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Evaluation of Environmental Benefits Caused by Reservation-Based Shared Parking: A Case Study of Beijing, China

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ABSTRACT With the help of accurate parking navigation systems, sharing vacant private parking spaces with public travelers may have the potential of reducing the number of cruising vehicles and contribute to traffic emission reduction. However, the quantitative effects of such a measure are still relatively unknown in traffic management. In this article, we firstly established an optimal allocation model of shared parking spaces, which is a pure integer linear programming model of maximizing the number of served public vehicles to avoid cruising for parking. Further, the parking space allocation model was expanded to an estimation model that quantifies the effect of emission reduction. Secondly, a branch-and-cut algorithm was introduced as the core algorithm to solve the proposed models. Finally, detailed sensitivity analysis, based on empirical data collected by electronic parking toll collections and questionnaire surveys in Beijing, China, evaluated the proposed model and algorithm. The results indicate that shared parking can not only effectively reduce the cruising time and the number of vehicles, but also has significantly a positive effect on emission reduction. This research is helpful to provide theoretical support for alleviating parking pressure and environmental problems.

INDEX TERMS Potential emission reduction, shared parking, optimal parking space allocation, pure integer linear programming model, branch-and-cut algorithm.

I. INTRODUCTION

In recent decades, massive consumption of fossil fuels has exacerbated a range of global problems, such as air pollution, ozone depletion, global warming, etc. Crude oil accounts for nearly 40% of fossil fuels, of which more than 95% was used in transportation industry [1].

Although parking is an essential part of each vehicle trip from the perspective of transportation, parking problem is usually ignored as parked vehicles do not consume energy [2]. In fact, cruising for parking spaces has been a common headache that usually happens in many metropolitan regions and accounts for a significant share of travel distance as well as travel time [3]. As a result, when the number of cruising vehicles or the time spent in cruising for parking can be effectively diminished, it will not only help to reduce energy consumption even abate environmental pollution, but also improve the parking difficulties and the quality of travel for public travelers [4], [5].

The ultimate reason for urban parking problems lies in the discrepancy between limited available parking spaces and unpredictable parking demand. Take Beijing for example, the number of registered motor vehicles is more than triples of the registered parking spaces in 2018, with 6.08 million and 1.89 million, respectively. Under this context, a natural idea of solving the parking problem is to build more parking facilities, but that is unrealistic because of the limited construction capital and urban space within an inner city, especially in a short term. On the other hand, the reality is that most of these (especially private) existing parking spaces

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are underutilized since they can only be utilized by these owners themselves. As a consequence, one potential way to overcome the parking difficulty is to share the using right of these parking spaces, which has a potential for improving parking resource utilization, reducing the number of vehicles that cruise for parking spaces, and lowering the traffic emissions.

During the sharing periods, how to allocate parking demand to the most appropriate parking spaces is critical, namely the problem of optimal shared parking space allocation [6]. With the help of advanced communication technology, it has become a reality for travelers to reserve their suitable parking spaces. Under this context, considering the given time constraints of both parking supply side and parking demand side, the problem of optimal shared parking space allocation can be regarded as a kind of integer programming problems, whose corresponding models can be classified as integer programming models, which are mathematically a class of NP-hard problems [7]. The methods for solving such problems can be roughly divided into two categories, one is heuristic algorithms, and the other is exact algorithms. Since the quality of heuristic algorithms is somehow difficult to evaluate so that these algorithms are not suitable to our objective here, our focus is mainly on exact algorithms and its corresponding models.

Most of the existing models for parking space allocation are nonlinear integer programming models, like in the literature [6], which leads to the weakness of exact algorithms. To effectively obtain the optimal solution, a feasible method is to further transform nonlinear integer programming models to linear integer programming models with some mathematical skills, such as adding valid inequalities.

In addition, although considerable work has been done on parking and related problems, such as parking reservation, shared parking, cruising for parking behavior analysis, traffic emission in recent years. As far as our knowledge goes, there has been lack of integrated research framework of estimating the reduction of traffic emission caused by optimal allocation of shared parking spaces. In view of the above research, this study aims to fill the aforementioned research gap and extend our knowledge of the relationships between the potential traffic emission reduction and the optimal shared parking space management.

