A study on parking supply optimization in central business districts considering the two-way interaction between car traveling and parking

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This paper proposes a bilevel programming model to optimize the parking supply in a central business district (CBD) considering the interaction between car traveling and car parking. The upper model (UM) determines the number and locations of parking lots in a CBD with the objective of minimizing the average impedance of all car trips. The lower model (LM) is a modal split and assignment combination model for calculating the traffic flow under various parking supply schemes. In addition to the bilevel model, a gravity model (GM) is proposed to calculate the car trips that are induced by the added parking lots. The interaction between car traveling and parking can be simulated by the feedbacks between the UM and LM. A case study is performed with real data from Dalian City. The results show that there is a negative correlation between parking supply increments and the average traveling impedance when the number of parking spaces is lower than the optimal value; however, the average traveling impedance will start to increase with the increase in parking supply when the number of parking spaces is higher than the optimal value.

Keywords: traffic demand management, parking supply, interaction between car traveling and parking, modal split and assignment model

1. Introduction

Both car traveling and car parking are characteristics of urban traffic. The former refers to the traffic flow on the road network, while the latter forms the car occupancy of parking spaces. A car trip typically contains three parts: 1) parked cars at the origin enter a road network when travelers decide to use such a network for travel; as a result, parked cars become moving cars (this step can be disregarded because it is somewhat quick); 2) cars travel on the road network; and 3) cars are parked in parking lots after reaching their destinations; moving cars subsequently become parked cars. The sum of the impedances of the three parts forms the impedance of the entire trip.

The switch between moving cars and parked cars is determined by traveler mode choice behavior. Mode choice behavior and the parking impedance are significantly affected by parking supply, i.e., a higher parking supply will make parking easier, causing an increase in the number of travelers who will use cars. For example, the parking impedance will decrease in a central

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business district (CBD) if a large number of parking lots are available, and thus, a larger number of trips to the CBD will be car trips. However, as the number of car trips increases, the difficulty of parking in a CBD may increase. If the increase in car trips is small and the increase in the travel impedance can be compensated by a decreased parking impedance due to an increased parking supply, then the decision to increase the number of parking lots is justified. Otherwise, the increase in parking lots may be a mistake. Therefore, the parking supply in an area (for example, a CBD) may be optimized from this perspective.

The management of parking supply and demand can affect many aspects of urban transport systems (Young et al. 1991):

- the level of service, congestion and access on urban roads;

- the operational efficiency of public transport systems; and

- the safety, environmental quality and property values in a developed urban space.

Regarding these mechanisms, Dowling et al. (2017) found that drivers who arrive in search of parking find that all spaces occupied must move onto an adjacent block face. This search dynamic driven by the rate of drivers turned away from a full block face is representative of the impact of drivers searching for parking and, hence, the impact of parking on through traffic. Gallo et al. (2011) investigated the impact of the shift from car moving to car parking on congestion. These studies explained the short-term negative correlation between an insufficient parking capacity and traffic congestion.

However, if it is easier to park in a CBD, then more travelers will use their cars to travel to the CBD, and the amount of congestion in the CBD will increase. Morrall and Bolger (1996) showed that the proportion of downtown commuters using public transportation is inversely proportional to the ratio of parking stalls per downtown employee. Shoup (1999) suggested that an oversupply of parking exacerbates urban sprawl by significantly increasing the land area devoted to parking, which reduces the resultant density of commercial and residential development and encourages increased car dependence. Manville and Shoup (2005) investigated how off-street parking requirements affect urban form and determined that new off-street parking is continually supplied due to minimum parking requirements that make new developments contingent on the provision of parking spaces. However, the ample supply of off-street parking worsens traffic congestion and inhibits street life. Guo (2013) analyzed 770 households randomly selected from a household travel survey in the New York City region and showed that parking supply can significantly determine household car ownership decisions based on a nested logit model. From different perspectives, these researchers illustrated the inducing effects of parking supply on parking demand and showed the positive correlation between parking capacity and congestion. Coulias et al. (2016) found that the number of trips driven is significantly influenced by householder ratings of parking availability. Franco (2017) examined the effects of changes in the downtown parking supply on modal choice decisions.

