 can be calculated by examining the wage level and the average travel cost of the survey area. In this study, the statistical data for Beijing indicate that the per capita disposable income in 2014 was 43,910 yuan (The yuan is a Chinese monetary unit. One yuan is approximately equal to 0.16 U.S. dollars.) [30]. Therefore, the per capita disposable income per day is 43910/365 = 120.30 yuan. In addition, the travel expense for each traveler per day (round-trip travel cost) was 40.23 yuan according to the 2014 travel survey data for Beijing, [31]. According to the per capita disposable income per day and the travel expenses for each traveler per day, π_i^0 is 70 yuan.

C_i refers to car user *i*'s parking cost for each instance of parking, which consists of two parts: the actual parking cost and the time cost of parking activities. Specifically, $C_i = p_i \times t_i + vot \times t_i'$, where t_i is the parking duration, t_i' is the time consumed by parking activities and *vot* is the car user's value of time. According to statistical information, the annual average wages of staff and workers in Beijing in 2014 was 64,116 yuan [30]. Thus, the average hourly wage can be calculated as 64116/(250 × 8) = 32.06 yuan/h because generally the total number of annual working days in China is 250. The average hourly wage (32.06 yuan/h = 0.53 yuan/min) is consequently adopted as the general value of *vot* [32]. Based on the general value of *vot*, a different specific value of *vot* is determined for the different types of time consumed by parking-related activities (Table 4) according to the travel survey data in Beijing and the estimation results presented by related previous studies [32–35]. The economic conditions, residents' consumption concept in China, and our previous experiences on travel behavior analysis were also involved in the estimation of the values of *vot*. The value of walking time was set to be less than that of cruising and parking operation times (see Table 4) because driving is more costly compared with walking (because of fuel consumption). The statistical data in China indicate that most travelers prefer to conduct a walking trip (especially a short-distance walking trip) than to drive a car in order to save money. In addition, the anxiety a traveler feels when waiting for a bus ora train and the congestion during getting on/off a bus or subway may be the reason for the relatively high value of the waiting and on/off times for public transport (see Table 4).

The time consumed due to parking activities (t_i') is defined as the sum of walking time from the parking location to the destination and the cruising time to search for available parking location (for simplicity, the cost of fuel consumption is taken as a part of the parking time). By assuming that different car users choose different parking decisions, we examine the basic time consumed in parking activities. When car user *i* chooses the same parking strategies as the other car users, a congestion cost, which is defined as 5.00 min, has to be concluded in his or her parking time (t_i').

t_i' is calculated according to different parking locations and parking starting times. According to statistics on Beijing's business zones, the average radius of such a zone is approximately 1 km. The average riding time for a trip by bus or subway from a parking location outside a business zone to a travel destination in the business zone was calculated as 8.00 min for parking during peak hours and 6.00 min for parking during off-peak hours based on the Beijing parking survey data [36–39]. In addition, according to the parking survey data, the average walking time (from the parking location to the destination) after parking in a business zone is approximately 3.14 min, and the average time required to walk from outside a business zone to a travel destination in the business zone was set at 8.00 min [40–42]. In addition, the cruising time was set at 8.00 min, 6.00 min, 2.00 min, and 0 min for the bz&p parking strategy (*i.e.*, business zones and peak hours), the bz&n-p strategy (*i.e.*, business zones and non-peak hours), the n-bz&p strategy (*i.e.*, non-business zones and peak hours), and the n-bz&n-p strategy (*i.e.*, non-business zones and non-peak hours), respectively. The parking operation time was defined as 3.00 min for any parking location and parking starting time. An additional cost of parking during off-peak hours was defined, which was set at 15.00 min based on the survey data. This cost represents the time loss of parking during non-peak hours because the driver would have arrived at the destination during peak hours. The time consumed and the value of time for the different parking activities of the four parking strategies is shown in Table 4.

If car user *i* does not choose the same parking strategy, *i.e.*, parking location or parking starting time, as the other car users in the Level-2 game, his or her parking time (t_i') for different parking strategies can be obtained from Table 4. In contrast, when car user *i* chooses the same parking strategies as the other car users, a congestion cost, which is defined as 5.00 min, must be included in the user's parking time (t_i'). The *vot* of congestion time was set to be 0.65 yuan/min. Thus, t_i' for car user *i* can be calculated. The results are shown in Table 5.