The rest of this article is organized as follows. In section II, relevant papers and reports are reviewed. In section III, we describe the research problem and some necessary assumptions. In particular, we formulate a pure integer linear programming model aiming at the optimal allocation for shared parking spaces. Moreover, a branch-and-cut algorithm for solving the proposed model is also introduced. In section IV, the validity of our proposed model and its algorithm are tested based on the empirical parking behavior data collected in a residential parking lot and a hospital parking lot in Beijing, China. Finally, we discuss the results and possible future research directions in Section V.

II. LITERATURE REVIEW

In this section, we briefly review relevant research related to parking reservation, shared parking, cruising for parking, and traffic emission.

A. PARKING RESERVATION

With the help of advanced information communication technology, parking reservation are becoming increasingly popular with travelers. In practice, various platforms or applications emerge in recent years, such as Park-Whiz, ParkMe, Parking Panda, etc, which effectively mitigate information uncertainty on parking availability. In the field of research, Ogiwara *et al.* (2001) introduced a parking reservation system and discussed the social demand for the parking reservation system and the initial parking reservation system [8]. Mor Kaspi (2014) studied the effectiveness of on-road parking sharing systems with parking reservation policies. Simulation results show that the policy can reduce the total time spent in cruising for parking by travelers [9]. Boudali *et al.* (2017) applied multi-agent based technology to develop a parking reservation system which provides real-time assistant decision-making function for drivers according to drivers' preferences. By optimizing the driver's preference for operating system, the system is more suitable for the driver's operation [10].

B. SHARED PARKING

Along with the prosperity of the sharing economy, shared parking in transportation industry recently has drawn increasingly attention [11]. It is a win-win operation: drivers save time for their trip, and homeowners make their parking spaces profitable. Generally, there are two types of studies involving the modeling shared parking management. One type is about the static programming model by aiming to maximize the revenue or utilization of shared parking resource management. For example, Shao *et al.* (2016) constructed a reservation mechanism that considers the sharing of parking spaces in residential areas between residents and public users, and established a binary integer programming model for the allocation of parking spaces [6]. Xiao *et al.* (2018) studied the matching problem under two auction mechanisms for the shared parking problem with multiple parking space demanders and multiple parking space providers [12]. The other type is related to dynamic parking management models. Guo *et al.* (2016) considered parking system as a queuing system and applied queuing theory to construct a stochastic programming to maximize the profit of parking resource management [13]. Lei *et al.* (2017) constructed a multi-stage non-cooperative bi-level programming model in which the upper model describes the pricing mechanism and the lower model describes the mechanism of the driver's parking space choice [14]. Zhao *et al.* (2020) developed a simulation-based model to solve the problem of the optimal number of reserved parking spaces ensuring that the owners of shared parking spaces have vacant space needs of parking spaces can be satisfied [15].

C. CRUISING FOR PARKING

Vehicles that cruising for an available vacant parking space significantly contribute to traffic congestion, vehicle emissions, air pollution, and climate change. According to the research result from [2], the number of cruising vehicles accounted for between 8 and 74 per cent of urban road traffic flow. Results of a study of Americans indicated that cruising for parking costs an average of 17 hours per traveler, which means it costs \$345 per year per traveler to find parking spaces in terms of wasted time and fuel.

With the help of communication technology, the intelligent parking guidance system can help drivers find the parking space they need efficiently. It has an obvious effect on energy saving and emission reduction. In the city center of Amsterdam, Netherlands, 10% of car drivers used guidance systems to find a parking place. For these drivers, the number of kilometers driven in and around Amsterdam related to parking decreased by 15%. A simulation-based research showed that the benefits of applying intelligent parking guidance systems can be up to 500 per day for a traffic network with 40,000 vehicles [16]. A survey in Southampton found that drivers reduced the time spent searching for a parking space on average by 50% from 2.2 to 1.1 minutes. Similarly, a survey of over 600 people in Valencia found that 61% of respondents were influenced by the information on variable traffic information display system signs and 30% had changed their parking destination as a result. Results from the COSMO project also showed that an approximate 7% reduction in fuel and hence CO_2 emissions were calculated for parking vehicles as a result of the reduced time and distance traveled needed to park with the help of parking guidance systems [17].

