

Article

On-Street Cruising for Parking Model in Consideration with Gaming Elements and Its Impact Analysis

Wei Wang, Yuwei Zhou , Jianbin Liu and Baofeng Sun * 

School of Transportation, Jilin University, No. 5988 Renmin Street, Changchun 130022, China

* Correspondence: sunbf@jlu.edu.cn

Abstract: On-street cruising by drivers impedes the effectiveness of road traffic conditions and increases energy consumption and environmental impact. Existing models of on-street cruising for parking mainly embody those intrinsic on-street parking factors and disregard the extrinsic impacts from off-street parking gaming factors. This research focused on both the intrinsic and extrinsic elements, especially gaming factors, of off-street parking, i.e., the price of off-street parking, the waiting time of off-street parking, and the difference in walking time between their parking lots to their destinations. On-street cruising for a parking model is reconstructed in this paper in consideration with the equilibrium cruising time, i.e., the maximum tolerable cruise time after evaluating the cost of on-street and off-street parking. Correlation analysis showed that the off-street parking gaming factors were all positively related with the maximum tolerable cruise time. A simulation model was further presented for on-street cruising for the parking model by the cellular automata approach with real-world data. Simulation experiments demonstrated that the average speed of vehicles on the street increases by 9.858 km/h, the average delay decreases by 44.934 s, and the price of on-street parking increases by 4.5 CNY/h. The proposed on-street cruising for parking model proved effective by decreasing the maximum tolerable cruising time to bring significant improvements in average speed, average delay, and on-street cruising vehicles in road traffic flow.

Keywords: on-street cruising for parking; cost evaluation of parking; cellular automata model; traffic impact analysis

MSC: 37B15; 76A30



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1. Introduction

The huge vehicle population in China has indeed improved travel convenience in people's lives, but it has also somehow brought up parking issues due to a lack of parking facilities of the same size. Parking issues are one of main bottleneck problems in the city's transportation system among other things [1]. In general, parking may be separated into two types, i.e., on-street and off-street parking. However, the two are not ideal equivalents owing to space availability discrepancies [2]. On-street cruising for parking has become a common choice for drivers due to its parking convenience, fast turnover, and affordability. Some surveys indicate that over 30% of vehicles travelling on city streets choose on-street cruising for parking, and up to 50% during rush hour [3,4]. In Ningbo, 9–30% of traffic flow id on-street cruising for parking behavior with an average cruise time of 6.03 min [5].

The growth of on-street cruising for parking vehicles has had a very negative impact on urban traffic flow. On-street cruising for parking at low speeds forces other vehicles to unwillingly car following or quickly changing lanes, which severely interferes with the regular order of traffic flow. On-street cruising for parking can significantly slow down the speed of other vehicles, increase unnecessary fuel consumption and vehicle emissions, seriously reduce road capacity, and even induce traffic congestion [6–8]. Los Angeles statistics show that low-speed vehicles of on-street cruising for parking totally

consumed an additional 1.61 million kilometers, travel time of 95,000 h, and 47,000 gallons of gasoline, creating 730 tons of CO₂ emissions annually [9]. Thereby, it is essential to reveal the mechanism behind on-street cruising for parking and to address the root of the problem in cutting down negative traffic impacts.

To find out the influence factors of on-street cruising for parking and their impacts, the existing research supports adopting the economic perspective to study the correlation between parking cost and on-street cruising for parking behavior. Arnott's studies indicate that on-street cruising for parking is an economic choice. Among factors, parking price has a substantial impact on on-street cruising for parking [10]. All drivers make economic judgments based on minimizing the parking cost [11]. When the on-street parking cost is excessively cheap, a big number of drivers may choose on-street parking [12]. Developing an efficient real-time parking pricing plan or adopting differential charging for on-street and off-street parking may thereby reduce on-street cruising [13,14]. Besides parking cost, other factors are considered at the same time, such as the time value, fuel consumption, the distance from the parking lot to the driver's destination, and the cruising time. Therefore, it is also conceivable to model on-street cruising for parking taking the time value as the parking cost [15], or valuing the parking cost by walking distance after parking [16,17]. However, the above studies paid more attention to parking cost and other intrinsic factors to model on-street cruising for parking. It is far from the real cruising for the parking scene. Those extrinsic impacts from off-street parking gaming factors tend to play a role in the parking choice decisions just because on-street and off-street parking are two kinds of alternative choices. That is why those parking guidance models with intrinsic factors for cruising vehicles on the street are often relatively poor. Some studies considered the impact of off-street parking price on the basis of on-street parking price. Another study offered an on-street cruising for parking model that takes the on-street parking and off-street parking as being of equal cost [2,18]. For solving the problem that the cruising time is 0 when the prices of on-street parking and off-street parking are equal, non-price factors are introduced, i.e., human factors and environmental factors, and so on [19]. After that, the researchers prefer to comprehensively consider both intrinsic and extrinsic factors together to establish an economic leverage model for on-street cruising for parking in order to better reflect the actual scene [9,20].

In actuality, the present research proved unclear in establishing a substantial understanding of extrinsic gaming factors, such as the limited access to off-street parking space, the requirement to process payments, and vehicles waiting time at the gate for off-street parking. Off-street parking normally requires longer walking distances and more time to reach destinations compared to on-street parking [21]. Consequently, off-street parking gaming factors, including the price of off-street parking, the waiting time of off-street parking, and the difference in walking time between their parking lots to their destinations, could affect on-street cruising for parking to a certain degree. This research focuses on those extrinsic gaming factors and their impacts in a real-world parking traffic zone, besides key intrinsic factors, to restructure a novel on-street cruising for parking model. Then, correlation analyses are performed to test the degree of correlation between the off-street parking gaming factors and the maximum tolerable cruise time.

Moreover, the above mentioned on-street cruising for parking model was not operated in the context of the parking space's traffic flow conditions to reveal its traffic impact. Some attempts failed to adequately account for the stochastic attributes of traffic participants. For this reason, this research explores a microscopic simulation model based on the cellular automaton approach rooted in an on-street parking scenario to discover the deeper traffic impact in a certain traffic zone. The rationality of the measures of parameters and the validation of the restructured on-street cruising for parking model are proven by numerical simulations of road traffic conditions. Here, simulation experiments are designed in different scenarios of on-street parking price and the maximum tolerable cruise time.

The rest of this paper is organized as follows. In Section 2, the modeling procedure for on-street cruising for parking model is described, and the relevance of the model's influence

factors is assessed. In Section 3, a cellular automaton simulation model was developed on the basis of a real-world situation. By comparing the time–space trajectory with the road traffic operating parameters, the improvements that the restructured model contributes to the road traffic environment are determined. Conclusions are addressed in Section 4.

2. Modelling of On-Street Cruising for Parking

When determining whether to park on or off the street, drivers need to evaluate the tradeoff between spending time (the cost of time) on on-street cruising and spending money for off-street parking [9]. That is in nature a kind of economic lever to adjust and regulate the parking choice. In that sense, those direct impacts on on-street cruising for parking could be attributed to the intrinsic factors shown as on-street parking cost, cruising time, fuel consumption, and easy access to destination, etc. Those indirect but also influential impacts on drivers' parking choice could be attributed the extrinsic factors, e.g., the price of off-street parking, the waiting time at the gate of off-street parking space, and the difference in walking time between their parking lot to their destinations. We proposed the cost of parking as the economic lever guiding drivers toward off-street parking instead of on-street cruising for parking and eliminating on-street parking when adjusting the on-street cruising for parking cost to be lower than the off-street parking cost.