The studies mentioned above show that a newly added parking supply can reduce the parking impedance in a CBD; however, it can also increase the congestion in and around the CBD by inducing more travelers to use cars to travel to the CBD. Therefore, in this paper, we study the optimization of parking supply in a CBD by considering the two-way interaction between car traveling and parking to minimize the average traveling time for travelers.

2. Literature review

2.1 Studies concerning the impact of parking supply
A substantial body of studies has shown that parking supply can influence the traffic situation, the modal splits of travelers, and parking demand. For example, Young et al. (1991) suggested

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that parking supply affects urban transport in many ways, such as the congestion and service level on the road network, the traveling efficiency of public transit, the safety of urban spaces and environmental quality. Merriman (1998) verified that parking supply may impact modal splits. Tam and Lam (2000) constructed a bilevel model to optimize car ownership with the constraints of the road and parking capacities and verified the influence of parking supply on path and destination choices. Hensher and King (2001) analyzed the effect of parking pricing and supply on whether travelers would like to drive and park in a CBD by conducting a stated preference survey of car drivers and public transport users. Habib et al. (2012) integrated parking behavior in activity-based travel demand modeling by using a sample data set that was collected in Montreal, Canada. Guo et al. (2012) proposed a proportional hazard-based duration model to analyze the influential factors related to on-street parking, including the effective lane width, the number of parking maneuvers, and occupancy. Su and Park (2015) and Yang et al. (2013) found that parking supply influences the departure time of trips during the morning peak hour. They suggested that congestion may be alleviated by dividing parking lots into reserved parking lots and free parking lots. Cao et al. (2017) proposed a macroscopic model to analyze the current conditions of cruising for parking and calculated the delays encountered by drivers while waiting for parking and the impact of such delays on the overall traffic stream.

2.2 Studies concerning parking demand

There is a considerable body of studies on the factors that can influence parking demand and that estimate the parking demand, namely, the number of car trips ending at the CBD studied in existing papers. Gur and Beimborn (1984) studied the major factors that affect the parking demand of each parking lot in urban areas, including walk to destination, parking fees, the intensity of enforcement, and supply-demand relationships. Bifulco (1993) applied a stochastic choice model to the path and parking levels of choice within a dynamic approach to analyze parking demand. Ibeas et al. (2011) employed multiple linear regression and geographically weighted regression models to estimate parking demand in areas with paid short-term parking systems. Angel et al. (2011) employed a multivariate linear regression and geographically weighted regression model to consider spatial disparity and estimated parking demand based on population density and car ownership. Cheng et al. (2012) established a parking demand-supply model based on a parking generation rate model to consider the influence of parking price and parking service on parking demand in a central commercial district. Cutter and Franco (2012) tested the hypothesis that "minimum parking requirements" bind to the majority of land uses by using data on suburban office, commercial, industrial and retail property sales from Los Angeles County as well as both direct and indirect approaches. Mackowski et al. (2015) and Qian and Rajagopal (2014) proposed a novel parking pricing strategy dependent on real-time sensing to manage parking demand. The strategy showed that setting appropriate parking prices is useful for reducing parking demand and solving parking congestion.

2.3 Studies concerning the optimization of parking supply

There are a small number of studies on parking supply optimization. For example, Iranpour and Tung (1989) proposed a new approach to the maximum parking supply capacity and the best layout for parking maneuvers with regard to a corner lot for parking spaces. García and Marín (2002) constructed a parking capacity and pricing model to minimize the total travel cost in a subnetwork of a multimodal transport system. Li et al. (2007) studied the optimal supply pattern on-street free of charge under a time-dependent network. Moradijoz et al. (2013) studied the optimal site and size of parking lots for vehicle to grid (V2G) from the perspective of the economic issue of parking lots. Wang et al. (2018) investigated the optimal parking supply under a policy of parking permit distribution, with the objectives of minimizing both the total travel cost and traffic emissions and providing a model for optimizing parking supply under a policy of free trading of parking permits. Few studies have investigated parking supply optimization considering the two-way interaction between parking supply and demand.