D. ENVIRONMENTAL IMPACTS OF URBAN TRAFFIC

The increase in urban traffic has a profound correlation with the increase in air pollutant emissions [18]. In many regions, urban traffic emissions have become a major source of air pollutants, including CO_2, NO_x, and so on. In the epidemiological studies of the effects of combustion-related (mainly traffic-generated) air pollution, NO_2 was shown to be associated with adverse health effects [19]. Furthermore, road traffic exhaust emissions account for 40% of volatile organic compounds, more than 70% of NO_x, and over 90% of CO in most European cities, and for about 45% pollutants released in the US [20]. A study carried out by the International Energy Agency shows that transportation sector consumed approximately 62% of the global oil, which releases nearly 25% of carbon emissions, with 75% of the contribution from road vehicles [21].

III. METHODOLOGY

The main objective of this study is to estimate the potential reduction of traffic emissions via reducing the number of vehicles that cruise for parking spaces after implementing the shared parking. In this section, we describe the problem and formulate the corresponding models, as well as the solution algorithm.

A. PROBLEM DESCRIPTIONS

Supposing that an intelligent parking management system (IPMS) operates a private parking lot with parking spaces provided by suppliers (denoted as O-users). These parking spaces will be shared with public travelers (denoted as P-users) when these parking spaces are vacant. P-users should submit their parking time windows information to the IPMS in advance, similarly O-users also submit the vacant time window information of their parking spaces to the IPMS. After that, the IPMS attempts to optimally match the parking demand and supply which is a classic matching problem with the NP-hard characteristic. With the successful matched result, P-users will have access to shared parking spaces. For the convenience of analysing, it is further assumed that all these P-users can accurately find the reserved shared parking space through an intelligent parking navigation system. As a result, the cruising for parking process of those P-users will be eliminated so that the goals of energy saving and emission reduction can be achieved.

B. MODELING

1) SHARED PARKING SPACE ALLOCATION MODEL

The parking space resources are both temporal and spatial. To quantitatively analyze the utilization of shared parking resources, a spatial-temporal model of shared parking spaces should be established. Without loss of generality, assuming that the total number of suppliers is N_{SPSs}, and each of the suppliers has only one shared parking space (they can be considered as multi-suppliers when they have multi-parking spaces to share in real life). Each of these shared parking spaces (i-th parking space) consists of the number of K_i (K_i is a positive integer) parking duration. Let $\Gamma_j^{t_j}$ donate the shared parking duration for the shared parking duration starting at time point t_j.

The multiple discontinuous shared time windows of the same shared parking space are decomposed. To simplify the expression, these discontinuous shared time windows can be transformed to the equal number of augmented shared spaces (denoted as: ASPSs). Each of these ASPSs has only one shared time period after transformation. The total number of ASPSs N_{ASPSs} can be calculated as follows:

$$N_{ASPSs} = \sum_{i=1}^{N_{SPSs}} K_i. \tag{1}$$

Then the total space and time of shared parking space resources can be expressed as:

$$R_{shared}^{total} = \sum_{i=1}^{N_{ASPSs}} \Gamma_i^{t_i} \tag{2}$$

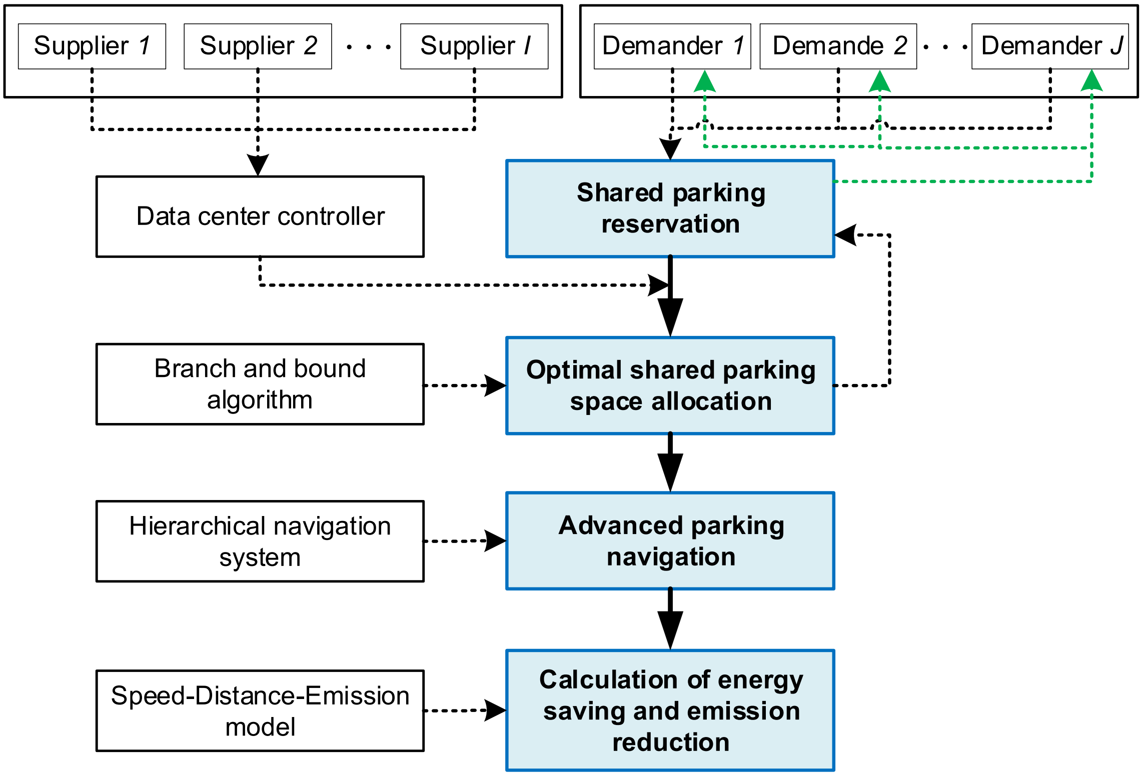

FIGURE 1. **Research framework.**

If the j-th parking demand matches i-th ASPS, the utilized parking resource can be expressed as:

$$R_{used}^{j,i} = \Gamma_j^{t_j} x_{i,j} \tag{3}$$

where $\Gamma_j^{t_j}$ represents the duration of j-th parking demand; t_j represents the start time of the j-th parking demand; is a binary variable, when the jth parking demand is successfully allocated to the ith augmented berth, $x_{i,j} = 1$, otherwise $x_{i,j} = 0$.

$$R_{used}^{total} = \sum_{i=1}^{N_{ASPSs}} \sum_{j=1}^{N_{P-users}} \Gamma_j^{t_j} x_{i,j} \tag{4}$$

The objective of shared parking space allocation is to maximize the number of served P-users (NoSP) so that the traffic emission caused by cruising for parking can be reduced as much as possible, which can be represented by a pure integer linear programming model as follows:

$$PILP : \max \text{NoSP} = \sum_{i=1}^{N_{ASPSs}} \sum_{j=1}^{N_{P-users}} x_{i,j} \tag{5}$$

subject to:

$$\sum_{i=1}^{N_{ASPSs}} x_{i,j} \leq 1 \quad \forall j \in \{1, 2, \cdots, N_{P-users}\} \tag{6}$$

$$-t_j + t_i \leq M\delta_{i,j} \quad \forall i \in \{1, 2, \cdots, N_{ASPSs}\}; \quad \forall j \in \{1, 2, \cdots, N_{P-users}\} \tag{7}$$

$$x_{i,j} \leq M(1 - \delta_{i,j}) \quad \forall i \in \{1, 2, \cdots, N_{ASPSs}\}; \quad \forall j \in \{1, 2, \cdots, N_{P-users}\} \tag{8}$$

where $\delta_{i,j} \in \{0, 1\}$ is used to judge whether the j-th parking demand is assigned to the i-th ASPS, if yes, $\delta_{i,j} = 1$, otherwise, 0. Let M be a sufficiently large positive real number. Eqs.(7) and (8) ensure that the demand starts no earlier than the supply.