Therefore, intrinsic factors bring changes in on-street cruising for parking cost and extrinsic factors lead to changes in off-street parking costs, which both in turn affect drivers' parking choices. This economic leverage model makes drivers select the less expensive alternative. On this premise, extrinsic factors play a role in the gaming factors of on-street cruising for parking.

2.1. Modelling On-Street Cruising for Parking

2.1.1. Costs of On-Street Parking

The driver's on-street parking expense consists of on-street parking fee, the gasoline consumption for cruising on the street, and the time value of persons in a car. Costs of on-street parking are displayed in Equation (1).

$$S_1 = c(f + nv) + pt \quad (1)$$

where S_1 denotes the cost of on-street parking, p denotes the price of on-street parking (CNY/h, CNY is the sign of Chinese Yuan), t denotes the parking time (h), c denotes the cruising time for parking on the street (h), f denotes the fuel cost of cruising (CNY/h), n denotes the number of persons in the car (persons), and v denotes the time value of cruising (CNY/h/person). The time value is influenced by a number of elements, including the purpose of the trip, personal occupation, and financial income, etc. More importantly, the time value of drivers should be evaluated using different methods to reflect the individual differences, such as different occupations and different travel purposes. Here, the calculation methods mainly include the production method, income method, and disaggregated model [22]. The production strategy is based on macroeconomics and takes into account the fact that the traveler's reduced trip time equals an increase in the production elements. Equation (2) is used to determine the traveler's time value based on the production method.

$$v = \frac{G}{PT} \quad (2)$$

where G denotes the region's GDP (CNY), P denotes the average number of employed individuals in the region (persons), and T denotes the average annual working time of local residents (h).

The income method indicates the opportunity cost of time required by the journey compared to the individual, i.e., the time consumed by the travel procedure reduces the traveler’s income. It is calculated as follows: Equation (3).

$$v = \frac{A}{H} \tag{3}$$

where A denotes annual personal income (CNY) and H denotes the average number of hours worked per year by the traveler (h).

The non-set count model is a model often employed in travel behavior prediction analysis. For calculating the time value of travel, the model’s utility function includes only two variables, i.e., trip time consumption and cost, and depends mostly on a predictive model of transport mode choice behavior, whose utility function is derived as indicated in Equation (4).

$$V_i = \rho + \varphi_1 t_i + \varphi_2 r_i \tag{4}$$

where V_i shows the value of the i -th mode of transportation. t_i and r_i denote the journey duration and expense of the i -th form of transportation, respectively. ρ, φ_1 , and φ_2 are the parameter to be calibrated. ρ, φ_1 and φ_2 are all calibrating parameters.

The equation for calculating the time value of the i -th mode of transportation is provided below (5)

$$vot(i) = \frac{\partial v / \partial t}{\partial v / \partial r} = \frac{\varphi_2}{\varphi_1} \tag{5}$$

Each of three methods for determining the time value of travel has unique characteristics and application requirements, which are compared in Table 1.

Table 1. Comparisons of three popular time value calculation methods.

Methods	Suitable Scenarios	Advantages	Disadvantages
production method	Commuting trips	<ul style="list-style-type: none"> ① No need for a lot of data on residents’ trips ② The results are target ③ Easy to calculate 	<ul style="list-style-type: none"> ① Ignoring the effect of subjective factors on the time values ② Inability to calculate the time value spent on leisure trips ③ Not suitable for estimating overall time value
income method	Non-work trips		
disaggregated model	All types of trips	<ul style="list-style-type: none"> ① Consider the impact of subjective factors on the time values ② Suitable for calculating the time value of all types of travel 	<ul style="list-style-type: none"> ① Need for large of data on residents’ trips ② Hard to calculate ③ Ignoring the effect of income on the time values

2.1.2. Costs of Off-Street Parking

Off-street parking space is enclosed. Two single access traffic lanes to the parking space are required for the arriving vehicles waiting in lines. Thus, it is necessary to count the waiting time of off-street parking in the cost of off-street parking. Here, the waiting time of off-street parking consists of the time spent in lining up while entering off-street car parks and the time spent on paying for services [21].

Based on queuing theory, the average waiting time for off-street parking in this study is evaluated as Equation (6).

$$t_a = (p_a - c_a)^2 \cdot \frac{t'}{2p_a c_a} \tag{6}$$

where t_a represents the average waiting time of off-street parking and p_a represents the total off-street parking cars. t' represents the average parking time in the off-street park and c_a represents the capacity of the off-street park.

Off-street parking is frequently located in remote areas distant from the street, which means that off-street parking necessitates longer walking lengths. This is why a number of drivers engage in on-street cruising instead of off-street parking because of Δt , shown as Equation (7). Δt represents the difference in walking time between the driver from the off-street parking slot to the destination and from the on-street parking slot to the destination.

$$\Delta t = \frac{d_{\omega 0} - d_{\omega i}}{v_{\omega}} \tag{7}$$

where $d_{\omega 0}$ displays the walking distance between the driver’s off-street parking slot and the destination (km), $d_{\omega i}$ displays the walking distance between the driver’s on-street parking slot and the destination (km), and v_{ω} denotes the average walking speed of the driver (km/h).

In conclusion, it takes longer for a driver to walk from an off-street parking slot to his destination than on-street parking scenario. Thus, the cost of off-street parking is determined as follows in Equation (8).

$$S_2 = mt + (\Delta t + t_a)nv \tag{8}$$

where S_2 denotes the costs of off-street parking and m denotes the price of off-street parking (CNY/h).

2.1.3. On-Street Cruising for Parking Model

The on-street cruising for parking model is restructured based on the economic leverage model by gaming on-street parking cost against off-street parking cost, as shown in Equation (10). Leverage in equilibrium occurs when the cost of on-street parking is equal to the cost of off-street parking, i.e., $S_1 = S_2$. At this stage, the drivers do not care for on-street cruising for parking or off-street parking. Leverage in equilibrium at this moment may be taken as the maximum endurance cruising time on-street for cruising symbolized by c^* , which is the so-called equilibrium cruising time and demonstrated as Equation (9).

$$c^* = \frac{t(m - p) + (\Delta t + t_a)nv}{f + nv} \tag{9}$$

The driver’s actual cruising time is represented by c , whose value is obtained from the actual survey data. The driver’s real parking decision-making stages can be stated in terms of the equilibrium cruising time c^* and the actual cruising time c .

The driver’s actual cruising time is represented by c , whose value is obtained from the actual survey data. The driver’s real parking condition-making stages can be stated in terms of the equilibrium cruising time c^* and the actual cruising time c . As shown in Equation (10).

$$\begin{cases} c < c^* & \text{on - streetcruisingforparking} \\ c > c^* & \text{off - streetparking} \\ c = c^* & \text{In equilibrium} \end{cases} \tag{10}$$

When $c = c^*$, drivers are indifferent about whether they park on-street or off-street. When $c < c^*$, drivers will choose on-street parking instead of off-street parking since it is less expensive. When $c > c^*$, on-street parking costs are more than off-street parking costs, and drivers prefer to choose off-street parking. Therefore, c^* is adjusted to make c^* less than c , so the on-street cruising for parking phenomenon can be decreased. Additionally, this brings a guarantee for the utilization off-street parking space. As can be seen, c^* plays an important role in regulating drivers’ parking choice.

