IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 12 May 2022, accepted 24 June 2022, date of publication 30 June 2022, date of current version 8 July 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3187534

RESEARCH ARTICLE

Analysis of the Effect of Demand-Driven Dynamic Parking Pricing on on-Street Parking Demand

HUANMEI QIN[1], FEI ZHENG[2], BINHAI YU[1], AND ZHONGFENG WANG[3]
[1]Beijing Key Laboratory of Traffic Engineering, Beijing University of Technology, Beijing 100124, China
[2]Beijing Shunjie Xinghong Engineering Design Consulting Company Ltd., Beijing 100124, China
[3]41st Institute of China Electronics Technology Group Corporation, Beijing 266000, China

Corresponding author: Huanmei Qin (hmqin@bjut.edu.cn)

This work was supported in part by the Beijing Natural Science Foundation of China under Grant 8212002, and in part by the National Natural Science Foundation of China under Grant 71971005.

ABSTRACT The rapid increase in the number of cars has caused many problems, such as ''cruising for parking'' and ''illegal parking''. In this study, we conducted several on-street parking surveys in Beijing's business districts. A parking location choice model and decision rules for the cruising process are established. A multi-agent based on-street parking simulation was constructed to explore the effects of time-varying parking prices on parking demand. It is concluded that demand-driven dynamic parking pricing can effectively regulate the distribution of parking demand and ensure the utilization of parking facilities within the desirable range in business districts. A lower desirable range and higher price change for the price adjustment can cause larger fluctuations in parking demand, fewer time intervals within the desirable range, and more price adjustment times. A higher desirable range and higher price change can result in longer cruising and driving times, and lower driving speeds. Considering the effectiveness and operating costs of the pricing schemes, it is recommended that the suitable range for parking occupancy rate is 60%–80% and the price change is 2 Yuan/h. The price adjustment threshold can be set based on the scale of the regional road network. The proposed dynamic parking pricing strategy can balance the distribution of the parking demand and reduce parking and traffic problems. The research conclusions can also provide a reference for the formulation of dynamic parking pricing strategies.

INDEX TERMS Demand-driven dynamic parking pricing, on-street parking, decision rules, multi-agent simulation.

I. INTRODUCTION

With the rapid development of the social economy, the number of motor vehicles has dramatically increased. By the end of 2018, car ownership in Beijing had reached 6.084 million, while the number of registered parking spaces was only 1.891 million. The imbalance between parking supply and demand is becoming increasingly serious. As a result, many problems such as ''cruising for parking'' and ''illegal parking'' have a significant impact on traffic operations and cause considerable environmental pollution. It has been proven that parking pricing strategies can regulate the spatial-temporal distribution of parking demand and improve the efficient utilization of parking facilities. Therefore, designing a reasonable parking pricing scheme is regarded as an effective method to alleviate parking problems.

Generally, parking pricing strategies remain unchanged for a long period (one year or many years). For example, a parking pricing scheme based on regional differentiation has been used in Beijing since 2015. The scheme cannot be dynamically adjusted according to parking demand, especially in central business areas with constantly changing high parking demands. Therefore, this weakens the moderating effect of parking prices on parking demand. As early as 1954, William Vickrey, a Nobel laureate in economics, recommended time-varying parking tariffs. He proposed that parking prices should be set at the level of ''fully reducing the total parking demand to ensure the parking spaces available to those willing to pay''. Demand-driven dynamic parking pricing is an adjustment mechanism that can change

The associate editor coordinating the review of this manuscript and approving it for publication was Abderrezak Rachedi.

the parking price for different parking facilities at regular intervals according to changing parking demand. In this way, parking demand can be balanced, and parking utilization can be maintained at an ideal level, thus reducing parking and traffic problems.

Demand-driven dynamic parking pricing has been piloted in several cities. For example, the ''SFpark'' project has been implemented for a quarter of public parking spaces in San Francisco. The objective of the project is to maintain the parking occupancy rate of parking facilities at a desired level of 60% to 80% using a time-varying parking price. The implementation of the project significantly improved the parking efficiency in the area. Taipei has implemented a dynamic regulation of parking prices based on the utilization of public parking lots during peak hours. Local authorities evaluated the utilization of parking facilities every six months. When the average parking occupancy rate was greater than 80% or less than 50%, the parking price increased or decreased, respectively.

As an innovative approach, demand-driven dynamic parking pricing has not been used in mainland China. Therefore, it is necessary to conduct an exploratory study based on the characteristics of travelers' parking behavior in big cities in China. At present, Beijing conducts electronic charging for on-street parking. More than 13800 on-street parking spaces have been installed with electronic charging equipment, providing preconditions for the implementation of demand-driven dynamic parking pricing.

In this study, we conducted a large number of parking surveys and collected data related to cruising behavior and choice preference for on-street parking in Beijing. Subsequently, the parking location choice model and decision rules for the cruising process were established. A multi-agent based method was used to simulate the on-street parking search and explore the effect of time-varying parking prices on parking demand and road traffic performance. Finally, different demand-driven dynamic parking pricing schemes were evaluated, and the recommended pricing scheme was presented. The conclusions can provide a reference for the formulation of dynamic parking pricing strategies.

II. LITERATURE REVIEW

In recent years, some researches have been conducted to explore the impact of parking prices on parking demand and travel mode choice behavior [1]–[5]. Nourinejad and Roorda [6] studied the effect of parking prices on parking demand, based mainly on the elasticity of parking duration. The results show that a change in parking price can stimulate parking demand when parking duration is elastic. Khordagui [7] analyzed the impact of parking prices on car use for commuting based on a household travel survey in California. It was found that a higher parking price could reduce car use. Increasing the parking price by 10% can decrease the proportion of car commutes by 1–2%. Mo *et al.* [8] used parking meter and survey data to analyze the impact of on-street parking prices on parking demand. The results showed that an increase in parking prices significantly reduced parking demand and parking duration.

Several researchers have studied parking pricing. In terms of static parking pricing, Schaller *et al.* [9] developed a parking pricing strategy based on land use and space utilization. The results demonstrate that regional characteristics, especially the current parking demand and utilization of off-street parking spaces, have a significant impact on on-street parking pricing. Simićević *et al.* [10] obtained the travel mode choice data of car travelers for different trip purposes when the parking price was increased. They then calculated the price elasticity coefficient and obtained the optimal parking price by considering the desired parking utilization level. Based on a parking survey of commuters, Qian and Rajagopal [11] used a linear programming method to obtain the parking price under system optimization. The research shows that optimal parking pricing can balance cruising time and parking convenience. Wang *et al.* [12] used a mixed-integer linear program (MILP) to study the optimal parking pricing problem considering parking permit management. The research results show that the hybrid model is more effective in obtaining the optimal parking price for park-and-ride facilities than the simple parking pricing model.

In the research of dynamic parking pricing, Qian and Rajagopal [13] proposed a stochastic control model to obtain the real-time parking price based on the time-varying parking demand. The results show that the parking pricing policy combined with information provision can minimize the total travel time for travelers. Van Ommeren and Russo [14] estimated the impact of parking prices on workers' parking demand using the difference-in-differences method. The results suggest that parking prices should be varied per day with demand to minimize deadweight loss and maximize welfare. Mackowski *et al.* [15] established a dynamic non-cooperative bi-level model to obtain real-time parking prices. Numerical examples show that the pricing model can eliminate cruising for parking, balance parking space utilization, and reduce traffic congestion. Lei and Ouyang [16] used a multi-period non-cooperative bi-level model to determine the location-dependent parking prices. The results indicate that a pricing policy combined with parking supply and demand information can improve the performance of the parking system. Fulman and Benenson [17] proposed a spatially explicit algorithm to obtain on- street and off-street parking prices. The application shows that adaptive parking prices can maintain 90% parking occupancy over the entire area.