$$t_j + \Gamma_j^{t_j} - t_i + \Gamma_i^{t_i} \leq M\delta_{i,j} \quad \forall i \in \{1, 2, \cdots, N_{ASPSs}\}; \quad \forall j \in \{1, 2, \cdots, N_{P-users}\} \tag{9}$$

$$x_{i,j} \leq M\left(1 - \delta_{i,j}\right) \quad \forall i \in \{1, 2, \cdots, N_{ASPSs}\}; \quad \forall j \in \{1, 2, \cdots, N_{P-users}\} \tag{10}$$

where the definitions of $\delta_{i,j}$ and M are as the same as those in Eqs.(7) and (8). Eqs.(9) and (10) ensure that the end of demand is no later than the end of parking supply.

In addition, any interval between two proximate P-users allocated to the same ASPS should large enough to avoid traffic congestion in shared parking lot. Thus, the following inequalities Eqs.(11) and (12) must hold.

$$M\psi_{i,j,k} \geq \begin{cases} \left(t_k + \Gamma_k^{t_k} - t_j\right) \times \left(t_j + \Gamma_j^{t_j} + \varepsilon - t_k\right) & \text{if } t_k > t_j \\ \left(t_j + \Gamma_j^{t_j} - t_k\right) \times \left(t_k + \Gamma_k^{t_k} + \varepsilon - t_j\right) & \text{if } t_k \leq t_j \end{cases} \quad \forall i \in \{1, 2, \cdots, N_{ASPSs}\}; \quad \forall j \in \{1, 2, \cdots, N_{P-users}\}; \quad \forall k \in \{1, 2, \cdots, N_{P-users}\} \tag{11}$$

$$x_{i,j}+x_{i,k}-1 \leq M(1-\psi_{i,j,k}) \quad \forall i \in \{1,2,\cdots,N_{ASPSs}\}; \quad \forall j \in \{1,2,\cdots,N_{P-users}\}; \quad \forall k \in \{1,2,\cdots,N_{P-users}\} \tag{12}$$

where ε is the minimum interval between two proximate P-users allocated to the same ASPS; $\psi_{i,j,k}$ is a binary parameter. If the j-th P-user and k-th P-user are allocated to the same i-th ASPS, $\psi_{i,j,k}=0$, otherwise, $\psi_{i,j,k}=1$.

Because of the limited shared parking duration for each ASPS, the maximum number of $N_{P-users}$ allocated to the same one ASPS (denoted as $N_{max}^{onespace}$) is limited. So we can claim that $N_{max}^{onespace}$ satisfies the following inequality constraint:

$$\sum_{j}^{N_{P-users}} x_{i,j} \leq N_{max}^{onespace} \quad \forall i \in \{1,2,\cdots,N_{ASPSs}\} \tag{13}$$

$$x_{i,j} \in \{0,1\}. \tag{14}$$

2) POTENTIAL EMISSION REDUCTION ESTIMATION MODEL

Once the matching problem between parking supply and demand is solved, we can easily obtain the total number of P-users that will have parking spaces ($N_{w/o}^{cru}$) through reservation, which can be calculated as follows:

$$N_{w/o}^{cru} = \sum_{i=1}^{N_{ASPSs}} \sum_{j=1}^{N_{P-users}} x_{i,j} \tag{15}$$

With the help of advanced parking guiding system, cruising for parking spaces of those P-users would be eliminated. Nowadays, vehicles commonly use petrol or diesel and, in minority, alternative fuels (primarily compressed natural gas-CNG). Distribution of fuel type of passenger cars can be investigated. Different types of fuel cause various energy consumption and levels of CO_2 emissions. In view of this, the $N_{w/o}^{cru}$ is divided into petrol, diesel and CNG vehicles, see Eq. (16):

$$\begin{aligned} N_{w/o}^{cru} &= N_{w/o}^{cru,p} + N_{w/o}^{cru,d} + N_{w/o}^{cru,CNG} \\ &= N_{w/o}^{cru} \times S_p + N_{w/o}^{cru} \times S_d \\ &\quad + N_{w/o}^{cru} \times S_{CNG} \end{aligned} \tag{16}$$

where S_p indicates the share of petrol powered vehicles; S_d is the share of diesel powered vehicles; S_{CNG} denotes the share of CNG powered vehicles.