2.2. Correlation Analysis between Variables of Model with c^*

Each factor has an impact on the maximum endurance cruising time c^* to a different degree. The correlation between c^* and those variables for the model in Section 2.1.3 is

analyzed by calculating the partial derivative of each variable. Some particular findings are displayed in Table 2.

Table 2. Correlation between parameters of model and leverage of c^* .

Parameters	Partial Derivate of c^*	Correlation
p	$\frac{\partial c^*}{\partial p} = -\frac{t}{f+nv} < 0$	Negative
m	$\frac{\partial c^*}{\partial p} = +\frac{t}{f+nv} > 0$	Positive
t	$\frac{\partial c^*}{\partial t} = +\frac{m-p}{f+nv}$	Negative or Positive
f	$\frac{\partial c^*}{\partial f} = -\frac{S_2-(S_f+pt)}{(f+nv)^2} < 0$	Negative
n	$\frac{\partial c^*}{\partial n} = \frac{v(\Delta t+t_a)}{f+nv} - \frac{v(S_2-(S_f+pt))}{(f+nv)^2} < 0$	Negative
v	$\frac{\partial c^*}{\partial v} = \frac{n(\Delta t+t_a)}{f+nv} - \frac{n(S_2-(S_f+pt))}{(f+nv)^2} < 0$	Negative
Δt	$\frac{\partial c^*}{\partial \Delta t} = +\frac{nv}{f+nv} > 0$	Positive
t_a	$\frac{\partial c^*}{\partial t_a} = +\frac{nv}{f+nv} > 0$	Positive

Above variables related with intrinsic factors of on-street cruising for parking include the price of on-street parking p , the price of fuel f , the number of people in the car n , and the time value v . c^* has negative correlation with them. Those variables related with extrinsic factors of on-street cruising for parking gaming factors include the waiting time t_a , the difference in walking time Δt , and the off-street parking price m . c^* is shown as positively associated with them while c^* increases as their values rise. Therefore, the on-street cruising for parking model should be modeled to reflect clearly their effects of those off-street gaming elements. From a user perspective, both the intrinsic and extrinsic factors need to be taken note.

One of the findings is that correlation between c^* and parking time t presents two results, i.e., either positive or negative, which depends on whether the price of off-street parking m is larger than the price of on-street parking p or not. If m is larger than p , the t is positively correlated with c^* . Conversely, the t is negatively correlated with c^* . The results well meet the analytical conclusion from the findings of Arnott [17]. On-street cruising time c increases as parking time t increases, and the phenomenon of cruising for parking becomes more severe as the cost difference between off-street and on-street parking increases. It was previously examined that both intrinsic factors and extrinsic factors with gaming view alter the equilibrium cruising time c^* . In view of traffic management, the c^* can be changed by altering one of the easily adjusted factors in order to keep c^* at a state less than the actual cruising time c . In this way, on-street cruising for parking and its negative effects on the road traffic environment are eliminated.

3. Simulation Model for On-Street Cruising for Parking

Simulation models are built based on realistic scenarios and actual data. In order to verify the positive effect of the reconstructed model above in improving traffic operating conditions, we carry out numerical simulations of road traffic operating conditions under different equilibrium cruising times and analyze the simulation results.

3.1. Model and Parameters Test

In Section 3.1, the model parameters are determined with survey examples, as seen in Table 3. Given the number of cruising vehicles observation and on-street cruising impact traffic analysis at different c^* , the proposed on-street cruising for parking model is considered valid and capable to improve surrounding road traffic congestion.

Table 3. Survey Data Sheet.

Parameters	Numerical Values	Units
m	6	CNY/h
p	6	CNY/h
c	5	min
t	60	min
Δt	6	min
t_a	3	min
n	2	persons
v	30	CNY/h/person
f	10	CNY/h

In a survey of the Red Flag Street shopping district in Changchun, China [22], Equation (8) and parameters in Table 3 allow for the conclusion that the current equilibrium search time c^* is 6.667 min. The actual cruising time c of the drivers is 5 min smaller than c^* . $c < c^*$ suggests that drivers prefer on-street parking. It was further found out that there is frequently traffic in the area and chaotic vehicle movements due to the region’s heavy on-street parking demand and excessive on-street cruising. Due to the non-working hours during the survey period, the majority of travel is conducted for non-work trips. Therefore, the time value v in this paper is calibrated by the income method.

Figure 1 depicts the correlation between equilibrium search time c^* and on-street parking cost p , and the difference in walking time Δt in the Red Flag Street survey sample. As p grows, c^* goes lower. As Δt increases, c^* increases. Consequently, one measure is adjusting on-street parking price p higher, which benefits a reduction in the number of cruising cars on the street and alleviates the negative impact on regional traffic flow. The other measure is decreasing the difference in walking time Δt to eliminate on-street cruising cars by increasing the number of convenient facilities located near off-street car park spaces (e.g., providing just-in-time guide services, introducing direct lift facilities between off-street car parks and destinations, etc.). Reconstruction and extension of off-street infrastructure is a kind of tough engineering to put into practice due to the limited space, large investment, and long construction period required. A proposed approach in this study is to raise the price of on-street parking p in order to decrease the equilibrium cruising time c^* and encourage on-street cruising drivers to choose parking off-street space.

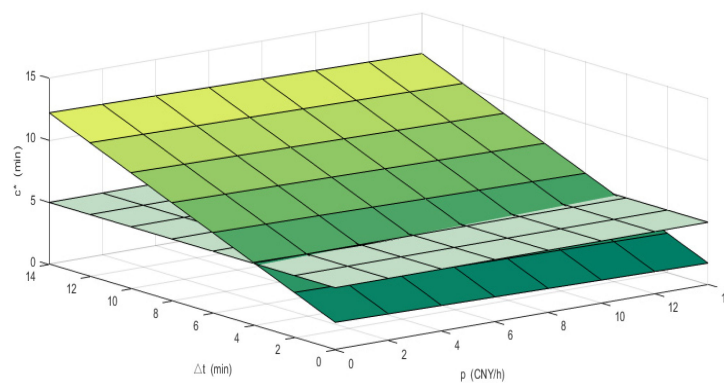


Figure 1. Correlation of Δt , p and c^* in the Red Flag Street survey.

3.2. Simulation Based Evaluation

Simulation models based on realistic scenarios and actual data are built based on the cellular automata principle with real-world data in Section 3.2. The above-mentioned mathematical models cannot consider the random nature of the urban transport system’s traffic participants and the conflicts of the traffic flow. In this research, a simulation model

of on-street cruising for parking is developed using the cellular automata approach, and the effect of changes in c^* on the traffic flow on street is also examined.

The cellular automata model in this paper considers the equilibrium cruising time c^* directly. Therefore, through the numerical simulation of the road traffic conditions under different c^* , the impact of changes in the on-street parking price on road traffic conditions is analyzed. In addition, the effect of the reconstructed model on inducing the cruising vehicle to park off-street can be effectively verified.