Some studies have been conducted on dynamic parking pricing based on parking data collected from an actual project. Pu *et al.* [18] evaluated the price sensitivity of on-street parking demand based on data collected from the SFpark project in San Francisco. The results show that time of day, regional features, and socio-demographic characteristics affect parking demand and its sensitivity to time-varying parking prices. Alemi *et al.* [19] discussed the impact of the dynamic parking pricing strategy on the demand for the ''SFpark'' project using a generalized mixed-effect difference-in-difference model. This research indicates that the implementation of the project can reduce the average cruising time and distance. Fabusuyi and Hampshire [20] established a two-stage regression and optimization model using panel data to determine time-varying parking prices. Then, the model was verified using the observed parking occupancy and parking price data in the SFpark project.

The aforementioned studies mainly used the optimization model and parking data collected from an actual project to study the relationship between dynamic parking pricing and demand. Few studies have examined this relationship based on travelers' parking decision-making process. To the best of our knowledge, some studies have used simulation methods to analyze parking behaviors and their effects on traffic operation. Benenson *et al.* [21] and Levy *et al.* [22] presented PARKAGENT to simulate parking behavior. They analyzed the impact of available or additional parking spaces on cruising for parking. Waraich *et al.* [23] established an agent-based cruising behavior model based on MATSim. The proposed model can produce less cruising time than previous parking search models. Steenberghen *et al.* [24] proposed an agent-based parking model, SUSTAPARK, to simulate the traffic effects generated by cruising behavior. Parking occupancy rate and cruising time were obtained from the simulation model. Horni *et al.* [25] simulated cruising for parking based on the cellular automaton approach. The simulation results show that the relationship between cruising time and parking demand is nonlinear. Zhuge *et al.* [26] developed a large-scale simulation model based on agents and activities to analyze enroute travel and parking behavior. The results show that the population scale and simplification of the road network affect the accuracy and computation time of the simulation. Levy and Benenson [27] introduced PARKFIT to estimate the matching between parking demand and parking capacity in the city of Bat Yam. Gu *et al.* [28] proposed a macro-micro parking simulation model to mimic on-street and off-street parking. The results suggest that parking occupancy, cruising speed, and parking duration are important factors that affect travelers' decision-making regarding the distance to the park.

This study examined the dynamic relationship between demand-driven dynamic parking pricing and parking demand. The innovations were as follows: (1) A large amount of data on parking behavior and choice preference were collected in Beijing. A parking location choice model and decision rules for travelers' cruising and parking processes were derived. (2) A multi-agent based on-street parking simulation for an area was established from the perspective of travelers' parking decision-making process. (3) The interactions between parking prices and parking demand under different demand-driven dynamic parking pricing schemes were discussed. An optimal dynamic parking pricing mechanism is recommended based on the effectiveness of the schemes.

The remainder of this paper is organized as follows. Section 3 introduces the survey and analyzes cruising behavior and choice preference for parking based on the collected data. Subsequently, a parking location choice model was established. Section 4 develops a multi-agent based parking simulation program and integrates the cruising process for on-street parking into the simulation. Section 5 presents a comparative analysis of the effectiveness of different demand-driven dynamic parking pricing schemes, and provides an optimal pricing strategy. Finally, Section 6 summarizes the conclusions of this study.

III. SURVEY AND ANALYSIS OF CRUISING BEHAVIOR AND CHOICE PREFERENCE FOR PARKING

To obtain travelers' behavioral characteristics and choice preference for on-street parking under the changed parking price, this study conducted field surveys using video capture and questionnaires. The surveys were conducted in three business districts in Beijing: the Youshige Shopping Center, the New World Department Store, and the Carrefour Shopping Mall. A large number of cars search for free parking spaces in these places. The surveys included three parts: cruising process for parking, cruising behavior for parking, and stated preference for parking locations. The surveys were conducted several times during rush hour from June 2017 to October 2018. The survey data provided substantial support for setting attributes and behavioral rules of agents for parking simulation.

A. SURVEY AND ANALYSIS OF CRUISING PROCESS FOR PARKING

A video survey at the Youshige Shopping Center was conducted to collect travelers' driving speed and cruising speed data during the cruising process for parking. There are 34 on-street parking spaces on the relief road in front of the center. The on-street parking road section is approximately 300 m long. Four cameras were set up on the relief road section, and each camera covered a length of approximately eight to nine on-street parking spaces. Based on video data and trajectory extraction software, 240 vehicle trajectories were obtained. The extracted data included the real-time position and driving speed of the passing and cruising vehicles [29]. When the car travelers drive through a distance of 200 m to the destination, their driving speed, that is, cruising speed, is between 10 and 20 km/h. The average cruising speed of the parked vehicles was approximately 15 km/h. The average driving speed of the passing vehicles was approximately 25 km/h. These data can be used as the basis for setting the driving and cruising speeds of cars in parking simulations.

B. SURVEY AND ANALYSIS OF CRUISING AND PARKING BEHAVIOR

A questionnaire survey was conducted for travelers who parked their cars on the street in the three business districts. The contents of the survey consisted of walking distance after parking, parking duration, cruising time, and acceptable levels of increase in on-street parking prices. A total of 505 samples were collected, of which 490 were valid.

As shown in Table1, the travelers' walking distance after parking is mainly within 150 m, accounting for 77%.

It indicates that car travelers prefer to park close to their destination. Most of the car travelers (88%) have an on-street parking duration within 2 h, and only 4% of them have an on-street parking duration of more than 3 h. It suggests that car travelers in business districts are generally short-term parkers. Although 21% of car travelers can find an on-street parking space as soon as they arrive at the destination, most of them need to spend some time searching for the parking space. There are 62% of car travelers whose cruising time is between 1 and 5 min.

TABLE 1. The characteristics of cruising and parking behavior.

Items	Options	Proportion (%)	Items	Options	Proportion (%)
Walking distance after parking	<50m	27	Parking duration	<30minute	18
	50-100m	33		30-60minute	30
	100-150m	17		60-120minute	40
	150-200m	13		120-180minute	8
	>200m	10		>180minute	4
Cruising time	none	21	Acceptable levels of the maximum increase in on-street parking prices	1Yuan/h	1
	1-5minute	62		3Yuan/h	6
	5-10minute	12		5Yuan/h	37
	10-15minute	3		10Yuan/h	43
	>15minute	2		>10Yuan/h	13

For the surveyed business districts, the current on-street parking charges is 10 Yuan/h. 44% of car travelers cannot accept an additional 5 Yuan/h or more increase in the existing parking price. When the parking price is increased by more than 10 Yuan/h, only 13% of travelers can accept it. Therefore, the maximum acceptable increase in the on-street parking price is 10 Yuan/h.

The analysis results provide a basis for setting the attributes and behavioral rules of agents and designing demand-driven dynamic parking pricing schemes.