Because of its convenience of calculation, average-speed-distance based model is applied to estimate potential reduction of traffic emission [1]. Let the average cruising speed and the average cruising duration for parking be $\overline{v_l}$ and $\overline{t_l}$, respectively. Thus, we can easily obtain the average cruising distance for each of the P-users with the l-th ($l \in 1, 2, 3$, which represents petrol, diesel, and CNG, respectively) type of fuel powered vehicles if they have no parking spaces:

$$\begin{aligned} D_l &= \overline{v_l} \times \overline{t_l} \\ &= \overline{v_l} \times \theta \times \overline{t_0} \end{aligned} \tag{17}$$

where $\overline{t_0}$ is the free flow travel time; θ is a coefficient that depicts the influence of cruising vehicles on free traffic flow travel time.

The θ can be calculated as following:

$$\begin{aligned} \theta &= \frac{1+\alpha\left(\frac{N+N_{w/o}^{cru}}{C}\right)^{\beta}}{1+\alpha\left(\frac{N}{C}\right)^{\beta}} \\ &\approx 1+\alpha\left(\frac{N_{w/o}^{cru}}{N}\right)^{\beta} \end{aligned} \tag{18}$$

where N is travel flow volume without cruising vehicles; α is a positive real coefficient.

Eq.(18) indicates that the cruising vehicles have positive impacts on travel time.

The total potential reduction of fuel consumption (PRFC) of cruising vehicles can be then calculated using Eq.(19):

$$PRFC = \sum_{l=1}^{3} PRFC_l = \sum_{l=1}^{3} D_l/100 \times q_l \times N_{w/o}^{cru,l} \tag{19}$$

where $PRFC$ presents the total reduction of fuel consumption for all the P-users, unit: l; D_l is the average cruising distance for the specific fuel powered vehicles, unit: km; q shows the specific fuel consumption, unit: l/100 km; V_c is the vehicle velocity, unit: km/h.

Accordingly, the potential reduction of CO_2 emission can be calculated as in Eq.(20):

$$\begin{aligned} PRE^{CO_2} &= \sum\nolimits_{l=1}^{3} PRFC_l \times EF_k^{CO_2} \\ &= \sum\nolimits_{l=1}^{3} D_l/100 \times q_l \times N_{w/o}^{cru,l} \end{aligned} \tag{20}$$

where PRE^{CO_2} represents the reduction of CO_2 emission, kg; $EF_l^{CO_2}$ expresses the potential reduction of CO_2 emission factor depending on the l-th type of fuel, kg/km.

C. SOLUTION TECHNIQUES

Based on the above problem description and the proposed mathematical model, the biggest difficulty lies in how to solve the optimal allocation problem of shared parking spaces. Here, we apply a branch-and-cut algorithm.

There are two main reasons for applying the branch-and-cut algorithm:

- The branch-and-cut algorithm is currently the most successful method for solving integer programs [7], [22].
- The InEq.(13) is proposed as an additional constraint, which can be regarded as the cut plane in solving the optimal allocation problem of shared parking spaces.

The basic idea of branch-and-cut algorithm is to use the frame structure of branch-and-bound algorithm to add effective inequalities at the nodes of branch-and-bound tree, so as to dynamically enhance the upper bound in solving our pure integer linear programming model. More specifically, the process can be described as follows.

Firstly, the simplex method is used to solve the linear relation problem without integer constraints. After obtaining the optimal solution, if the solution is integer, then the optimal value is obtained. Otherwise, the cut-plane method is used to find a further linear constraint which ensures that all feasible integer points satisfy the constraints, but the present optimal solution does not satisfy the constraint. These inequality constraints can then be added to the linear problem, so that the next solution can be closer to the integer results. More details can be referred to reference [22].

IV. CASE STUDY

In this section, we present some numerical results to illustrate the essential ideas in the article.

A. DATA RESOURCE

The empirical data we used here was collected by smart parking systems of ETCP company that is a giant intelligent parking company in China. The P-users' parking behaviour data was collected in the People's Liberation Army Second Artillery General Hospital (denoted as: PLSAGH) in Beijing, China, where physicians and patients usually cruise for parking spaces. The O-users' parking behaviour data was collected in a community located at No.25, A, Xinjiekou Outer street, Beijing, China. The distance between the hospital and the community is 300 meters, which is within acceptable range of walking distance [23]. The totally valid sample sizes of P-users and O-users are 1,958 and 1,640, respectively, accounting for 96.8% and 98.1% of the collected raw data.