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In this paper, we adopt a dynamic view of the relationship between parking demand and supply. Specifically, we simulate the escalating process in which parking demand requires an increment in the parking supply and parking supply encourages parking demand. Integrating the mode choice model, queuing theory, the route choice model and the trip generation model, this paper optimizes the number of parking lots in a CBD in the context of long-term equilibrium of the interaction between parking supply and demand.

This paper makes several contributions. First, it proposes a problem regarding how to optimize both the location and amount of parking supply in a CBD considering the two-way interaction between car traveling and parking. Second, it describes the parking process using dummy links and establishes the corresponding impedance function, in which we mainly consider two exogenous variables (parking cost and walking time) and one endogenous variable (waiting time at the gate of parking lots); waiting time is determined based on queuing theory. Third, it conducts a case study based on personal trip survey data from Dalian City. The results show that there is negative feedback between parking supply increments and the average traveling impedance in the initial stage; additionally, an inflection point exists in the average travel time curve.

3. Model construction

3.1 Problem description and the model structure

Figure 1 shows the study area (Dalian, China). The initial origin-destination (OD) trips and modal split between buses, private cars, taxis, etc. within the segment of people using motorized vehicles (except motorbikes) are known. Travelers select modes based on a stochastic utility principle, and they select paths between origins and destinations based on the user equilibrium principle. The parking impedance at a destination is part of the impedance of an entire trip
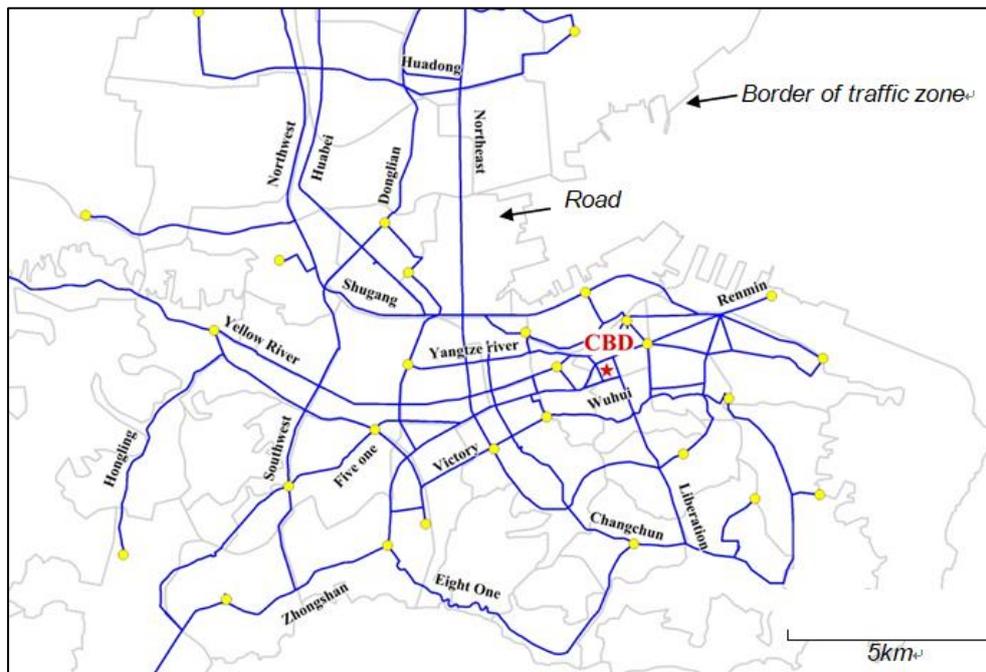

Figure 1.   Zones and the road network in the study area

According to the "trip impedance → traffic flow → mode choice → trip impedance" interaction, we link the activities of car traveling with car parking. By analyzing the equilibrium between the parking supply in a CBD and the average travel impedance of all car trips in the entire city, the

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optimal number of parking lots and their locations in a CBD can be determined. To calculate the parking impedance, we take parking lots along roadways as dummy nodes and connect them to the destinations by dummy links. The traffic impedance along a dummy link for a parking lot is equivalent to the parking impedance, including the waiting time at the gate of the parking site, the walking time and the parking cost.