C. SURVEY AND ANALYSIS OF PARKING LOCATION CHOICE

A stated preference (SP) survey was conducted at Carrefour Shopping Mall to analyze travelers' parking location choice preferences. A travel scenario was designed for the SP survey, as illustrated in Figure 1. The hypothetical travel destination is a business district. There are six road sections with available on-street parking spaces in the area. Three important factors influencing parking location choice by providing parking information are chosen to design hypothetical scenarios. The parking price has four levels: 10, 13, 17, and 20 Yuan/h. The utilization rate of parking spaces on each road section is represented by the number of empty parking spaces, which changes over time, and is set to five levels: 2, 6, 10, 13, and 16. The walking distance from the available parking location to the destination can be obtained from the travel scenario based on the spatial positions. Subsequently, six hypothetical scenarios with different parking prices and empty parking spaces on different road sections were obtained using an orthogonal design. Figure 1 shows an example of a hypothetical scenario. Personal information, including gender, age, and monthly income, are also included in the questionnaire.

Each respondent is assigned two hypothetical scenarios. He/she needs view the information of each scenario and chooses the preferred parking location among the six road sections. The survey objects are car travelers with driving experience. In total, 202 valid questionnaires were obtained.

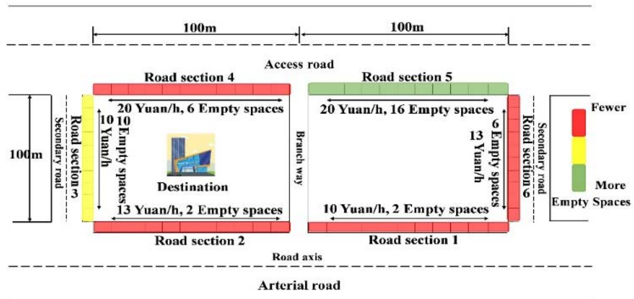

FIGURE 1. An example of the hypothetical scenarios.

Based on the survey data, an on-street parking location choice model was established using the multinomial Logit model, as shown in Table 2. The overall goodness-of-fit of the model is good with the McFadden Pseudo R-squared of 0.23 [30].

TABLE 2. The estimation of parking location choice model.

Variables	Coefficient	T-test
Constant	0.330	1.678
Monthly income	0.480	2.689
On-street parking price	-0.282	-8.512
Empty parking spaces	0.150	5.767
Walking distance after parking	-0.004	-2.732
$L(0)$	-315.35	
$L(\theta)$	-267.98	
$-2(L(0)-L(\hat{\theta}))$	94.75	
R-squared	0.23	

The factors of monthly income, on-street parking price, empty parking spaces, and walking distance after parking have an important impact on parking location choices. Their corresponding T test are 2.689, −8.512, 5.767, and −2.732, respectively. It can be seen that parking price has the greatest impact on parking location choice, followed by the number of empty parking spaces on the road section and walking distance. Changing the on-street parking price can effectively regulate parking demand. Moreover, the lower the parking price, the more the empty parking spaces, and the closer to the destination for the road section, the more travelers are willing to choose to park their cars.

Based on the estimated model, the parking choice probability for each road section can be obtained using Eq. (1) and Eq. (2) when parking spaces are available on a road section.

$$q_k = \frac{e^{V_k}}{\sum_j e^{V_j}} \; (j = 1, \ldots, 6) \tag{1}$$

$$V_k = 0.33 - 0.282 \cdot P_k + 0.15 \cdot O_k - 0.004 \cdot D_k + 0.48 \cdot I \tag{2}$$

where q_k is parking the choice probability for road section k; V_k is the utility of choosing to park on road section k; O_k, P_k is the number of empty parking spaces and parking price on road section k, Yuan/h; D_k is walking distance from road section k to destination, Meter; I is the monthly income of car travelers, Yuan. When there are no empty parking spaces on a road section (i.e., O_k equals zero), the utility V_k of choosing to park on road section k is set to zero.

IV. ON-STREET PARKING SIMULATION BASED ON A MULTI-AGENT APPROACH

The agent-based modelling method is more suitable for describing the individual cruising behavior and decision-making process for parking. In this study, we used Netlogo software based on a multi-agent approach to simulate on-street parking in a small area. The simulation data can be used to analyze the effect of demand-driven dynamic parking pricing on parking demand and road traffic performance.

A. CONSTRUCTION OF SIMULATED ENVIRONMENT

1) SCENARIO DESCRIPTION FOR SIMULATION

Figure 2 shows a simplified scenario for the simulation abstracted from the Carrefour Shopping Mall. The Mall is marked as a red house and is regarded as the travel destination for all cars entering the study area. The area is 200 m long and 100 m wide. There are six road sections, and approximately 20 on-street parking spaces are distributed along each section. Road sections 1 and 2 are arterial roads, and road sections 3 and 6 are secondary roads. Sections 4 and 5 are access roads.

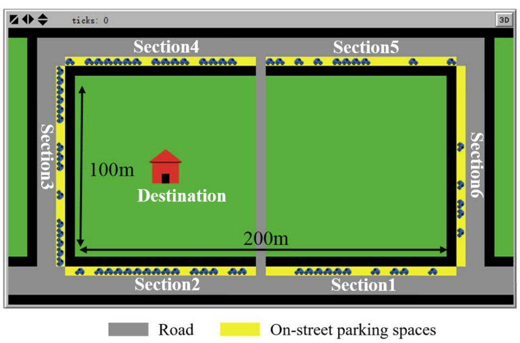

FIGURE 2. Simplified scenario for on-street parking simulation.

According to the survey data, the initial speed of cars for the on-street parking simulation is set to 5 m/s-7.5 m/s and the expected speed is less than 10 m/s. The acceleration and deceleration of cars are respectively 2.5 m/s^2 and -2.5 m/s^2. The arrival of cars follows a Poisson distribution with a mean of 15, and the arrival rate is approximately 240 vehicles during peak hours. These cars are divided into passing and cruising vehicles by a certain proportion when they enter the study area. The parking time of cars follows the distribution of parking duration shown in Table 1 in Section 3.2.

2) CLASSIFICATION AND INTERACTION OF AGENTS

There are three types of agents for parking simulation: car-traveler agent, road section-parking space agent, and price adjustment agent. The functions and attributes of different agents are listed in Table 3.

Different agents exhibit different behavioral responses to the simulation environment. All the agents can communicate and interact with each other in real time. The interaction between car-traveler agents can simulate the car-following process on the road. Car-traveler agents can perceive the real-time state of road section-parking space agents and make parking decisions. Price adjustment agents can change the parking price for each road section within a certain period according to the parking utilization obtained from the road section-parking space agents. The adjusted on-street parking price can be delivered to car-traveler agents.

TABLE 3. Functions and attributes for each type of agents.

Agents	Definition	Functions	Attributes
Car-traveler agent	Car driver	Driving, route choice and parking decisions (cruising for parking, parking location choice etc.)	Driving speed, acceleration, deceleration, parking duration, cruising or parking status, decision rules
Road section - parking space agent	On-street parking space	Providing on-street parking spaces for car travelers	Number of empty parking spaces, parking price, walking distance to destination
Price adjustment agent	On-street parking manager	Adjusting the parking price according to the utilization of parking spaces	Desirable parking occupancy rate, price change and threshold for price adjustment

B. DECISION RULES DURING CRUISING PROCESS FOR PARKING

It is assumed that car travelers can obtain real-time parking information before and during a trip. They can make parking decisions based on the demand-driven dynamic parking price and utilization of parking spaces. The decision rules during the cruising process for parking are shown in Figure 3. The parking decision-making process can be divided into three sequential steps.