In addition, to obtain other information related to cruising for parking, a questionnaire survey was carried out near the the area of PLSAGH. A total of 306 valid questionnaires were obtained. The information being investigated includes average time of cruising for parking, vehicle fuel type, average speed of cruising for parking, etc. Further, we obtained some statistics shown in the next subsection.

B. SETTING OF PARAMETERS

Based on our questionnaire data, the average cruising speed was 11.3 km/h. Time distribution of cruising for parking is shown in Figure 2. Further, we can obtain the average cruising time of each traveler, which is approximately 7.9 min. The shares of petrol, diesel and CNG vehicles are 57.4%, 30% and 12.6%, respectively, as shown in Figure 3. According to the usually used emission inventory tools, we focus on the CO_2 emission factors for petrol and diesel. Considering the share of engine capacities and fuel types, average emission was: 0.234 kg/km for petrol, 0.222 kg/km for diesel. For CNG, the emissions were reduced by 10% compared to petrol which led to 0.211 kg/km [24]. To compare the effects of shared parking in various scenarios, five levels of the value of $N_{P-users}$ are set, which are 60, 120, 240, 360, and 480, respectively. Six levels of the value of β are configured from 1 to 2 with the same interval. Under each combination scenario, the α is set to 1. In addition, the parameter of $N_{max}^{onespace}$ is set to 5.

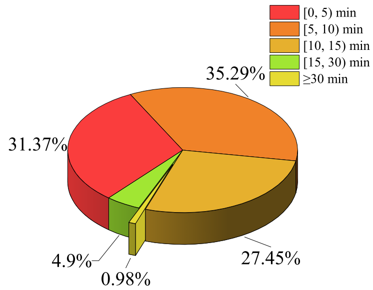

FIGURE 2. Duration distribution of cruising for parking spaces.

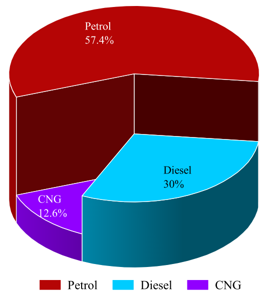

FIGURE 3. The fuel types of interviewees' vehicles in Beijing.

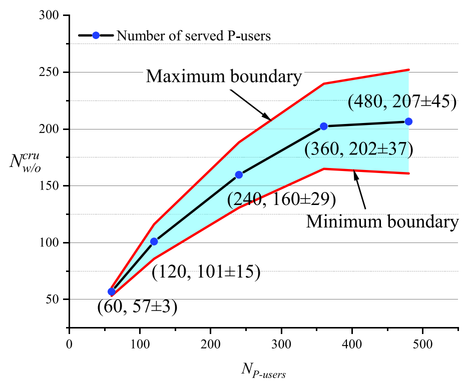

FIGURE 4. Relationships between the number of served P-users and the total number of P-users.

C. RESULTS

Figure 4 shows the relationship between $N_{w/o}^{cru}$ and $N_{P-users}$. The blue dots represent the average of $N_{w/o}^{cru}$. With the increase of $N_{P-users}$, the average value of w/o^{cru} increases, but its increasing speed becomes smaller and smaller. The solid red lines show the maximum and minimum of w/o^{cru} with different configures of $N_{P-users}$. Obviously, as $N_{P-users}$ increases, the gap between the maximum and the minimum becomes larger and larger. In all the experiments, the maximum $N_{w/o}^{cru}$ was 252, as a result, the maximum average turnover rate during the period of shared parking spaces was more than 2 vehicle/stall/day.

Figure 5 demonstrates the relationship among reduction of cruising time and β, $N_{\text{P-users}}$. It can be Obviously seen that the reduction of cruising time of each P-user increases with the increasing $N_{\text{P-users}}$ at the same β. The maximum of reduction cruising time is up to nearly 25 min for each P-users.