The optimization of parking supply in the previously described CBD resembles a master-slave system. Thus, a bilevel programming model, in which the parking supply in the upper level determines the behaviors of followers in the lower level, can be employed. Followers' mode and path choice behaviors may affect the parking supply in the upper level. The input/output of the model and the equilibrium between parking and traveling are shown in Figure 2, where the upper model (UM) assesses whether the parking supply in a CBD is optimal. If "Yes", then the model outputs the result; otherwise, it determines the location of newly added parking lots based on the ratio between the degree of saturation of the links and the parking impedances. The lower model (LM) is a modal split and traffic assignment combination model, which is based on a stochastic utility principle and path selection behavior. The OD traffic is assigned by the user equilibrium traffic assignment model, which is estimated by the Frank-Wolfe (F-W) method, and the traffic impedances are fed back into the UM. In addition, a gravity model (GM) is added to the bilevel model to calculate the newly added car trips to a CBD that are induced by the increase in parking lots. The increased car trips will be added to the initial OD trips and employed as inputs to the next iteration.
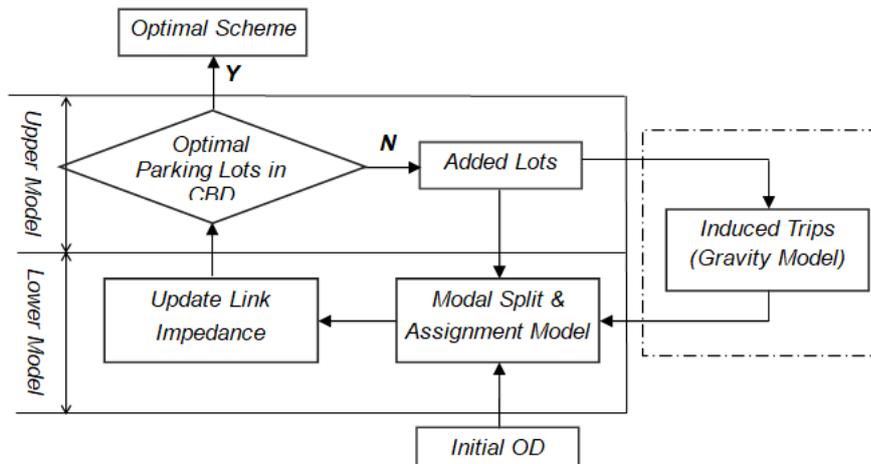

Figure 2.   Equilibrium structure of car parking and traveling

To describe parking, we use dummy link $a'_i \in A'$ to represent the process of parking and traveling from parking lots to the final destination. A parking lot can be treated as a node/intersection in the urban road network. It will be linked to the final destinations by a dummy link. When a single parking lot is used by persons with different destinations, the parking lot can be connected to more than one destination. The impedance of the dummy link includes the time cost (i.e., the waiting time at the gate of parking lots and the walking time from the parking lots to the destination) and the monetary cost (parking fee). In this way, we integrate the parking problem into a normal path search problem. Then, we use links $a_i \in A$ to represent normal roadways.
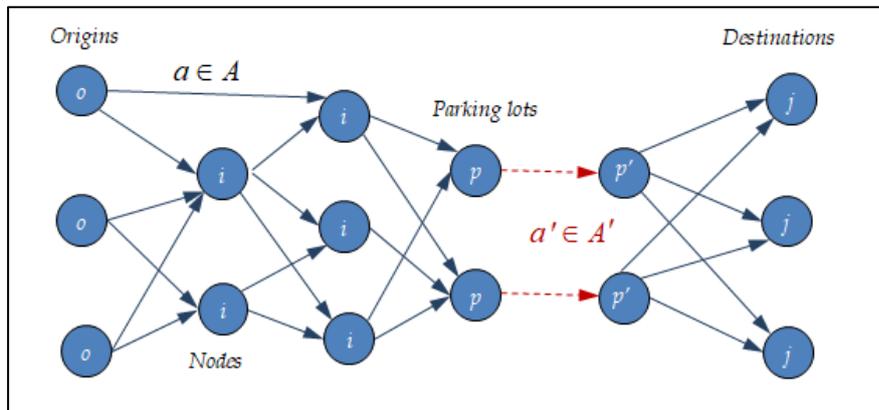
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Figure 3.   *Network of car parking and traveling*