Step I: Initial parking location choice before a trip

Before a trip, car travelers can use the mobile app to choose a road section to park their cars based on parking information around their destination. The parking choice probabilities for

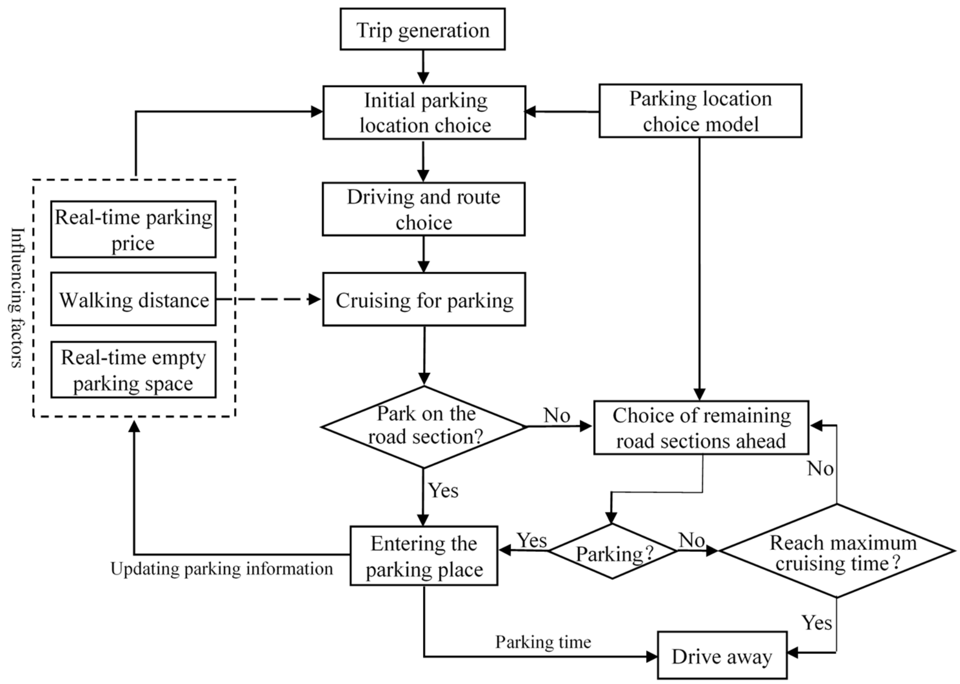

FIGURE 3. The decision-making process for on-street parking.

each road section are obtained using the on-street parking location choice model described in Section 3.3. The road section with the maximum choice probability is regarded as the initial preferred parking location.

Step II: Driving process and route choice

During the trip, car travelers follow the car-following rule while driving on the road. They accelerate or decelerate according to the headway distance to the car ahead. When car travelers enter the study area, as shown in Figure 2, the car-traveler agent can allocate the best route to them based on the initially chosen road section for parking and the Shortest Path Algorithm.

Step III: Cruising process for parking

Firstly, each road section is divided into three continuous segments. Each segment has approximately six on-street parking spaces. It is assumed that travelers can see the parking situation of one segment ahead within their visual range while driving.

When travelers arrive at the initially chosen road section for parking, they are assumed to reach the first segment on the road section. As long as there is an empty parking space on the first segment, the choice probability for parking is determined by the walking distance and its observed distribution in Table1. If the walking distance is within the range randomly sampled based on the observed distribution, the travelers will park their car on the first segment and enter one empty parking space. Walking distance is defined as the shortest path length from the center point of the segment on the road section to the travel destination. Otherwise, they continue to drive to the next segment on the same road section and make a parking decision similar to the decision-making process for the first segment.

If there are no empty parking spaces on the three segments of the initially chosen road section, or travelers do not choose to park on this road section, they continue to drive. At this moment, they need to re-select a parking place among the remaining available road sections in the forward direction according to the decision rules of Step I. When car travelers arrive at the re-selected parking section, their decision process follows the same rules as in this Step. Car travelers can continue circling around this area to search for a parking place until the maximum cruising time is reached. They then drive away from the survey area. Cruising and driving times are defined as the time that car travelers spend from the position where they enter the survey area to the position where their car is parked. If some travelers keep cruising for parking and do not park their cars, their cruising and driving time is continuously accumulated from the position where they enter the area. Based on the survey data, the maximum cruising and driving time is set at 30 min in this study.

C. ADJUSTMENT PROCESS OF DEMAND-DRIVEN DYNAMIC PARKING PRICING

The adjustment process for the demand-driven dynamic parking pricing is illustrated in Figure 4. N is the total number of road sections in the study area. β, θ is the threshold and change for parking price adjustment.

The principle of parking price adjustment is to calculate the average parking occupancy rate, ρ_k, for each road section k for a given time interval t. It is assumed that the upper and lower limits for the desirable parking occupancy rate are γ and δ, respectively. The number of road sections b in an area whose parking occupancy rate is outside the desirable range and their proportion q can then be obtained by calculation.

Once proportion q reaches or surpasses the threshold β, the price adjustment agent is triggered to regulate the on-street parking price. If the parking occupancy rate of the road section is higher than the upper limit of γ, its parking price P_{kt} is increased by θ. If the parking occupancy rate of the road section is lower than the lower limit of δ, its parking price P_{kt} is decreased by θ. If the parking occupancy rate is within the desired range, the parking price remains the same.

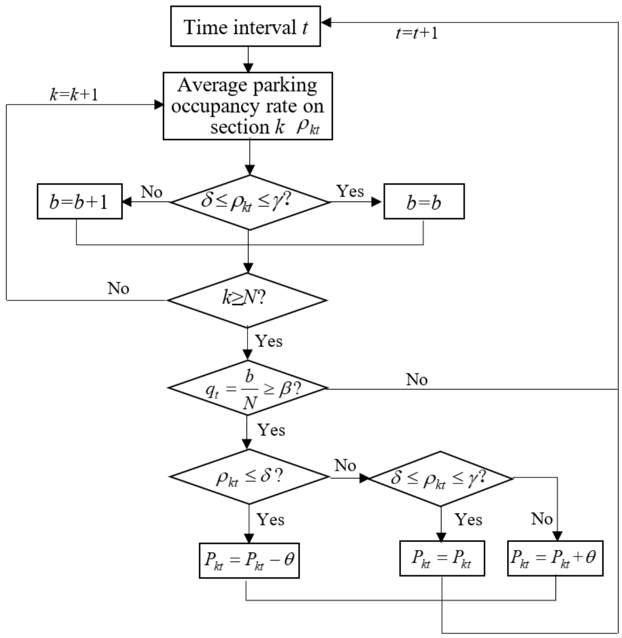

FIGURE 4. Adjustment process of demand-driven dynamic parking price.

V. SIMULATION AND ANALYSIS OF DEMAND-DRIVEN DYNAMIC PARKING PRICING SCHEMES

For the demand-driven dynamic parking pricing mechanism, parking price change, desirable range for parking occupancy rate, and threshold for price adjustment are three important factors for the design of parking pricing schemes. The aim of setting a desirable parking occupancy rate is to guarantee that car drivers can easily find an empty parking space without spending more time cruising for parking when they arrive at their destination. Meanwhile, the utilization of parking facilities is maintained at a relatively high level.

It is assumed that these factors vary at different levels, as listed in Table 4. The parking price change for each adjustment has three levels: 1, 2, and 3 Yuan/h. The desirable range for the parking occupancy rate has three levels: 50%-70%, 60%-80%, and 70%-90%. The threshold for the price adjustment has three levels: 1/6, 1/3, and 1/2. Then, seven different dynamic parking pricing schemes are obtained, as shown in Table 5. Based on the relative research and travelers' acceptable levels of on-street parking price s, Scheme 1 with

TABLE 4. The variables and their values for price adjustment.