Table 4. Time consumed and the value of time for the different parking activities of the four parking strategies.

The Composition of t_i'	***vot* (yuan/min)**	**Car User *i*'s Parking Strategy--s_i (*p*)**			
		bz&p [a]		**bz&n-p**	
		t_i' (min)	***vot* × t_i' (yuan)**	**t_i' (min)**	***vot* × t_i' (yuan)**
Cruising time	0.65	8.00	5.20	6.00	3.90
Parking operation time	0.55	3.00	1.65	3.00	1.65
Walking time after parking	0.45	3.14	1.41	3.14	1.41
Loss of parking before peak hours	0.45	0.00	0.00	15.00	6.75
Riding time by bus or subway	0.50	0.00	0.00	0.00	0.00
Waiting time and on/off time for bus or subway	0.60	0.00	0.00	0.00	0.00
Total value	-	14.14	8.26	27.14	13.71
Cruising time	0.65	2.00	1.30	0.00	0.00
Parking operation time	0.55	3.00	1.65	3.00	1.65
Walking time after parking	0.45	8.00	3.60	8.00	3.60
Loss of parking before peak hours	0.45	0.00	0.00	15.00	6.75
Riding time by bus or subway	0.50	8.00	4.00	6.00	3.00
Waiting time and on/off time for bus or subway	0.60	5.00	3.00	3.00	1.80
Total value	-	26.00	13.55	35.00	16.80

Note: [a] bz&p means parking in the business zone during peak hours, bz&n-p denotes parking in the business zone during non-peak hours, n-bz&p signifies parking outside the business zone during peak hours, and n-bz&n-p represents parking outside the business zone during non-peak hours.

Table 5. Value of *vot* × t_i' for different parking strategies (yuan).

Car User *i*'s Parking Strategy: s_i (*p*)	**The Other Car Users' Parking Strategy: s_{-i} (*p*)**	***vot* × t_i'**	**Congestion Cost**	**Total Value of *vot* × t_i' for s_i (*p*)**
bz&p [a]	Not same as s_i (*p*)	8.26	0.00	8.26
bz&n-p		13.71	0.00	13.71
n-bz&p		13.55	0.00	13.55
n-bz&n-p		16.80	0.00	16.80
bz&p	Same as s_i (*p*)	8.26	3.25	11.51
bz&n-p		13.71	3.25	16.96
n-bz&p		13.55	3.25	16.80
n-bz&n-p		16.80	3.25	20.05

Note: [a] bz&p means parking in the business zone during peak hours, bz&n-p denotes parking in the business zone during non-peak hours, n-bz&p signifies parking outside the business zone during peak hours, and n-bz&n-p represents parking outside the business zone during non-peak hours.

4.2. Model Solution

4.2.1. Nash Equilibrium

In the previously described two-level parking model, the objective of the model's solution is to determine the Nash equilibrium. In game theory, the Nash equilibrium is a solution concept of a game that involves two or more players in which each player is assumed to know the equilibrium strategies of the other players and no player has anything to gain by changing only his or her own strategy [43]. Thus, if each player has chosen a strategy and no player can benefit by changing strategies while the other players keep maintain their strategies unchanged, then the current set of strategy choices and the corresponding payoffs constitute a Nash equilibrium.

In the Level-2 game, each car user chooses the optimal parking strategy under the influence of the parking rate (p) in order to maximize individual parking utility. In detail, car user i chooses parking strategy s_i according to p, while the other car users' strategies are $s_{-i} = (s_1, \ldots, s_{i-1}, s_{i+1}, \ldots, s_n)$ accordingly (s_i, $s_{-i} \in S_i$). S_i denotes the set of available parking strategy choices, *i.e.*, S_i={parking in the business zones during peak hours (bz&p), parking in the business zones during non-peak hours (bz&n-p), parking outside the business zones during peak hours (n-bz&p), parking outside the business zones during non-peak hours (n-bz&n-p)}. We also assumed that parking duration (t_i) is selected by car users considering the parking rate (p_i) with respect to the specific parking strategy, which he or she chooses accordingly. Therefore, the value of t_i can be calculated using Equation (1).