3.2.1. Simulation Model Based on Cellular Automata

Figure 2 illustrates a scenario of the simulation model of on-street cruising for parking based on cellular automata. Where, a blue cell represents a vehicle on the road, and the green box indicates the on-street parking slots. The simulation system is considered to have two lanes of traffic in a single direction and on-street parking space next to the lanes. Each lane of traffic is 3.5 m wide, and each meta-cell is 6 m long. The direction of vehicle travel is from left to right. The simulated street segment includes the on-street parking space zone part L_2 and the non-street parking space zone parts L_1 and L_3 . X_{start} and X_{end} are, respectively, the beginning and end of the on-street parking space zone. In addition, the whole length of the set-up section is 400 metric cells, and the total number of on-street parking spaces is 120, which means that 120 metric cells are occupied.

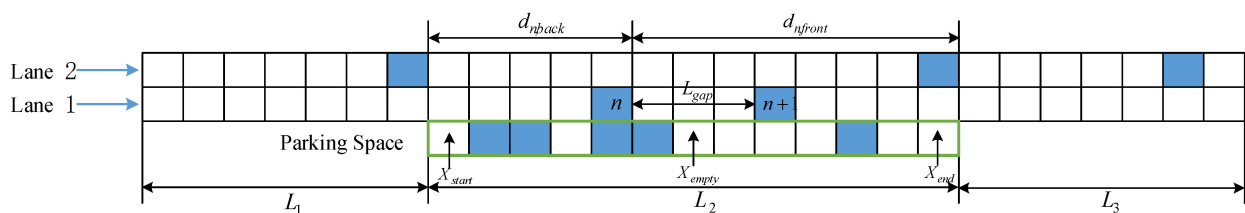


Figure 2. Simulation model based on the cellular automata model for on-street cruising for parking.

The vehicles in the system can be divided into three categories according to their parking needs and status: non-parking vehicles, cruising for parking vehicles, and parked vehicles. The driving rules are set for each of them.

(1) Driving rules of non-parking vehicles

The non-parking vehicle goes forward according to the NaSch model [23], which updates the vehicle position using the following four rules.

- (1) Acceleration: $v_n(t + 1) \rightarrow \min(v_n(t) + 1, v_{\max})$;
- (2) Deceleration: $v_n(t + 1) \rightarrow \min(v_n(t), d_n(t))$;
- (3) Random deceleration with a certain probability: $v_n(t + 1) \rightarrow \max(v_n(t) - 1, 0)$;
- (4) Location updating: $x_n(t + 1) \rightarrow x_n(t) + v_n(t + 1)$.

where $v_n(t)$ and $x_n(t)$ denote the speed and position of the vehicle at time, respectively. $d_n(t)$ is the number of cells between vehicle n and its preceding vehicle. v_{\max} is the maximum speed of the vehicles.

Under normal conditions, non-parking vehicles move forward in all street sections according to the NaSch model. Its random slowing probability is p_a . However, when a non-parking vehicle observes a parking behavior in lane 1, the driver can change lanes according to the safe gap in the traffic flow in lane 2. The lane change rule for non-stop vehicles on lane 1 at this point consists of two parts.

- Motivation to change lanes: non-stopping vehicles are affected by vehicles waiting to stop in front of them, $d_n(t) < \min(v_n(t) + 1, v_{\max})$
- Safety conditions for changing lanes: To ensure that the vehicle does not come into contact with the vehicle ahead in lane 2, the distance between the two vehicles must be greater than the safe distance ahead, i.e., $d_{n,front} > l_{safe}$. To ensure that the vehicle

does not come into contact with the vehicle ahead in lane 2, the distance between the two vehicles must be greater than the safe distance ahead, i.e., $d_{n,back} > d_{safe}$, where $l_{safe} = d_n, d_{safe} = v_{max}$.

If the non-parking vehicle satisfies the above conditions, it changes their present lanes to lane 2 with probability p_{change} .

(2) Driving rules of Cruising for parking vehicles

In the system, each vehicle cruising for parking goes through the steps of cruising to locate an empty parking space, parking in the vacant parking space, and driving out of the vacant parking space in turn. At sections L_1 and L_3 , the vehicles cruising for parking to be halted follow the NaSch model in line with the non-parking vehicles. Its random slowing probability is p_a . In section L_2 of the on-street parking strip, the stochastic slowing probability should rise to $p_d(p_d > p_a)$ due to the low speed of other vehicles cruising for parking. In addition, vehicles cruising for parking entering the on-street parking space from lane 2 must switch lanes to lane 1 in advance. Define its channel switching policy as:

- Motivation to change lanes: Vehicles need to be parked in on-street parking spaces.
- Safety conditions for changing lanes: To prevent a collision with vehicles ahead of lane 1 and behind lane 1, the distance between the vehicle and vehicles ahead of lane 1 must exceed the forward safety distance l_{safe} , i.e., $d_{n,front} > l_{safe}$. Moreover, the distance between the vehicle and vehicles behind lane 1 must exceed the rear safety distance d_{safe} . i.e., $d_{n,back} > d_{safe}$, where $l_{safe} = d_n, d_{safe} = v_{max}$. A vehicle cruising for parking in the L_1 or L_2 section of lane 2 must change lanes to lane 1 if the preceding requirements are satisfied.

For the vehicles cruising for parking in the L_2 section of lane 1, the rules driving into a parking space are defined as follows.

- To judge if there is an empty parking slot between the vehicle and other vehicle in front of it, with the condition $d_{k,empty}(t) < d_k(t)$, where $d_{k,empty}(t)$ represents the distance between the vehicle cruising for parking k and it is close to the front parking slot, $d_{k,empty}(t) = X_{empty} - x_k(t) - 1$. X_{empty} indicates the position of the closely next to the front parking slot.
- To judge whether the vehicle cruising for parking will be able to arrive near the empty parking slot at the next time step with the condition of $d_{k,empty}(t) + 1 \leq v_{max}$.

If the above two conditions are met, the vehicle arrives at X_{empty} at the next time step. The driver needs T time steps to park the vehicle in the right parking slot. T indicates the parking time mobility generally taken in the range of 5–15 s, which is influenced by the driver’s skill, the operation of the traffic flow, the size of the parking slot, etc.

The above rules can be summarized as follows:

$$\begin{aligned}
 & \text{if } d_{k,empty}(t) < d_k(t) \text{ and } d_{k,empty}(t) + 1 \leq v_{max} : \\
 & \text{then } \begin{cases} v_k(t + 1) = 0 \\ x_k(t + 1) = x_k(t) + d_{k,empty}(t) \end{cases}
 \end{aligned}$$

It should be noted that when the actual on-street cruising time c of the cruising for parking vehicles exceeds the equilibrium search time c^* , the driver will simply abandon on-street cruising and turn to off-street parking. At this point, the vehicle cruising for parking is converted into a non-parking vehicle and proceeds in accordance with the above-mentioned rules of travel for non-parking vehicles.

In summary, the parking in slots procedure for cruising for parking vehicles is shown in Figure 3.