Variables	Description	Value
N	Total number of road sections	6
β	Threshold for price adjustment	1/6, 1/3, 1/2
θ	Parking price change for each adjustment (Yuan/h)	1, 2, 3
γ	Upper limits for the desirable parking occupancy rate	70%, 80%, 90%
δ	Lower limits for the desirable parking occupancy rate	50%, 60%, 70%
P_{kt}	Parking price for road section k for a given time interval t (Yuan/h)	Range from 2 to 20
ρ_k	Average parking occupancy rate for road section k	Computed in real time

TABLE 5. Different dynamic parking pricing schemes.

Schemes	Price change for each adjustment (θ)	The desirable range for parking occupancy rate (γ - δ)	The threshold for price adjustment (β)
Scheme 1	2 Yuan/h	60%-80%	1/3
Scheme 2	2 Yuan/h	50%-70%	1/3
Scheme 3	2 Yuan/h	70%-90%	1/3
Scheme 4	1 Yuan/h	60%-80%	1/3
Scheme 5	3 Yuan/h	60%-80%	1/3
Scheme 6	2 Yuan/h	60%-80%	1/6
Scheme 7	2 Yuan/h	60%-80%	1/2

a price change of 2 Yuan/h, a desirable range of 60%-80%, and an adjustment threshold of 33% is regarded as the initial reference scheme [20] [31]. Based on the survey data, the highest on-street parking price is set at 20 Yuan/h, and the lowest price is 2 Yuan/h.

Parking simulation is performed continuously for 18 time intervals. Each time interval lasts 40000ticks in the simulation software. The simulation for each time interval represent s the parking situation during one month. Parking price remain s unchanged in the survey area during each time interval. After the simulation for each time interval, the average parking occupation rate of each road section and the proportion of sections whose occupancy rate is outside the desirable range are updated for price adjustment.

A. SIMULATION AND ANALYSIS UNDER DIFFERENT DESIRABLE PARKING OCCUPANCY LEVELS

The implement ation of demand-driven dynamic parking pricing involves maintaining the parking occupancy rate of parking facilities within the desirable range. If the desirable parking occupancy rate is set too high, a price adjustment can be triggered when the on-street parking occupancy rate

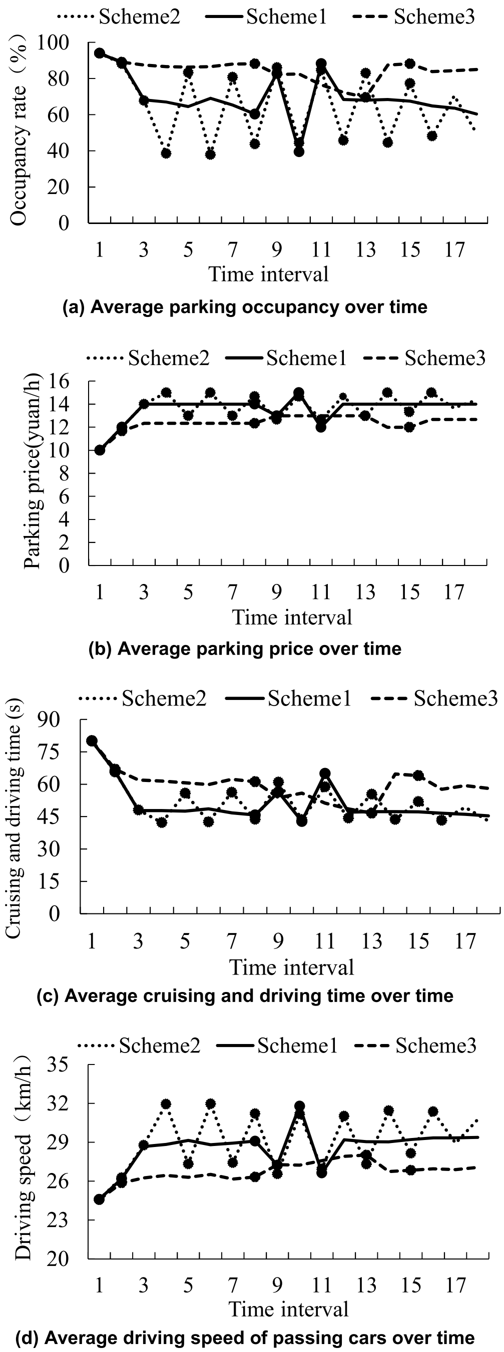

FIGURE 5. Simulation results under different desirable parking occupancy levels.

reaches a high level. At this time, fewer available empty parking spaces will increase the number of cruising cars and the cruising time. If the desirable parking occupancy rate is set too low, more available empty parking spaces will waste parking resources.

The following is a comparative analysis of Scheme s 1, 2, and 3 for different desirable parking occupancy levels. These schemes have the same price change of 2 Yuan/h and the same adjustment threshold of 1/3.

TABLE 6. The effectiveness of pricing schemes with different desirable range.

Schemes	Desirable range for parking occupancy rate (γ_δ)	Average cruising and driving time (s)	Average driving speed of passing cars (km/h)	Price adjust ment times	The number of time intervals within desirable range
Scheme 2	50%-70%	42.98	30.76	17	1
Scheme 1	60%-80%	47.25	29.02	6	13
Scheme 3	70%-90%	61.21	26.32	5	16

1) COMPARATIVE ANALYSIS OF PARKING PRICING SCHEMES 1, 2, 3

The black dots in the Figures represent the time interval when the on-street parking price in the area was adjusted to meet the desirable parking occupancy rate. Cruising and driving times are defined as the time that car travelers spen d from the position where they enter the survey area to the position where their car is parked. The average driving speed of all passing cars during a given time interval is used to estimate the effect of cruising for parking on road traffic performance.

As shown in Figure 5(a), for Scheme 2 with the desirable range of 50 –70%, the average parking occupancy rate of the road sections shows great fluctuations over time around the desirable range in the first half of the simulation. After several price adjustments, the fluctuation gradually decreases and tends to be within the desirable range. The curves of the average parking occupancy rate for Scheme s 1 and 3 with desirable rang es of 60% –80% and 70% –90% show small fluctuations near the desirable rang e. The higher the desirable range, the smaller is the fluctuation of the parking occupancy rate of the road sections. It indicates that demand-driven dynamic parking pricing can regulate the utilization of parking facilities within a desirable range.

Figure 5(b) shows the average parking price for road sections in the area. The average parking price of Scheme 2 changes significantly over time owing to the large changes in parking demand on the road sections. The parking price changes for the other two schemes with higher desirable range s are small.

As shown in Figures 5(c) and 5(d), the average cruising and driving time s of cruising cars and the average driving speed of passing cars in the area for Scheme 2 have greater fluctuations than those in Scheme 1 and Scheme 3. In Scheme 3, the average cruising time is longer and the average driving speed is lower. Therefore, a higher desirable range has a greater effect on road traffic performance.