Based on car user i's utility function in the Level-2 model,

$$\pi_i(s_i(p), s_{-i}(p), p) = \pi_i^0 - C_i \tag{2}$$

we obtain car user i's objective function,

$$\max \pi_i(s_i^*(p), s_{-i}^*(p), p) \tag{3}$$

When other car users choose strategy $s_{-i}{}^*$, car user i's optimal strategy is,

$$s_i^*(p) = \arg\max \pi_i(s_i^*(p), s_{-i}^*(p), p) \tag{4}$$

If an arbitrary car user i, i = (1,…,n), can obtain the optimal strategy with Equation (4), then $S^*(p) = (s_i{}^*(p), s_{-i}{}^*(p))$ are the optimal strategies for all of the car users, *i.e.*, the Nash equilibrium solutions of the Level-2 game.

Based on the government's utility function in the Level-1 game,

$$\pi_g(S^*(p), p) = \sum_{i=1}^{n} \pi_i + \sum_{i=1}^{n} p_i \times t_i \tag{5}$$

We obtain the government's objective function:

$$\max \pi_g = \sum_{i=1}^{n} \pi_i + \sum_{i=1}^{n} p_i \times t_i \tag{6}$$

Assuming p^* is the optimal parking rate for the government, then p^* can be determined as follows:

$$p^* = \arg\max \pi_g(S^*(p), p) \tag{7}$$

If all the players in the two-level game, *i.e.*, the government and car users, can obtain their optimal strategies using Equations (4) and (7), then $p = p^*$ is the Nash equilibrium of the Level-1 game.

4.2.2. Solution of Level-2 Game

The Level-2 and Level-1 games are solved sequentially. Car users choose to park only if the utility of parking is non-negative, *i.e.*, if the benefit obtained from parking is greater than the cost. Therefore, we obtain a constraint for the objective function of car users:

$$s.t. \quad \pi_i^0 - p_i \times t_i \geq vot \times t_i'(i = 1,2,\ldots,n) \tag{8}$$

According to this constraint function, the function of t_i (Equation (1)) and the value of $vot \times t_i$' (Table 4), we obtain:

$$b \times p_i^2 + a \times p_i + (vot \times t_i' - \pi_i^0) \leq 0 \tag{9}$$

By solving this quadratic function, we obtain two solutions for p_i for each value of $vot \times t_i$', respectively (different parking strategy corresponds to different value of $vot \times t_i$', as shown in Table 4. In addition, two sets of $vot \times t_i$' were defined according to car user $-i$'s two strategies, *i.e.*, being same as car user *i's* strategy *vs.* being distinct with car user *i*'s strategy (Table 5). Therefore, two sets (*i.e.*, totally four solutions) of p_i were obtained for each parking strategy, respectively. By deleting the solutions, which are too large (*i.e.*, greater than 100 yuan/h) to be used as parking rate, we obtain the ranges of $p_{\text{bz\&p}}$, $p_{\text{bz\&n-p}}$ and $p_{\text{n-bz\&p}}$. The results are shown as follows:

$p_{\text{bz\&p}} \in (0, 12.41], (12.41, 13.20]$ (yuan/h)
$p_{\text{bz\&n-p}} \in (0, 11.12], (11.12, 11.88]$ (yuan/h)
$p_{\text{n-bz\&p}} \in (0, 11.15], (11.15, 11.92]$ (yuan/h)

Table 6. Values of p_i and t_i for different parking strategies.

Parking Strategies	Parking Rate (yuan/h)		Parking Duration (t_i) (min)	
	p1 [c]	***p2*** [c]	***t1***	***t2***
bz&p [a]	13.20	12.41	4.68	4.71
bz&n-p	11.88	11.12	4.74	4.77
n-bz&p	11.92	11.15	4.73	4.77
n-bz&n-p	-	-	4.82 [b]	4.82 [b]

Note: [a] bz&p means parking in the business zone during peak hours, bz&n-p denotes parking in the business zone during non-peak hours, n-bz&p signifies parking outside the business zone during peak hours, and n-bz&n-p represents parking outside the business zone during non-peak hours. [b] The value of t_i for parking outside the business zone during non-peak hours (*i.e.*, n-bz&n-p) is calculated based on $p_{\text{n-bz\&n-p}} = 10$ yuan/hour. [c] *p1* refers the upper limit value of the value ranges of parking rate calculated using the value of $vot \times t_i$' when car user $-i$'s strategy is as same as car user *i's* strategy. *p2* refers the upper limit value of the value ranges of parking rate calculated using the value of $vot \times t_i$' when car user $-i$'s strategy is distinct with car user *i's* strategy (Table 5).