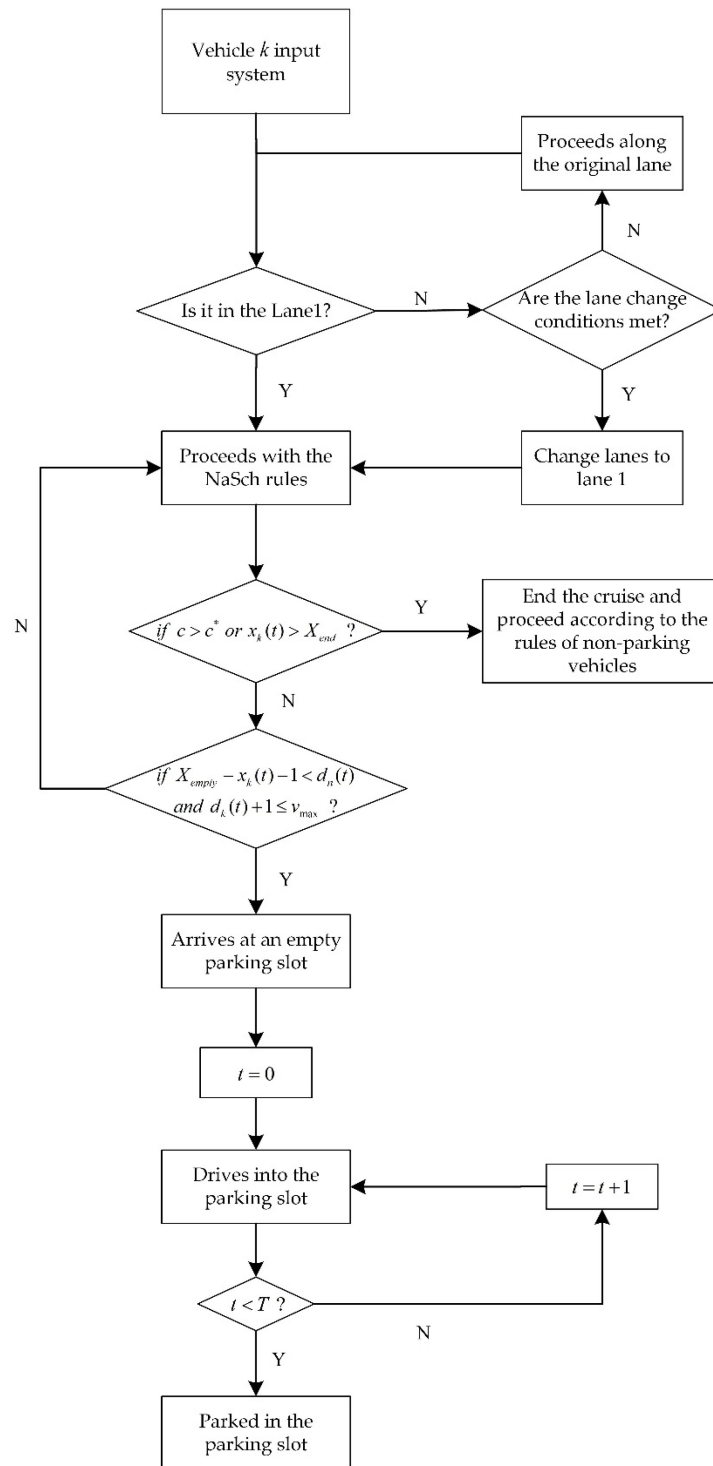


Figure 3. Parking in slots procedure for cruising for parking vehicles.

(3) Rules of the parked vehicles

When the parked vehicle k is ready to departure after parking for a certain period of time, and if the distance headway in lane 1 meets the safety conditions, it will then drive from the parking slot to the corresponding position in lane 1. Here, its safety conditions is: $d_{k,back}(t) \geq v_{k,back}(t) + 1$, where $d_{k,back}(t)$ denotes the number of empty cells between vehicle k and the vehicle adjacent to the rear of lane 1 and $v_{k,back}(t)$ is the speed of the

vehicle adjacent to the rear of lane 1. The vehicle position is updated according to the NaSch model after it departs the parking slot.

(4) Simulation conditions

This simulation employs open conditions. At each time step, record the position x_{lead} of the first vehicle and the position and x_{last} of the last vehicle. If $x_{last} > v_{max}$, each lane enters a car at cell $\min(x_{last} - v_{max}, v_{max})$ with probability p_{input} . At the same time, if $x_{last} > L_{road}$, the lead vehicle will leave the stop directly and the other vehicle following it becomes the lead vehicle.

3.2.2. Simulation Experiment Scheme

According to the survey data in Section 3.1, it can be seen that the price of on-street parking p is 6 CNY/h now. The corresponding equilibrium search time c^* is 6.667 min. This shows that the drivers are willing to choose to on-street cruising for parking if the cruising time does not exceed 6.667 min. At this time, chaotic and congested street traffic can be seen.

The two goals of the simulation experiment with two goals lie in:

(1) To further test the sensitiveness of drivers' parking price p in bringing the exact effects of their parking choice. Thereby, 4 groups of simulation experiments are designed with c^* scenarios of 6, 5, 4 and 3 min, p scenarios of 7, 8.5, 10 and 11.5 CNY/h, respectively. Four relevant kinds of road traffic conditions of c^* and p are observed by the on-street cruising for parking simulation model based on the cellular automata simulation approach.

(2) To evaluate the effects that leverage in equilibrium of c^* contributes to the improvement of road traffic conditions in the surrounding parking environment.

Simulation running parameters are set up as follows: The simulation time is 10,000 steps, and one step is 1 s. The first 2000 steps of each simulation are discarded in order to exclude transient effects and the effects from random disturbances. Simulation experimental parameters are shown in Table 4, where p_a , p_d , p_{change} and v_{max} are referenced by the reference [24]. p_{input} and T are determined according to empirical values and calibrated based on observations of real traffic conditions.

Table 4. Experimental parameters of cellular automata simulation model.

Parameters	Numerical Values	Units
p_{input}	0.2	-
p_a	0.2	-
p_d	0.4	-
p_{change}	0.4	-
v_{max}	2	cell/s
T	15	s

The input parameter of the actual parking time T_{park} of the vehicle is difficult to express with a certain value because of the diversity of travel behaviors. T_{park} is measured here by the statistical frequency distribution curve of a small sample size in order to make the reconstructed model more realistic. A field investigation is conducted on the on-street parking situation in the Red Flag Street, Changchun City between 5:00 p.m. and 8:00 p.m. on normal working days. T_{park} of 120 groups of vehicles were obtained by manual investigation. The survey results of T_{park} frequency distribution are shown in Figure 4.

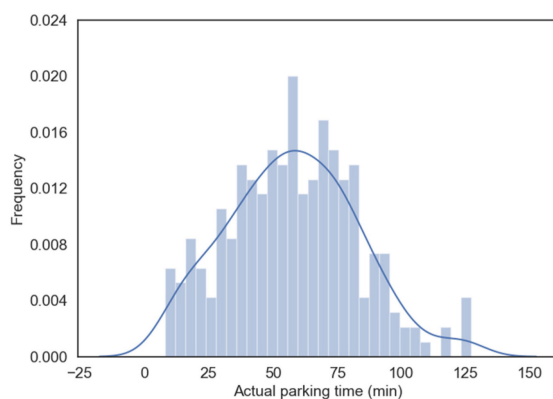


Figure 4. T_{park} of frequency distribution histogram.

Output results show that T_{park} approximately obeys a normal distribution. Further, the Kolmogorov–Smirnov test results confirm that the p -value of the normality test was 0.2, significantly greater than 0.05. Therefore, T_{park} in the established cellular automata model is set to a normal distribution with the mean value of 60 and the standard deviation of 25 min.

3.3. Analysis of Simulation Results

3.3.1. Trajectory Analysis in Time-Space of c^* and Choices Changes of On-Street Cruising for Parking

The time-space trajectory of 4 scenarios of c^* is shown in Figure 5 where the horizontal axis indicates the vehicle's location and the vertical axis represents time. Observations by those vehicle trajectories in time-space are as follows:

(1) As c^* decrease from 6, 5, 4, to 3, the effects from on-street cruising vehicles to the surrounding road traffic are diminished step by step. This means a number of on-street cruising drivers have migrated to off-street parking. c^* showed obvious sensitivity to the drivers' choices of on-street cruising for parking.