2) SUMMARY FOR THE EFFECTIVENESS OF PARKING PRICING SCHEMES 1, 2, 3

Table 6 shows the effectiveness of pricing schemes with different desirable range s. It is known that higher price adjustment times result in higher operating costs. The price adjustment times for Scheme s 1 and 3 are 5 to 6, which are much less than that for Scheme 2 with a value of 17. The number of time intervals during which the average parking occupation rate of the road sections is within the desirable range is 13 and 16 for Scheme s 1 and 3. It indicates that Schemes 1 and 3 are significantly more effective than Scheme 2. Meanwhile, the average cruising and driving time for all time intervals for Scheme 3 is 61.21s which is much higher than that for Scheme 1. The average driving speed of passing cars for Scheme 1 is 29.02, which is higher than that for the field survey at a speed of 25 km/h. It indicates that demand-driven dynamic parking pricing can improve traffic network performance.

In summary, considering the effectiveness and operating costs, the desirable rang e of 60 -80% for parking occupancy rate is more suitable for demand-driven dynamic parking price adjustment in business districts with a high parking demand.

B. SIMULATION AND ANALYSIS UNDER DIFFERENT PARKING PRICE CHANGES

Schemes 1,4, and 5 have different parking price changes and the same desirable range of 60% -80% and adjustment threshold of 1/3.

1) COMPARATIVE ANALYSIS OF PARKING PRICING SCHEMES 1, 4, 5

Figures 6(a) and 6(b) show that the higher the parking price change for the price adjustment, such as in Scheme 5 with 3 Yuan/h, the greater the change in parking demand. Accordingly, the average parking occupancy rate in the study area fluctuate s significantly over time.

For Scheme 4, with a price change of 1 Yuan/h, the fluctuation of the average parking occupancy rate is small. Meanwhile, the average parking utilization reaches the desirable range for the parking occupancy rate after four price adjustments. For Scheme 1, with a price change of 2 Yuan/h, only two price adjustments are required to make parking utilization always lie in the desirable range. When the price change is 3 Yuan/h, it is difficult to reach a desirable range for parking utilization after many price adjustments, and the average parking price in the area change s significantly over time. It suggests that a higher parking price change for price adjustment may have a greater effect on the road traffic performance.

As shown in Figures 6(c) and 6(d), the fluctuations of the average cruising and driving time of cruising cars and the average driving speed of passing cars in the area increase with an increase in the price change in parking price adjustment. After several price adjustments, the trends of these indices gradually stabilized.

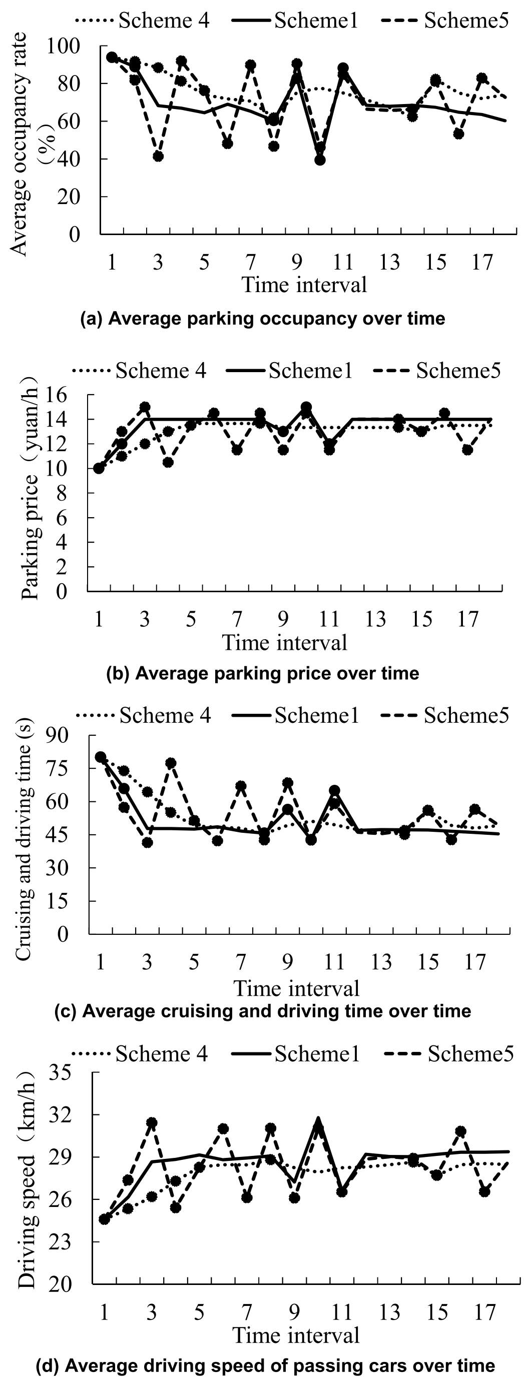

FIGURE 6. Simulation results under different parking price changes.

2) SUMMARY FOR THE EFFECTIVENESS OF PARKING PRICING SCHEMES 1, 4, 5

As can be seen from Table 7, when the parking price change is 3 Yuan/h, the price adjustment times are 15, and the number of time intervals within the desirable range is only four during the simulation. Meanwhile, the higher price

TABLE 7. The effectiveness of pricing schemes with different parking price changes.

Schemes	Price change for each adjustment (θ)	Average cruising and driving time (s)	Average driving speed of passing cars (km/h)	Price adjustment times	The number of time intervals within desirable range
Scheme 4	1 Yuan/h	48.44	28.34	7	13
Scheme 1	2 Yuan/h	47.25	29.02	6	13
Scheme 5	3 Yuan/h	49.43	27.65	15	4

TABLE 8. The effectiveness of pricing schemes with different thresholds.

Schemes	The threshold for price adjustment (β)	Average cruising and driving time (s)	Average driving speed of passing cars (km/h)	Price adjustment times	The number of time intervals within desirable range
Scheme 6	1/6	46.81	28.16	11	10
Scheme 1	1/3	47.25	29.02	6	13
Scheme 7	1/2	48.67	28.18	8	11

change for each adjustment can cause the parking demand to change significantly with time and lead to a longer average cruising time and lower driving speed in the area. Therefore, Scheme 5 shows poor performance, and frequent price adjustments also increase the operating costs.

When the parking price change is 1 or 2 Yuan/h for Schemes 4 and 1, the price adjustment times and the number of time intervals within the desirable range are basically the same. Compared with Scheme 4, the average cruising and driving time s of the cars in the area are slightly lower, and the average driving speed of passing cars is slightly higher, as shown in Scheme 1. It indicates that a parking price change of 2 Yuan/h has good performance and low operating costs.

C. SIMULATION AND ANALYSIS UNDER DIFFERENT THRESHHOLDS FOR PRICE ADJUSTMENT

The threshold for price adjustment to be started is expressed as the ratio of the number of road sections whose parking occupancy rate is outside the desirable range to the total number of sections. The following is a comparative analysis of Scheme s 1, 6, and 7 under different thresholds of price adjustment. These schemes have the same price change of 2 Yuan/h and the same desirable rang e of 60-80% for parking occupancy rate.

1) COMPARATIVE ANALYSIS OF PARKING PRICING SCHEMES 1, 6, 7

From Figure 7, it can be observed that the simulation results show a similar trend and small differences in the average parking occupancy rate, parking price, cruising time, and driving speed in the area.It indicates that different thresholds for price adjustment can regulate parking demand.