3.2 Model assumptions

1) Travelers know the parking and road traffic situation;

2) Travelers select the path with the smallest impedance;

3) The service efficiencies at all parking lots are equivalent; and

4) On-street parking in a CBD is unavailable.

Assumptions 1 and 2 are commonly used in the field of urban transportation and were given in Wardrop's first principle, in which it is assumed that each traveler is identical, noncooperative and rational in selecting the shortest route and that travelers know the exact travel time they will encounter; that is, they know the parking and road traffic situation well (Sheffi, 1985). Assumption 3 is reasonable because the ability of the staff and the technology used in each parking lot in a CBD are usually quite similar; thus, little difference in the service efficiencies of parking lots can be found. Assumption 4 is reasonable because a CBD always faces the problem of road space shortage.

3.3 Model formulation

● Upper Model:

1) Decision variable

$p_{a'}^i$ = number of parking spaces in a lot (link a') in the ith round of calculation

2) Other variables and parameters

Z_1^i - Value of the objective function of the UM

x_a^i - Traffic flow on link a in the ith round of calculation

t_a^i - Impedance of link a in the ith round of calculation

θ_k - Parameters in the impedance function

$\overline{q}_{od}^i$ -Total of car o/d trips and bus o/d trips in the ith round of calculation；

q_{od}^i - Car OD trips in the ith round of calculation

q_{od}^0 -Initial car OD trips

χ_a^i - Ratio between link saturation and parking impedance in the ith round of calculation

U_d - Trips ending at zone d

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s - A constant representing the gradient of the increase in parking spaces in each loop; the smaller the value of s is, the higher the computational accuracy will be

t_{od}^i - Generalized impedance of the CBD in the ith round of calculation

$\tau_{aa'}$ - 1 means link a' connects link a; otherwise 0

3) Model structure

$$Min: Z_1^i = \left[\sum_a (x_a^i \times t_a^i) + \sum_{a'} (x_{a'}^i \times t_{a'}^i)\right] \Big/ \sum_o \sum_d q_{od}^i, \forall a \in A \quad \forall a' \in A' \tag{1}$$

$$\sum_o \sum_d q_{od}^i \geq \sum_o \sum_d q_{od}^0 \tag{2}$$

$$\chi_{a'}^i = \sum_a \left(\frac{V_a^i}{C_a} \times \tau_{aa'}\right) \Big/ t_{a'}^i, \forall a' \in A' \tag{3}$$

$$a' = \arg Min(\chi_{a'}^i) \tag{4}$$

$$\Delta p_{a'}^i = \begin{cases} s, If\ Z_1^i - Z_1^{i-1} < 0 \\ 0, Otherwise \end{cases} \tag{5}$$

$$p_{a'}^i = p_{a'}^{i-1} + \Delta p_{a'}^i \tag{6}$$

$$\overline{q}_{od}^i = k_1 U_o U_d \left(t_{od}^i\right)^{-k_0} \Big/ \sum_d U_d \left(t_{od}^i\right)^{-k_0} \tag{7}$$