(2) As shown in Figure 5a,b, i.e., $c^* = 6$ and $c^* = 5$ min, there is still a significant number of vehicles on-street cruising which slowed down other vehicles driving freely on the street and increased the traffic congestion risk in a wide traffic impact area. However, there is also a certain proportion of on-street cruising vehicles converting from on-street cruising to off-street parking. On the other hand, as $p = 7$ CNY/h increase to $p = 8.5$ CNY/h, there is still a certain number of drivers cruising on the street that have not opted for off-street parking because of the extra cost. The reason for this is that the increase of p is too small to reach the driver's margins of tolerance. Drivers' parking choices are not sensitive to the increase of p in these two scenarios.

(3) In Figure 5 c, d, i.e., $c^* = 4$ and $c^* = 3$ min, the corresponding price p increases to 10 CNY/h and 11.5 CNY/h. By this time, the road traffic conditions are improved greatly compared to the Figure 5a,b. This suggested that c^* approaches the cruising time tolerance limit for the most of drivers. A significant number of on-street cruising vehicles are relocated to off-street parking, such that the traffic flow is much smoother on the road.

In brief, the above observations suggested that on-street cruising vehicles can be effectively induced to park off-street by modifying the price of on-street parking p to reduce the equilibrium cruising time c^* . The phenomenon of on-street cruising for parking could be eliminated in this way and the operation efficiency of regional traffic is improved well in the neighborhood surrounding the parking space as a whole.

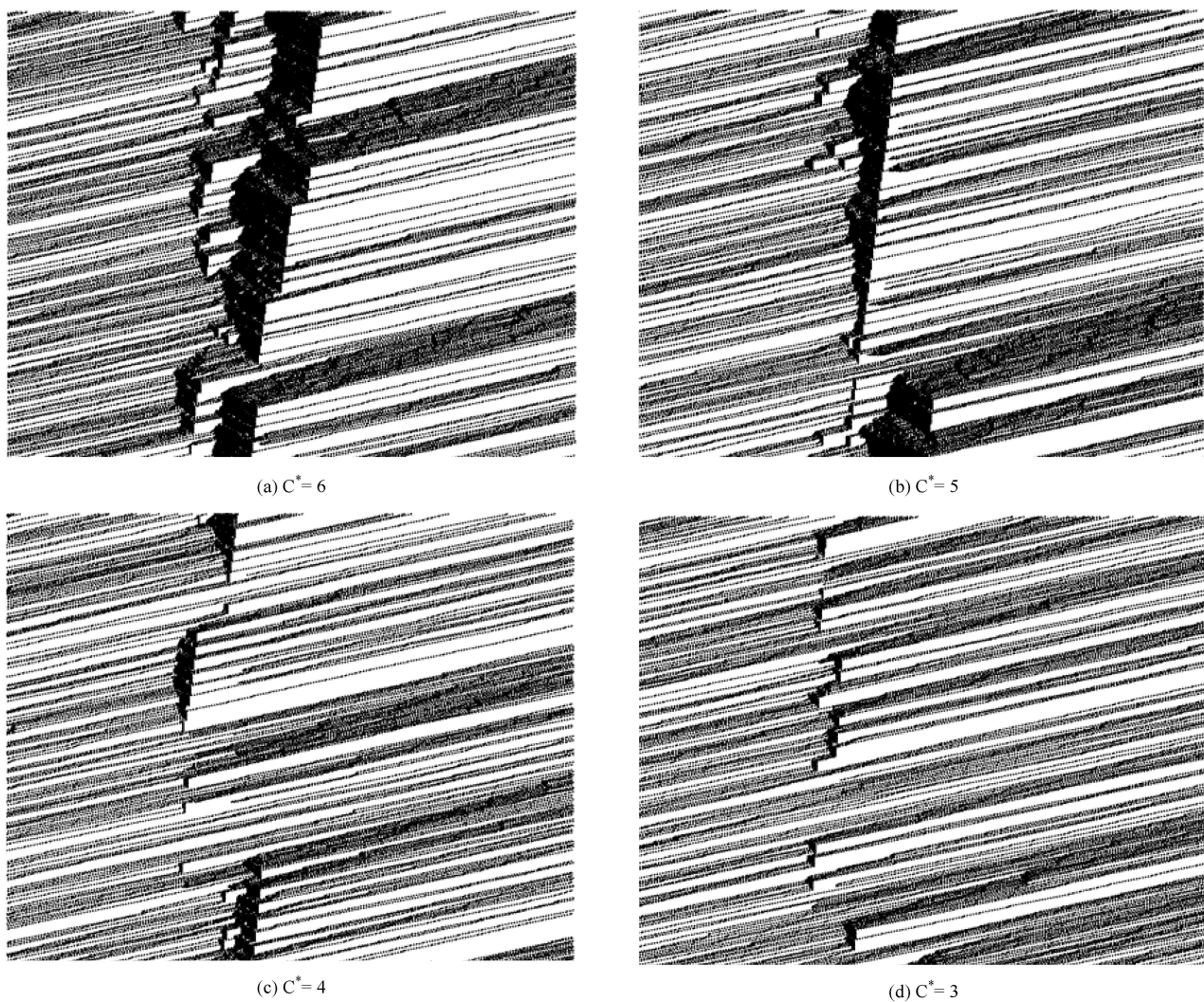


Figure 5. Time-space trajectories in four scenarios of c^* .

3.3.2. Delay Analysis on Road Traffic Flow

Descriptive statistics results from the simulation outputs are shown in Figure 6 and Table 5. Four scenarios of c^* are labeled as Group1, Group2, Group3, and Group4 for illustrative reasons. We addressed the findings about the impact mechanism of c^* on the observed indexes of the average speed $\bar{V}_{on-street}$ and the average delay $\bar{D}_{on-street}$ of the road traffic flow.

(1) In Figure 6, observations from Group1 to Group 4 illustrate that $\bar{V}_{on-street}$ increased and $\bar{D}_{on-street}$ declined along with a dramatic decrease in c^* . The decrease in c^* is indicated to play a significant role in affecting the delay improvements of the road traffic flow with from the maximum $\bar{D}_{on-street}$ of 63.559 s to the minimum $\bar{D}_{on-street}$ of 18.625 s. This finding is consistent with the results of Sana Ben Hassine [25], i.e., the cost of parking has a significant impact on whether drivers select on-street cruising for parking versus off-street parking.

In addition, it can also be seen from Table 5 that, under different c^* , the standard deviation of the $\bar{V}_{on-street}$ changes slightly from the minimum value of 3.878 to the maximum value of 6.758. The reasons behind this are that the speed recorded in the simulation is the average instantaneous speed of all vehicles passing by the street, and the speed difference among four scenarios of c^* are not distinguished in view of road traffic capacity. However, there is a relative difference in the standard deviation of $\bar{D}_{on-street}$ with a range from 18.788 to 78.093. The delay data are collected by a single vehicle, and all vehicles with

the aggregated mode affect on-street parking and then road traffic conditions. Delays on smooth traffic street are obviously smaller than those on the jammed traffic street. That means delays on different streets may lead to greater deviations.