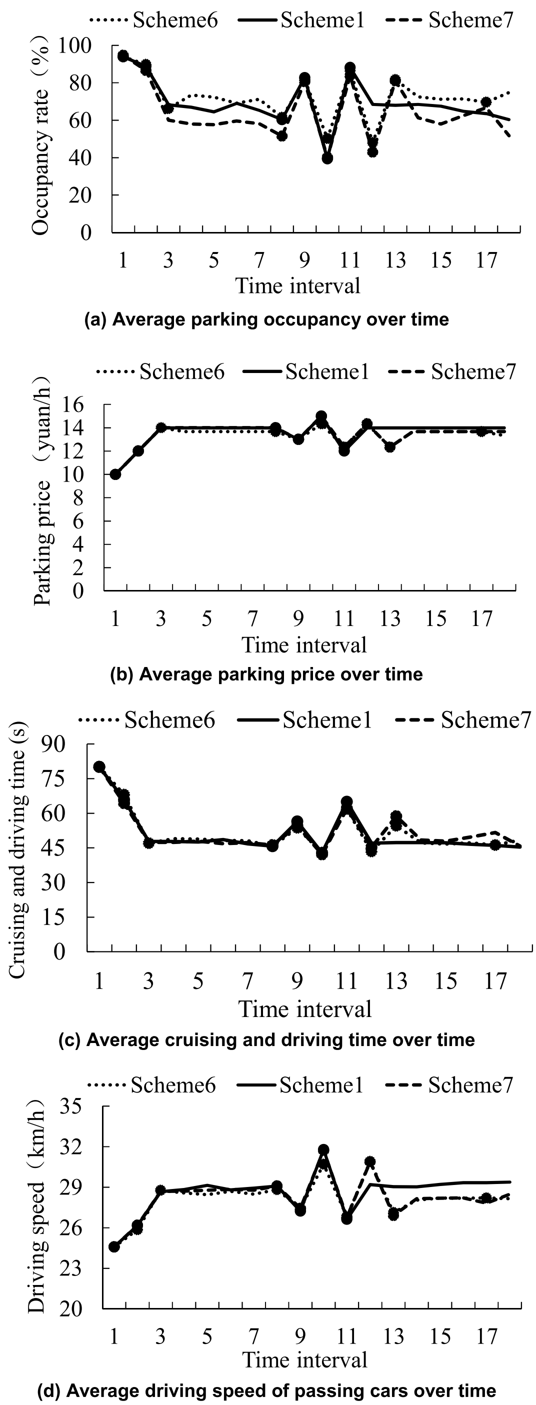

FIGURE 7. Simulation results under different thresholds for price adjustment.

2) SUMMARY FOR THE EFFECTIVENESS OF PARKING PRICING SCHEMES 1, 6, 7

Table 8 shows that the average cruising and driving time of cruising cars and the average driving speed of passing cars under the three schemes shows small differences. When the threshold for price adjustment is 1/6 for Scheme 6, the price adjustment times are 11 during the simulation, which are highest among the three schemes. Generally, the higher the threshold for price adjustment, the less the price adjustment times and the more the number of time intervals within desirable range. When the threshold for price adjustment is 1/3 in Scheme 1, the price adjustment times decrease slightly and the number of intervals within desirable range increase slightly compared with Scheme 7. It indicates that the threshold of 1/3 is more suitable for parking price adjustment in a small area and leads to a better performance for parking and road traffic.

VI. CONCLUSION

The rapid increase in the number of cars has caused many problems, such as ''cruising for parking'' and ''illegal parking''. These problems have a significant impact on dynamic traffic systems and cause considerable environmental pollution. The demand-driven dynamic parking pricing mechanism can dynamically regulate the parking price for different parking facilities based on changing parking demand. In this study, we conducted several on-street parking surveys in Beijing's business districts. Subsequently, a parking location choice model and decision rules for the cruising process for parking were established. A multi-agent based on-street parking simulation was constructed to explore the optimal demand-driven dynamic parking pricing strategy. The main conclusions are as follows:

Based on the survey data for the cruising process and choice preference for parking, the driving speed of cruising cars is between 10 km/h and 20 km/h while approaching the destination. Most car travelers in business districts are short-term parkers, and their walking distance after parking is mainly within 150 m. 62% of car travelers need to spend about one minute to five minutes searching for a parking space. The maximum acceptable increase in the current on-street parking price is 10 Yuan/h. Based on a stated preference survey, an on-street parking location choice model is established using a multinomial Logit model. These data can be used for setting the attributes and behavioral rules of agents in the parking simulation and the design of demand-driven dynamic parking pricing schemes.

A multiagent approach is used to simulate on-street parking in a small area. Three types of agents with different functions and attributes were defined, and car travelers' behavioral rules during the cruising process for parking were established. The dynamic evolution of the average parking occupancy rate, parking price, cruising time, and driving speed over time was analyzed for the designed seven parking pricing schemes. It is concluded that the desirable range for the parking occupancy rate and parking price change have an important effect on the performance of the implementation of demand-driven dynamic parking pricing. A lower desirable range and higher price change can cause larger fluctuations in parking demand and fewer time intervals during which the average parking occupation rate of the road sections is within the desirable range. Accordingly, more price adjustments are required to ensure that the utilization of parking facilities is within the desirable range. A higher desirable range and higher price change can result in longer cruising and driving times and lower driving speeds, and then produce a greater effect on road traffic operations in the area. The threshold for price adjustment has a small impact on the performance of the demand-driven dynamic parking-pricing schemes.

These results show that demand-driven dynamic parking pricing can effectively regulate the distribution of parking demand and make the utilization of parking facilities within the desirable range in business districts. Considering the effectiveness and operating costs of the pricing schemes, it is recommended that the suitable desirable range for parking occupancy rate is 60%–80% and the price change is 2 Yuan/h for dynamic parking price adjustment. The price adjustment threshold can be set based on the scale of the regional road network. A threshold of 1/3 is more suitable for parking price adjustments in small areas. The proposed demand-driven dynamic parking pricing strategy shows good performance for parking and road traffic operations. Meanwhile, collecting real-time parking occupancy data for parking facilities and releasing real-time parking information to car travelers are important to guarantee the implementation of demand-driven dynamic parking prices. In this way, the distribution of parking demand can be balanced and parking and traffic problems can be reduced.

This research carried out a preliminary exploration of demand-driven dynamic parking pricing. A large-scale regional road network with large amounts of actual parking data will be simulated to further analyze the relationship between demand-driven dynamic parking pricing and demand. The deep exploration of behavioral changes and adaptive processes of travelers in response to parking price changes is important for decision rule settings in on-street parking simulation. The effectiveness of implementing demand-driven dynamic parking pricing also deserves significant attention. Related studies will be conducted in the future.

REFERENCES

[1] G. Marsden, ''The evidence base for parking policies—A review,'' *Transp. Policy*, vol. 13, no. 6, pp. 447–457, Jul. 2006.

[2] J. A. Kelly and J. P. Clinch, ''Temporal variance of revealed preference on-street parking price elasticity,'' *Transp. Policy*, vol. 16, no. 4, pp. 193–199, Jul. 2009.

[3] C. Piccioni, M. Valtorta, and A. Musso, ''Investigating effectiveness of on-street parking pricing schemes in urban areas: An empirical study in Rome,'' *Transp. Policy*, vol. 80, pp. 136–147, Aug. 2019.

[4] A. Mirheli and L. Hajibabai, ''Utilization management and pricing of parking facilities under uncertain demand and user decisions,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 5, pp. 2167–2179, May 2020.

[5] J. Li, S. Wu, and X. Feng, ''Optimization of on-street parking charges based on price elasticity of the expected perceived parking cost,'' *Sustainability*, vol. 13, no. 10, p. 5735, May 2021.

[6] M. Nourinejad and M. J. Roorda, ''Impact of hourly parking pricing on travel demand,'' *Transp. Res. A, Policy Pract.*, vol. 98, pp. 28–45, Apr. 2017.