Eq. (1) minimizes the weighted average traveling and parking impedances of all car trips. In this way, we can avoid situations in which the average traveling impedance for travelers ending at the CBD decreases significantly but the average traveling impedance for travelers who pass through or near the CBD increases. As shown in Eq. (2), the number of cars that arrive at the CBD in the ith round of calculations should not be less than the current number of cars to avoid situations in which the travel impedance of all car trips decreases but the travel impedance of car trips ending at the CBD increases. Eq. (3) is the ratio of the parking impedance to link saturation. Eq. (4) identifies the parking a' to be updated in the next iteration. Eqs. (5) and (6) update the parking capacities in the model, and in this paper, "s" is set as "5". Eq. (7) is a one-sided constrained GM, where $t_{od}^{-k_0}$ is determined by the LM and the increase in parking supply can influence $t_{od}^{-k_0}$ and, subsequently, the OD trips.

● Lower Model:

1) Decision Variable

$x_{a'}^i$ -Traffic flow to a lot (link a') in the ith round of calculation

f_{odk}^i -Traffic flow on path k between origin and destination in the ith round of calculation

2) Other Variables and Parameters

V_a^i -Maximum flow on link an in i^{th} round of calculation

C_a -Capacity of link a

δ_{aodk}^i -1 if link a in path k between origin and destination in the ith round of calculation; otherwise 0

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$\delta^i_{a'odk}$ -1 if link a' in path k between origin and destination in the ith round of calculation; otherwise 0

$\hat{q}^i_{od}$ -Total bus OD trips in the ith round of calculation

$\bar{q}^i_{od}$ -Total car OD trips and bus OD trips in the ith round of calculation

$\hat{u}^i_{od}$ -Minimum impedance of a bus between origin and destination in the ith round of calculation

u^i_{od} -Minimum impedance of a car between origin and destination in the ith round of calculation

θ -Parameter

α, β -Parameters, a=0.15, β=4

$t_a(0)$-Free-flow impedance on link a

Z^i_2 -Value of the objective function of the LM

$t^i_{a'}$ -Parking impedance to lot (link a') in the ith round of calculation

$X^i_{ka'}$- The kth type of parking impedance in a lot in the ith round of calculation. When k=1, $X^i_{ka'}$ represents the parking fee; when k=2, $X^i_{ka'}$ represents the walking time from park lot a' to the destination; when k=3, $X^i_{ka'}$ represents the waiting time at parking lot a'

c_1, c_2-Parking fees for indoor/outdoor parking

w -Duration of parking (given)

$\delta_{a'}$-1 means indoor parking; otherwise 0

$\lambda^i_{a'}$-Car arrival pattern (Poison distribution) in a lot (link a') in the ith round of calculation

d_1 -Walking distance for indoor parking to the gate of the parking lot

d_2 -Walking distance for outdoor parking to the gate of the parking lot

$d_{a'd}$ -Walking distance from a lot (link a') to destination d

v -Walking speed

$\mu^i_{a'}$ -The service speed at a lot entrance in the ith round of calculation

$\mu'^i_{a'}$ -The service speed at a lot in the ith round of calculation

$\lambda''^i_{a'}$ -Car leaving pattern at a lot in the ith round of calculation

$\gamma^i_{a'}$ -Turnover rate at a lot in the ith round of calculation

$\varepsilon^i_{a'}$ -1 if all lots are in use; otherwise 0

k_0, k_1 -Parameters in the GM

d_{CBD} -The destination (the CBD)