As it is expected to encourage parking outside business zones during off-peak hours, the minimum value of parking utility in business zones during peak hours, the maximum value in each range for $p_{\text{bz\&p}}$, $p_{\text{bz\&n-p}}$ and $p_{\text{n-bz\&p}}$ in other words, is chosen, respectively. Then the upper limit value of each range of parking rate is selected and taken as its potential values. The values of p_i for different parking strategies are shown in Table 6. Accordingly, the values of t_i for different parking rate values are calculated using Equation (1). The results are shown in Table 6.

Then, for each available value of $p_{bz\&p}$, $p_{bz\&n\text{-}p}$, and $p_{n\text{-}bz\&p}$, the payoffs (*i.e.*, the parking utilities) of car user i and $-i$ in the Level-2 game are calculated. The results are shown in Table 7.

Table 7. Parking utilities and optimal parking strategies for different parking strategies in the Level-2 model.

Parking Rate (yuan/h)			Car User i parking Strategy	Car User $-i$ Parking Strategy $s_{-i}(p)$ = bz&p	$s_{-i}(p)$ = bz&n-p	$s_{-i}(p)$ = n-bz&p	$s_{-i}(p)$ = n-bz&n-p
$p1$ [a]	$p_{bz\&p}$	13.20	$s_i(p)$ = bz&p	(−3.25, −3.25)	(0, 0)	(0, 0)	(0, 5.00)
	$p_{bz\&n\text{-}p}$	11.88	$s_i(p)$ = bz&n-p	(0, 0)	(−3.25, −3.25)	(0, 0)	(0, 5.00)
	$p_{n\text{-}bz\&p}$	11.92	$s_i(p)$ = n-bz&p	(0, 0)	(0, 0)	(−3.25, −3.25)	(0, 5.00)
	$p_{n\text{-}bz\&n\text{-}p}$	10	$s_i(p)$ = n-bz&n-p	(5.00, 0)	(5.00, 0)	(5.00, 0)	(1.75,1.75) *
$p2$ [a]	$p_{bz\&p}$	12.41	$s_i(p)$ = bz&p	(0, 0)	(3.25, 3.25)	(3.25, 3.25)	(3.25, 5.00) *
	$p_{bz\&n\text{-}p}$	11.12	$s_i(p)$ = bz&n-p	(3.25, 3.25)	(0, 0)	(3.25, 3.25)	(3.25, 5.00) *
	$p_{n\text{-}bz\&p}$	11.15	$s_i(p)$ = n-bz&p	(3.25, 3.25)	(3.25, 3.25)	(0, 0)	(3.25, 5.00) *
	$p_{n\text{-}bz\&n\text{-}p}$	10	$s_i(p)$ = n-bz&n-p	(5.00, 3.25) *	(5.00, 3.25) *	(5.00, 3.25) *	(1.75,1.75)

Note: [a] $p1$ refers to the upper limit value of the value ranges of parking rate calculated using the value of $vot \times t_i'$ when car user $-i$'s strategy is as same as car user i's strategy. $p2$ refers to the upper limit value of the value ranges of parking rate calculated using the value of $vot \times t_i'$ when car user $-i$'s strategy is distinct with car user i's strategy (Table 5). The solutions with * are the Nash equilibrium solutions. The utilities with negative value are not considered in choosing the optimal solution. The game matrix is composed of different players' utilities (yuan).

To calculate the Nash equilibrium, we must determine the mixed strategies for each player that yield the best expected parking utility when the other player also chooses the best possible mixed strategy. If the game matrix under the condition of boundary value $p1$ is used as an example, the method of choosing the best mixed strategy is as follows:

Car user i is the row player, and car user $-i$ is the column player. To start, we find the best response for car user i for each of the strategies that car user $-i$ can play. In this step, because the utility of $s_i(p)$ = n-bz&n-p, which equals to 5.00, is larger than that of other strategies (3.25, 0 and 3.25 for $s_i(p)$ for bz&p, bz&n-p and n-bz&p, respectively), $s_i(p)$ = n-bz&n-p is chosen as the optimal strategy. We underline 5.00 to mark it. The underlining indicates that $s_i(p)$ = n-bz&n-p is the dominant strategy when $s_{-i}(p)$ = bz&p. Similarly, 5.00, 5.00 ,and 1.75 are underlined for $s_i(p)$ under the condition that $s_{-i}(p)$ is bz&n-p, n-bz&p and n-bz&n-p, respectively.