Based on the above results, we further estimated the impact on emission reduction. Figure 6 shows the impact of shared

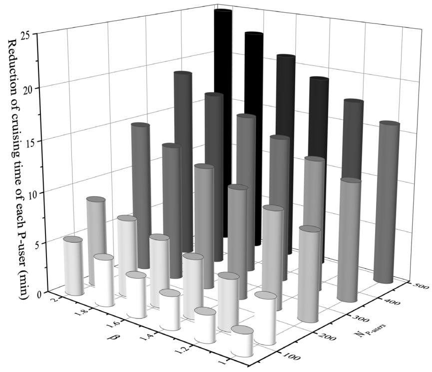

FIGURE 5. Relationships among the reduction of cruising time, β, and $N_{P-users}$.

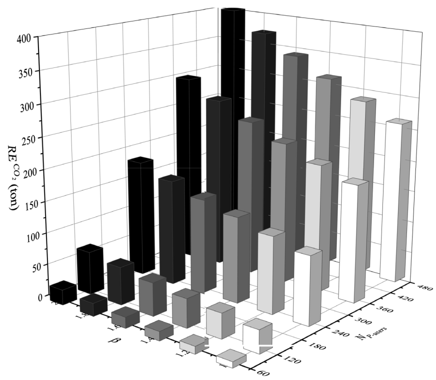

FIGURE 6. Relationship among the reduction of CO_2, β, and $N_{P-users}$.

parking on the reduction of CO_2 emission. It can be seen that the more p-users, the better the effect of shared parking on emission reduction. Supposing that implementing shared parking in these 120 parking spaces during the working days (365/7*5 $\approx$ 261 days) of one year, the maximum of CO_2 emission can be reduced by about 400 tons. According to statistics, there are 2.19 million parking spaces in residential areas of Beijing. After sharing 20% of the existing parking spaces in Beijing, the annual CO_2 reduction could reach to 7.3 million tons, which will have a certain impact on reducing greenhouse gas effect.

V. DISCUSSION AND FUTURE RESEARCH DIRECTIONS

This article constructs a quantitative model to estimate the effect of emission reduction in the implementation of shared parking policy. First, a pure integer linear programming model was proposed aiming to absorb the cruising vehicles as many as possible. This goal is different from the topics in most existing studies, since most existing studies pursue the maximization of parking space utilization [6]. In addition, although the matching of parking supply and demand is involved in both our model and some of existing studies, the minimum interval between two proximate P-users allocated to the same shared parking space was also considered for the first time, which makes the proposed model more applicable in real life.

Second, we present a branch-and-cut algorithm for solving the optimal solution of parking supply and demand matching problem. To the best of our knowledge, this is the first time that a branch cut algorithm has been used to solve the problem of allocating shared parking spaces, with the aim of maximizing the number of satisfied parking needs. Although some heuristic algorithms, such as the ant colony optimization algorithm, can be used to solve such large-scale NP-hard problems, the gap between the solution of these heuristic algorithms and the optimal solution is difficult to measure.

Third, based on the above theoretically derived results, we further construct a quantitative model to calculate the effect of emission reduction caused by shared parking. Finally, the validity of the proposed model is verified by a real-world case study in Beijing, China.

Based on the results in Section IV, we have reason to believe that reducing the number of seeking parking spaces and traffic emissions could be achieved through the shared parking. However, it should note that there is a "scale effect", that is, although with the increase in the number of shared parking spaces, the average number of served P-users has increased, however, the actual number of served may decrease, like the minimum boundary shown in Figure 4, in some practical situations. This change cannot be ignored, which plays an important role in guiding how to management and control the parking demand in practice.

There are many possible future research opportunities. In this study, we only study the matching problem with certain parking supply and demand. Certainly, there are a lot of uncertainties in real life, which will lead to the start time and end time of parking uncertainty [15]. This optimal matching problem of parking supply and demand also has great challenges and practical significance. In addition, after reducing the number of cruise vehicles on the road, road traffic conditions will be improved. This will not only improve the efficiency of transport operations but also reduce the energy consumption. As a result, it is also a highly valuable research to quantify the impact of parking on energy saving and emission reduction by taking into account the change of road traffic operation.

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