[7] N. Khordagui, "Parking prices and the decision to drive to work: Evidence from California," *Transp. Res. A, Policy Pract.*, vol. 130, pp. 479–495, Dec. 2019.
[8] B. Mo, H. Kong, H. Wang, X. C. Wang, and R. Li, "Impact of pricing policy change on on-street parking demand and user satisfaction: A case study in Nanning, China," *Transp. Res. A, Policy Pract.*, vol. 148, pp. 445–469, Jun. 2021.
[9] B. Schaller, T. Maguire, D. Stein, W. Ng, and M. Blakeley, "Parking pricing and curbside management in New York City," in *Proc. Transp. Res. Board 90th Annu. Meeting*, Washington, DC, USA, Jan. 2011.
[10] J. Simićević, N. Milosavljević, G. Maletić, and S. Kaplanović, "Defining parking price based on users' attitudes," *Transp. Policy*, vol. 23, pp. 70–78, Sep. 2012.
[11] Z. S. Qian and R. Rajagopal, "Optimal dynamic parking pricing for morning commute considering expected cruising time," *Transp. Res. C, Emerg. Technol.*, vol. 48, pp. 468–490, Nov. 2014.
[12] J. Wang, H. Wang, and X. Zhang, "A hybrid management scheme with parking pricing and parking permit for a many-to-one park and ride network," *Transp. Res. C, Emerg. Technol.*, vol. 112, pp. 153–179, Mar. 2020.
[13] Z. S. Qian and R. Rajagopal, "Optimal occupancy-driven parking pricing under demand uncertainties and traveler heterogeneity: A stochastic control approach," *Transp. Res. B, Methodol.*, vol. 67, pp. 144–165, Sep. 2014.
[14] J. van Ommeren and G. Russo, "Time-varying parking prices," *Econ. Transp.*, vol. 3, no. 2, pp. 166–174, Jun. 2014.
[15] D. Mackowski, Y. Bai, and Y. Ouyang, "Parking space management via dynamic performance-based pricing," *Transp. Res. C, Emerg. Technol.*, vol. 59, pp. 66–91, Jul. 2015.
[16] C. Lei and Y. Ouyang, "Dynamic pricing and reservation for intelligent urban parking management," *Transp. Res. C, Emerg. Technol.*, vol. 77, pp. 226–244, Apr. 2017.
[17] N. Fulman and I. Benenson, "Establishing heterogeneous parking prices for uniform parking availability for autonomous and human-driven vehicles," *IEEE Intell. Transp. Syst. Mag.*, vol. 11, no. 1, pp. 15–28, Jan. 2018.
[18] Z. Pu, Z. Li, J. Ash, W. Zhu, and Y. Wang, "Evaluation of spatial heterogeneity in the sensitivity of on-street parking occupancy to price change," *Transp. Res. C, Emerg. Technol.*, vol. 77, pp. 67–79, Apr. 2017.
[19] F. Alemi, C. Rodier, and C. Drake, "Cruising and on-street parking pricing: A difference-in-difference analysis of measured parking search time and distance in San Francisco," *Transp. Res. A, Policy Pract.*, vol. 111, pp. 187–198, May 2018.
[20] T. Fabusuyi and R. C. Hampshire, "Rethinking performance based parking pricing: A case study of SFpark," *Transp. Res. A, Policy Pract.*, vol. 115, pp. 90–101, Sep. 2018.
[21] I. Benenson, K. Martens, and S. Birfir, "PARKAGENT: An agent-based model of parking in the city," *Comput., Environ. Urban Syst.*, vol. 32, no. 6, pp. 431–439, Apr. 2008.
[22] N. Levy, K. Martens, and I. Benenson, "Exploring cruising using agent-based and analytical models of parking," *Transportmetrica A, Transp. Sci.*, vol. 9, no. 9, pp. 773–797, Feb. 2013.
[23] R. A. Waraich, C. Dobler, and K. W. Axhausen, "Modelling parking search behaviour with an agent-based approach," in *Proc. 13th Int. Conf. Travel Behaviour Res. (IATBR)*. Zürich, Switzerland: ETH Zurich, Jul. 2012, pp. 1–13.
[24] T. Steenberghen, K. Dieussaert, S. Maerivoet, and K. Spitaels, "SUSTAPARK: An agent-based model for simulating parking search," *Urban Regional Inf. Syst. Assoc.*, vol. 24, no. 1, pp. 62–76, Jan. 2012.
[25] A. Horni, L. Montini, R. A. Waraich, and K. W. Axhausen, "An agent-based cellular automaton cruising-for-parking simulation," *Transp. Lett.*, vol. 5, no. 4, pp. 167–175, Oct. 2012.
[26] C. Zhuge, C. Shao, and X. Yang, "Agent- and activity-based large-scale simulation of enroute travel, enroute refuelling and parking behaviours in Beijing, China," *J. Comput. Sci.*, vol. 38, Nov. 2019, Art. no. 101046.
[27] N. Levy and I. Benenson, "GIS-based method for assessing city parking patterns," *J. Transp. Geography*, vol. 46, pp. 220–231, Jun. 2015.
[28] Z. Y. Gu, F. Safarighouzhdi, M. Saberi, and T. H. Rashidi, "A macro-micro approach to modeling parking," *Transp. Res. B*, vol. 147, pp. 220–244, May 2021.
[29] H. Qin, Q. Pang, B. Yu, and Z. Wang, "Analysis on cruising process for on-street parking using an spectral clustering method," *IET Intell. Transp. Syst.*, vol. 14, no. 14, pp. 2113–2121, Dec. 2021.
[30] D. A. Hensher and P. R. Stopher, *Behavioural Travel Modelling*. London, U.K.: Routledge, Jan. 1979.
[31] A. Millard-Ball, R. R. Weinberger, and R. C. Hampshire, "Is the curb 80% full or 20% empty? Assessing the impacts of San Francisco's parking pricing experiment," *Transp. Res. A, Policy Pract.*, vol. 63, pp. 76–92, May 2014.

HUANMEI QIN received the B.S. and Ph.D. degrees from the Beijing University of Technology, China, in 2005 and 2013, respectively. She is currently an Associate Professor with the Beijing University of Technology. She is also the author of more than 50 articles and two books. Her research interests include traffic behavior analysis and modeling, parking planning and management, and traffic psychology. She was a recipient of the Second Prize of the Beijing Science and Technology Award from the Beijing Municipal Science and Technology Commission, in 2016.

FEI ZHENG received the bachelor's degree from Shandong Jiaotong University, China, in 2016, and the B.S. degree from the Beijing University of Technology, China, in 2019. He is currently working with Beijing Shunjie Xinghong Engineering Design Consulting Company Ltd., China. His research interests include traffic planning, consultation, and design.

BINHAI YU received the bachelor's degree from Shandong Jiaotong University, China, in 2020. He is currently pursuing the master's degree in transportation engineering from the Faculty of Urban Construction, Beijing University of Technology. From 2018 to 2019, he won the Second-Class Scholarship from Shandong Jiaotong University for two consecutive years. His research interest includes travel behavior for automatic driving.

ZHONGFENG WANG received the bachelor's degree from Beijing Jiaotong University, China, in 2000, and the B.S. degree from the China Academy of Railway Sciences, China, in 2005. He is currently working with 41st Institute of the China Electronics Technology Group Corporation. His research interests include traffic simulations and traffic control.