(2) Descriptive statistical results of $\bar{V}_{on-street}$ and $\bar{D}_{on-street}$ in four scenarios of c^* are shown in Table 5. Observation showed that $\bar{V}_{on-street}$ of Group 2 increased 2.339 km/h compared to that of Group1, whereas the $\bar{D}_{on-street}$ also dropped at just 7.485 s. By now, with $c^* = 6$ to $c^* = 5$ min with corresponding the price of on-street parking $p = 7$ to $p = 8.5$ CNY/h, there are only a very small number of on-street cruising vehicles that will turn to off-street parking space to park. The model does not have a significant effect on reducing on-street cruising vehicles.

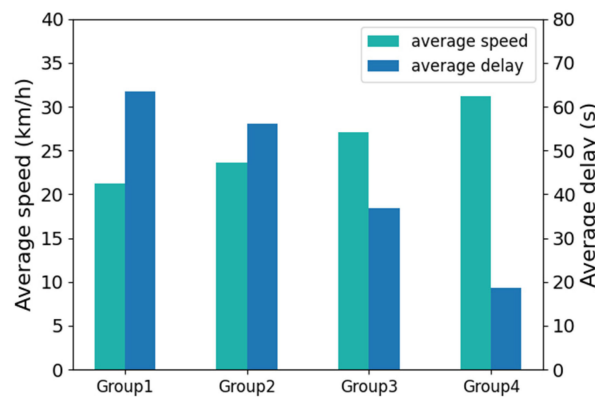


Figure 6. Histogram of $\bar{V}_{on-street}$ and $\bar{D}_{on-street}$ in four scenarios of c^* .

Table 5. Descriptive statistical results of the speed and delay on road traffic flow in four scenarios of c^* .

Group		Speed		Delay	
		Average (km/h)	Std. Deviation	Average (s)	Std. Deviation
Group1	$c^* = 6$	21.282	5.156	63.559	78.093
Group2	$c^* = 5$	23.621	6.758	56.074	77.979
Group3	$c^* = 4$	27.112	5.071	36.820	39.467
Group4	$c^* = 3$	31.140	3.878	18.625	18.788

Similarly, as observed, Group3 to Group2, $\bar{V}_{on-street}$ Group 3 increased 3.491 km/h compared to that of group 2, and the $\bar{D}_{on-street}$ also dropped at just 19.254 s. $\bar{V}_{on-street}$ and $\bar{D}_{on-street}$ are both improved well, while c^* drops from $c^* = 5$ to $c^* = 4$ min corresponding to $p = 8.5$ rising until $p = 10$ CNY/h. Comparing Groups 4 and 3, $\bar{V}_{on-street}$ and $\bar{D}_{on-street}$ are consistent with this trend. In short, the change at the two points of c^* and p would have an obvious impact on eliminating on-street cruising vehicle phenomena and improving the road traffic conditions.

3.3.3. Two-Independent-Samples Z-Test of Four-Group Sample Sets

Hypothesis testing on the four sample sets c^* listed above should be conducted in this study to determine the significant difference of the traffic population parameters with scenarios of c^* , i.e., $\bar{V}_{on-street}$ and $\bar{D}_{on-street}$ of road traffic flow. As all four sets of sample data are big samples, and the sample statistics follow a normal distribution. Therefore, a two-independent-samples Z-test was used for Hypothesis testing.

The null hypothesis was that the impact of a decrease in c^* on the population speed of the street segment is not significant, while the alternative hypothesis is that the effect is considerable.

$$H_0 : \mu_i - \mu_j \geq 0; H_1 : \mu_i - \mu_j < 0$$

Z-test results of population speed with $\bar{V}_{on-street}$ are shown in Table 6. The significance difference of any two data sets of Group (I) and Group (J), seen as the p -value, is less than

0.05. Hence, the first hypothesis may be discarded. That is, it can be anticipated that adjusting c^* has a considerable influence on the section’s population speed and may greatly raise the average speed of the paused portion. On the other hand, it can be shown that an excessive number of on-street cruising for parking pauses may result in a substantial decrease in the average speed of a road segment.

Table 6. Two-independent-samples test (I-J) of the $\bar{V}_{on-street}$ of road traffic flow.

(I) Group	(J) Group	(I-J) $\bar{V}_{on-street}$ Change Range (km/h)	Two-Independent-Samples Test (I-J)	
			Z Value	Sig(p)
Group1	Group2	2.339	−19.457	0.000
Group1	Group3	5.830	−56.999	0.000
Group1	Group4	9.858	−108.047	0.000
Group2	Group3	3.491	−29.213	0.000
Group2	Group4	7.519	−68.239	0.000
Group3	Group4	4.028	−44.623	0.000

Using the same test, it was determined whether there was a substantial variation in population delay on the road segment for varied equilibrium search time c^* . The null hypothesis states that a decrease in c^* has no impact on the population delay on the road segment, whereas the alternative hypothesis states that the effect is considerable.

$$H_0 : \mu_i - \mu_j \leq 0; H_1 : \mu_i - \mu_j > 0$$

Z-test results of population delay with $\bar{D}_{on-street}$ are shown in Table 7. The significance level of any two data sets of Group (I) and Group (J), seen as the p -value, is less than 0.05. Hence, the first hypothesis may be discarded. In other words, the impact of adjusting c^* on the total delay of the section is statistically significant, and decreasing c^* considerably reduces the average time of the halting portion. Conversely, it has been shown that an excessive number of in-road cruising breaks may dramatically increase the average delay on a road segment.

Table 7. Two-independent-samples test (I-J) of the $\bar{D}_{on-street}$ of road traffic flow.

(I) Group	(J) Group	(I-J) $\bar{D}_{on-street}$ Change Range (s)	Two-Independent-Samples Test (I-J)	
			Z Value	Sig (p)
Group1	Group2	7.485	3.408	0.001
Group1	Group3	26.793	15.139	0.000
Group1	Group4	44.934	28.507	0.000
Group2	Group3	19.254	10.901	0.000
Group2	Group4	37.441	23.784	0.000
Group3	Group4	18.195	21.091	0.000

4. Conclusions

The previous on-street cruising for parking model did not pay more attention to the role of off-street parking than those extrinsic gaming factors affecting the driver’s parking choice. A novel on-street cruising for parking model based on the economic leverage model is restructured to solve this problem. In this model, the equilibrium cruising time c^* is taken as the economic leverage by gaming on-street parking cost against off-street parking cost. Those on off-street parking gaming factors include the price of off-street parking m , the waiting time of off-street parking t_a , and the difference in walking time between their parking lots to their destinations Δt . This model enables to reflect the game features of drivers more clearly. The correlation analysis showed that all gaming factors above are positive with c^* .

Further simulation experiments are pursued. A cellular automata simulation model was firstly developed on the basis of a real-world situation. Three goals of simulations: (1) trajectory analysis in time-space of c^* and choice changes of on-street cruising for parking to reveal the impact mechanism that c^* effects on parking choices; (2) delay analysis of road traffic flow to examine the influences of eliminating on-street cruising for parking and their improvement effects on the road traffic environment; (3) two independent samples Z-test to the average of speed and delay of road traffic flow to confirm the significance difference of the traffic population parameters.

Some findings are addressed as bellows:

(1) This research focused on both the intrinsic and extrinsic elements, especially gaming factors, of off-street parking, i.e., the price of off-street parking, the waiting time of off-street parking, and the difference in walking time between their parking lot to their destinations. The on-street cruising for parking model is reconstructed in this paper in consideration of the equilibrium cruising time, i.e., the maximum tolerable cruise time after evaluating the cost of on-street and off-street parking.