The next step is to determine the best response for car user $-i$ for each of the strategies that car user i can play. Using the same method in the previous step, 5.00, 5.00, 5.00, and 1.75 are underlined, which indicates that $s_{-i}(p)$ = n-bz&n-p is the dominant strategy when $s_i(p)$ is bz&p, bz&n-p, n-bz&p, and n-bz&n-p, respectively. Thus, the underlined mixed strategies (1.75, 1.75) * represent the Nash equilibrium choices of this level of game.

Using this method, the Nash equilibrium choices for each available value of p are calculated and identified with asterisks. Thus, we obtain the Nash equilibrium solutions for the Level-2 game, which are shown in Table 7.

4.2.3. Solution of Level-1 Game

According to the Nash equilibrium solutions obtained for the Level-2 game, the optimal parking strategy and utility for the alternative parking strategies are as shown in Table 8. Of the two players in the Level-1 model, the government first chooses the game strategy, *i.e.*, determines parking rates p to maximize its utility. Then, parking rates p with the maximal value of government utility is the Nash equilibrium for the Level-1 game. Next, the optimal parking rates with respect to different parking strategies are calculated (identified with *) (Table 8).

Table 8. Optimal parking strategies and utilities in the Level-1 game.

P (yuan/h)		**Game Strategy**		**Car User *i*'s**	**Car User −*i*'s**	**The Government's**
		$s_i(p)$	$s_{-i}(p)$	**Utility** π_i **(yuan)**	**Utility** π_{-i} **(yuan)**	**Utility** π_g ^{a} **(yuan)**
$p1$ ^{b}	$p_{\text{bz\&p}} = 13.20$ $p_{\text{bz\&n-p}} = 11.88$ $p_{\text{n-bz\&p}} = 11.92$	n-bz&n-p	n-bz&n-p	1.75	1.75	101.5
$p2$ *	$p_{\text{bz\&p}} = 12.41$	bz&p *	n-bz&n-p *	3.25	5.00	114.94 *
	$p_{\text{bz\&n-p}} = 11.12$	bz&n-p	n-bz&n-p	3.25	5.00	109.49
	$p_{\text{n-bz\&p}} = 11.15$	n-bz&p	n-bz&n-p	3.25	5.00	109.65
$p2$ *	$p_{\text{bz\&p}} = 12.41$	n-bz&n-p *	bz&p *	5.00	3.25	114.94 *
	$p_{\text{bz\&n-p}} = 11.12$	n-bz&n-p	bz&n-p	5.00	3.25	109.49
	$p_{\text{n-bz\&p}} = 11.15$	n-bz&n-p	n-bz&p	5.00	3.25	109.65

Note: * are the Nash equilibrium solutions. ^{a} π_g is calculated with Equation (5). ^{b} $p1$ refers to the upper limit value of the value ranges of parking rate calculated using the value of $vot \times t_i$' when car user $-i$'s strategy is as same as car user *i's* strategy. $p2$ refers to the upper limit value of the value ranges of parking rate calculated using the value of $vot \times t_i$' when car user $-i$'s strategy is distinct with car user *i's* strategy (Table 5).

4.2.4. Optimal Solution

The results reveal that the car users and the government obtain the maximum utility when $p_{bz\&p}$ is 12.41 yuan/h, $p_{\text{bz\&n-p}}$ is 11.12 yuan/h, $p_{\text{n-bz\&p}}$ is 11.15 yuan/h, and $p_{\text{n-bz\&n-p}}$ is 10 yuan/h. Under this condition, the parking strategy of car user i and $-i$ is that $s_i(p)$ = bz&p when $s_{-i}(p)$ = n-bz&n-p or $s_i(p)$ = n-bz&n-p when $s_{-i}(p)$ = bz&p. These outcomes indicate that car users prefer a parking strategy opposite to that of the other car users to avoid the congestion loss.

According to the estimation results for the two-level game model, the optimal parking rate structure is 12.41 yuan/h for parking in the business zone during peak hours, 11.12 yuan/h for parking in the business zone during non-peak hours, 11.15 yuan/h for parking outside the business zones during peak hours, and 10 yuan/h for parking outside the business zones during non-peak hours.

5. Parking Utility Analysis

According to the optimal parking strategies shown in Table 8, under the condition of the optimal structure of parking rates, car users prefer a parking strategy opposite to that of the other car users. That is, the parking strategy of car user i and $-i$ is that $s_i(p)$ = bz&p when $s_{-i}(p)$ = n-bz&n-p or $s_i(p)$ = n-bz&n-p when $s_{-i}(p)$ = bz&p. Therefore, to simplify the process of parking utility analysis, we consider only the scenario of parking in business zones during peak hours (bz&p) *vs.* parking outside business zones during non-peak hours (n-bz&n-p).

We suppose that the number of car users who park in the business zone during peak hours share r of the total number of parkers. Thus, the number of car users who park outside business zones during non-peak hours share $1 - r$ of the total number of parkers.

Then, the parking utilities (π_i) for bz&p *vs.* n-bz&n-p are calculated with $p_{\text{bz\&p}}$ = 12.41 yuan/h and $p_{\text{n-bz\&n-p}}$ = 10 yuan/h. The results are shown in Figure 4.

The three lines represent the benefit of parking stategy bz&p before adjusting the parking rate (p_{bz} = 10 yuan/h), parking strategy bz&p after adjusting the parking rate ($p_{\text{bz\&p}}$ = 12.41 yuan/h), and parking strategy n-bz&n-p ($p_{\text{n-bz\&n-p}}$= 10 yuan/h), respectively.

The comparison of parking utility before and after the parking rate adjustment in the business zone during peak hours reveals that the parking utility of parking in the business zone during peak hours before the parking rate adjustment is higher than that of parking outside the business zone during non-peak hours because of the advantages of parking in the business zone during non-peak hours, such as short walking distance. Therefore, parking in the business zone during peak hours is the dominant strategy if there is no increase in the parking rate. Thus, a large number of car users choose this parking strategy, which results in the increases in road traffic pressure.

Consequently, the parking costs of car users increase and parking utilities decrease when the parking rate in the business zone during peak hours increases from 10 yuan/h to 12.14 yuan/h. We obtain an intersection point, *i.e.*, r^* = 0.237, of the two curves of parking utilities. At point r^*, the utilities of the bz&p and n-bz&n-p parking strategy are equal. That is, car users will choose to park outside the business zone during non-peak hours when the ratio of parking in the business zone during peak hours to the total number of parkers reaches 0.237. This outcome reflects the objective of the government, which is to guide the car users who usually park in the business zone during peak hours to park outside the business zone during non-peak hours. The positive impacts of the adjustments of the bz&n-p and n-bz&p parking rates can also be explained using a similar method.

The above parking utility analysis indicates that the parking system gets the equilibrium, in which both the government and car users obtain the optimal benefits, if we define the parking rate as 10 yuan/h for parking during off-peak hours outside the business zone, 12.41 yuan/h for parking during peak hours in the business zone, and 11.12 yuan/h for parking during non-peak hours in the business zone, and 11.15 yuan/h for parking during peak hours outside the business zone.