(2) On-street cruising vehicles can be effectively induced to park off-street by modifying the price of on-street parking p to reduce the equilibrium cruising time c^* . The constructed model has a positive effect on urban environmental protection and urban traffic safety. In addition, the model can also provide a basis for the government to formulate urban parking pricing plans.

(3) Hypothesis testing showed that the impact of both a decrease in c^* on the population speed and delay of the street segment is significant.

It is important to note that a simulation scene based on the actual situation of Red Flag Street is studied. Red Flag Street, a city shopping area, generates a large parking demand for a certain number of on-street parking lots together with large-size off-street parking spaces in the nearby area, such as underground car parks and above-ground garages, etc. The model is suitable for streets with similar characteristics.

5. Suggestions

(1) There exist both working periods and non-working periods in a day. Their corresponding trips include working trips and non-working trips. These two trips with different purposes may generate different time values, which means that the same on-street parking price may have different induction effects in these two periods. So, it is necessary to set a time segment pricing rule for parking in different time periods in order that the adjustment of c^* according to the time-space traffic characters would contribute more to smooth road traffic conditions.

(2) The traffic impacts of the restructured on-street cruising for parking model are examined both in the macroscopic and microscopic aspects and a traffic measure is proposed to reduce on-street cruising vehicles by increasing on-street parking prices. The economic affordability of drivers related with parking costs should be considered in the model in further research to overcome the difficulty of a survey. It is also necessary to conduct a questionnaire survey on drivers from more kinds of parking environment to determine their affordable and maximum parking prices.

(3) Different streets have different land uses. Therefore, the trip purposes of on-street drivers are normally different at the same time. When this model is used, the calculation method of time value needs to be determined according to the purpose of the driver's trip. Therefore, in the next research, it is necessary to explore the detailed land use attributions of the traffic impact area where the street is located, as well as the driver's travel purpose.

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References

1. Diallo, A.; Bourdeau, J.S.; Morency, C.; Saunier, N. Methodology of parking analysis. *Can. J. Civ. Eng.* **2015**, *42*, 281–285. [[CrossRef](#)]
2. Arnott, R.; Rowse, J. Downtown parking in auto city. *Reg. Sci. Urban Econ.* **2009**, *39*, 1–14. [[CrossRef](#)]
3. Arnott, R.; Williams, P. Cruising for parking around a circle. *Transp. Res. Part B Methodol.* **2017**, *104*, 357–375. [[CrossRef](#)]
4. Kazi, S.; Nuzhat, S.; Nashrah, A.; Rameeza, Q. Smart parking system to reduce traffic congestion. In Proceedings of the 2018 International Conference on Smart City and Emerging Technology (ICSCET), Mumbai, India, 5 January 2018; IEEE: Piscataway, NJ, USA, 2018.
5. Zhu, Y.; Ye, X.; Chen, J.; Yan, X.; Wang, T. Impact of Cruising for Parking on Travel Time of Traffic Flow. *Sustainability* **2020**, *12*, 3079. [[CrossRef](#)]
6. Assemi, B.; Baker, D.; Paz, A. Searching for on-street parking: An empirical investigation of the factors influencing cruise time. *Transp. Policy* **2020**, *97*, 186–196. [[CrossRef](#)]
7. Geroliminis, N. Cruising-for-parking in congested cities with an MFD representation. *Econ. Transp.* **2015**, *4*, 156–165. [[CrossRef](#)]
8. Guo, H.; Gao, Z.; Yang, X.; Zhao, X.; Wang, W. Modeling travel time under the influence of on-street parking. *J. Transp. Eng.* **2012**, *138*, 229–235. [[CrossRef](#)]
9. Shoup, D.C. Cruising for parking. *Transp. Policy* **2006**, *13*, 479–486. [[CrossRef](#)]
10. Kobus, M.B.W.; Gutiérrez-I-Puigarnau, E.; Rietveld, P.; Van Ommeren, J.N. The on-street parking premium and car drivers' choice between street and garage parking. *Reg. Sci. Urban Econ.* **2013**, *43*, 395–403. [[CrossRef](#)]
11. Arnott, R.; Inci, E. An integrated model of downtown parking and traffic congestion. *J. Urban Econ.* **2006**, *60*, 418–442. [[CrossRef](#)]
12. Lee, J.; Agdas, D.; Baker, D. Cruising for parking: New empirical evidence and influential factors on cruising time. *J. Transp. Land Use* **2017**, *10*, 931–943. [[CrossRef](#)]
13. Arnott, R.; Rowse, J. Curbside parking time limits. *Transp. Res. Part A Policy Pract.* **2013**, *55*, 89–110. [[CrossRef](#)]
14. Gu, Z.; Najmi, A.; Saberi, M.; Liu, W.; Rashidi, T.H. Macroscopic parking dynamics modeling and optimal real-time pricing considering cruising-for-parking. *Transp. Res. Part C Emerg. Technol.* **2020**, *118*, 102714. [[CrossRef](#)]
15. Ding, H.; Guo, H.W.; Wang, W.H. Modeling of in-road parking and cruising behavior considering time value. *Transp. Syst. Eng. Inf. Technol.* **2015**, *15*, 187–191.
16. Qin, H.; Yang, X.; Wu, Y.-J.; Guan, H.; Wang, P.; Shahinpoor, N. Analysis of parking cruising behaviour and parking location choice. *Transp. Plan. Technol.* **2020**, *43*, 717–734. [[CrossRef](#)]
17. Arnott, R.; Inci, E.; Rowse, J. Downtown curbside parking capacity. *J. Urban Econ.* **2015**, *86*, 83–97. [[CrossRef](#)]
18. Anderson, S.P.; De Palma, A. The economics of pricing parking. *J. Urban Econ.* **2004**, *55*, 1–20. [[CrossRef](#)]
19. Van Ommeren, J.N.; Wentink, D.; Rietveld, P. Empirical evidence on cruising for parking. *Transp. Res. Part A Policy Pract.* **2012**, *46*, 123–130. [[CrossRef](#)]
20. Ding, H. Behavior Characteristic Analysis and Modeling of On-Street Parking Selection. Master's Thesis, Beijing Institute of Technology, Beijing, China, 2016.
21. Prevost, F. *Curb Parking: Theory and Model*; Institute of Transportation Studies: Davis, CA, USA, 1985.
22. Yang, W. Research on the Influence of Curbside Parking on Dynamic Traffic. Ph.D. Thesis, Jilin University, Changchun, China, 2007.
23. Nagel, K.; Schreckenberg, M. A cellular automaton model for freeway traffic. *J. De Phys. I* **1992**, *2*, 2221–2229. [[CrossRef](#)]
24. Hu, X.; Hao, X.; Wang, H.; Su, Z.; Zhang, F. Research on on-street temporary parking effects based on cellular automaton model under the framework of Kerner's three-phase traffic theory. *Phys. A Stat. Mech. Its Appl.* **2020**, *545*, 123725. [[CrossRef](#)]
25. Hassine, S.B.; Mraïhi, R.; Lachiheb, A.; Kooli, E. Modelling parking type choice behavior. *Int. J. Transp. Sci. Technol.* **2021**, *11*, 653–664. [[CrossRef](#)]