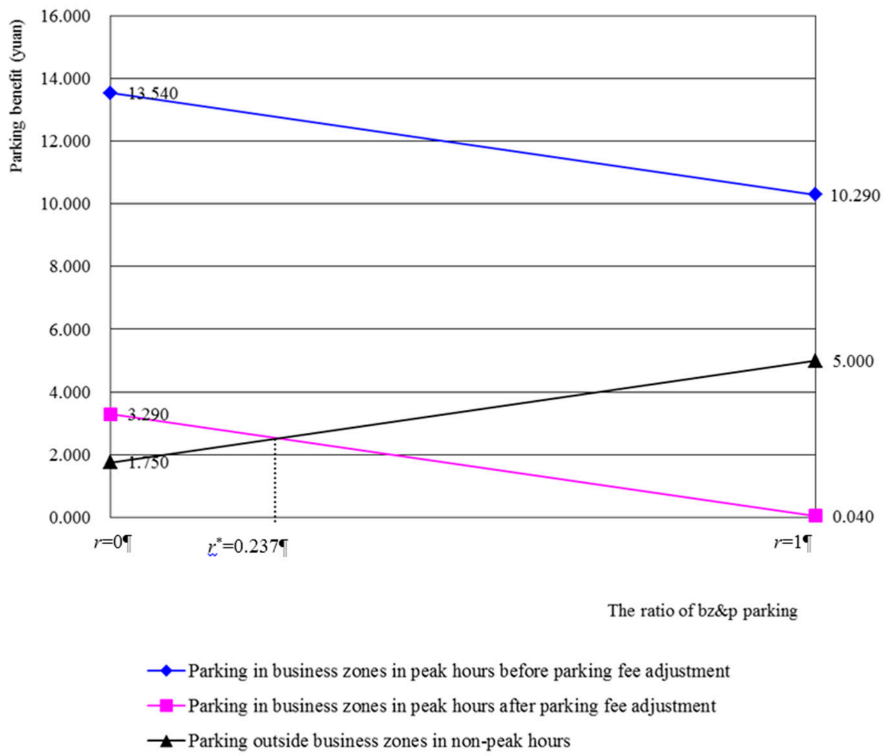


Figure 4. Parking utilities for the bz&p and n-bz&n-p parking strategy.

6. Conclusions

This paper established a two-level parking model based on game theory using parking data collected in Beijing in 2014. The model was estimated based on the Stackelberg game and the Nash equilibrium theory. With the two-level parking model, we described the relationships between the government and car users as well as among car users in the parking system. The optimal parking rates for parking inside/outside the business zone and during peak/off-peak hours were determined. The results indicate that there is competition between the government and car users, in which the government desires to maximize the social benefit by establishing an optimal parking rate structure, whereas car users try to choose the best parking strategy to obtain the maximal individual parking benefit. In addition, there is also competition between various car users, in which all of the car users pursue their maximal parking utility. The Nash equilibrium of the two-level parking game represents an equilibrium of the parking system, with which we obtain the optimal parking rate structure. The investigation of competition suggests that not only the parking behaviors of car users but also the actions of the government or non-car users should be considered in parking behavior analysis.

The two-level parking model presented in this paper can be used to determine the optimal parking rate and thus to balance the temporal and spatial distribution of the parking demand in urban areas. Thus, the model helps reduce car use and parking-related cruising time and therefore contributes to the reduction of carbon emissions and air pollution. By addressing the parking problems and traffic congestion in the business zone and during peak hours, the results also contribute to the economic development of large cities.

It should be noted that the individual and household socio-demographic attributes of car users were not considered in the parking modeling described in this study. However, these factors may influence the parking decisions of car users. For example, certain individuals who are employed in the city center can only choose to park in the business zone or during peak hours even if the parking rate is high. In addition, in certain circumstances, car users must arrive at their workplaces by a specific time even if their parking behavior results in negative utility. Such decisions indicate that not only the parking rate but also other factors, such as a car user's individual and household socio-demographic attributes, employment-related restrictions and subjective intentions should be considered in the analysis of parking behavior and parking pricing. Based on the finding of this paper, this issue can be addressed by developing a parking demand forecasting model. Such a model would enable us to examine the parking behavior adjustments of car users (e.g., parking location choice, parking starting time and parking duration) and the price elasticity of parking rates under the influence of these factors. This approach would provide a more convincing parking rate structure. In addition, the values of some of the parameters, such as π_i^0 and t_i, which are determined at a general level in the present study, should also be examined at an individual level in further studies.

Today, certain employers offer to pay for parking as an additional benefit to their employees, which decreases the cost of parking and thus alters the parking utilities for such employees. Employer-paid parking is not considered in this study. This topic could be addressed by dividing car users in the parking game into two player types: those with free parking spaces in a business zone and those who must pay their parking fee themselves. In addition, this factor, *i.e.*, employer-paid/self-paid parking, could be used as a variable in a parking demand forecasting model.

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Author Contributions

The research scheme was mainly designed by Fang Zong. Yanan He and Yixin Yuan performed the research and analyzed the data. The paper was mainly written by Fang Zong. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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