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3) Model Structure

$$Min: \quad Z_2^i = \sum_a \int_0^{x_a^i} t_a^i(w)dw + \sum_{a'} \int_0^{x_{a'}^i} t_{a'}^i(w)dw + \sum_{od} \int_0^{\hat{q}_{od}^i} (\frac{1}{\theta} \ln \frac{\omega}{\overline{q}_{od}^i - \omega} + \hat{u}_{od})d\omega \quad (8)$$

$$x_a^i = \sum_o \sum_d \sum_k f_{odk}^i \delta_{aodk}^i, \forall a \in A \quad (9)$$

$$x_{a'}^i = \sum_o \sum_d \sum_k f_{odk}^i \delta_{a'odk}^i, \forall a' \in A' \quad (10)$$

$$f_{odk}^i \geq 0, \forall o, d, k \quad (11)$$

$$\sum_k f_{odk}^i = q_{od}^i, \forall o, d \quad (12)$$

$$0 < \hat{q}_{od}^i < \overline{q}_{od}^i, \forall o, d \quad (13)$$

$$q_{od}^i + \hat{q}_{od}^i = \overline{q}_{od}^i, \forall o, d \quad (14)$$

$$\frac{1}{\theta} \ln \frac{\hat{q}_{od}^i}{\overline{q}_{od}^i - \hat{q}_{od}^i} + \hat{u}_{od}^i = u_{od}^i, \forall o, d \quad (15)$$

$$t_a^i = t_a(0) \times \left[1 + \alpha(x_a^i / C_a)^\beta \right], \forall a \in A \quad (16)$$

$$\delta_{aodk}^i = \begin{cases} 1, \text{If link } a \text{ on path } k \text{ from } o \text{ to } d \text{ in } i^{th} \text{round of calculation}; \\ 0, \text{Otherwise}; \end{cases} \quad (17)$$

$$\delta_{a'odk}^i = \begin{cases} 1, \text{If parking lot } a' \text{ on path } k \text{ from } o \text{ to } d \text{ in } i^{th} \text{ round of calculation}; \\ 0, \text{Otherwise}; \end{cases} \quad (18)$$

$$t_{a'}^i = \sum_{k=1}^3 \theta_k X_{ka'}^i, \forall a' \in A' \quad (19)$$

$$X_{ka'}^i = C_1 \times \lceil w / 0.5 \rceil + (1 - \delta_{a'}) \times C_2 \times \lceil w / 0.5 \rceil, \forall a' \in A', k = 1 \quad (20)$$

$$X_{ka'}^i = \left[d_{a'd} + \delta_{a'}^i \times d_1 + (1 - \delta_{a'}^i) \times d_2 \right] / v, \forall a' \in A', k = 2, d = d_{CBD} \quad (21)$$

$$X_{ka'}^i = \varepsilon_{a'}^i \times 1 / (\mu_{a'}^i - \lambda_{a'}^i) + (1 - \varepsilon_{a'}^i) \times \lambda_{a'}^i / \gamma_{a'}^i + 1 / (\mu_{a'}^{\prime i} - \lambda_{a'}^{\prime i}), \forall a' \in A', k = 3 \quad (22)$$

$$\gamma_{a'}^i = \lambda_{a'}^{\prime i} / p_{a'}^i, \forall a' \in A' \quad (23)$$

$$\varepsilon_{a'}^i = \begin{cases} 1, \text{ parking lot } a' \text{ is full}; \\ 0, \text{ parking lot } a' \text{ is not full}; \end{cases} \quad (24)$$

$$\lambda_{a'}^i = x_{a'}^i \quad (25)$$

Eq. (8) is the objective function of the modal split and traffic assignment combination model
(Sheffi, 1985), and $\frac{1}{\theta} \ln \frac{\omega}{\overline{q}_{od}^i - \omega} + \hat{u}_{od}$ is the excess demand function. Eqs. (9)-(14) are flow

constraints (should be conservative and nonnegative). Eq. (15) denotes that the bus travel
impedance is equivalent to the minimum car travel impedance on a link under equilibrium

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between modes (Sheffi, 1985). Eq. (16) is the link impedance function of normal links. Eq. (19) is the impedance function of dummy links. Eq. (20) represents the parking fee, Eq. (21) means the walking time from the parking lot to destination d, and Eq. (22) represents the waiting time at the parking lot on link a'. When the parking lot on link a' is not full, the waiting time can be calculated based on queuing theory; that is, the waiting time equals $1/(\mu_{a'}^i - \lambda_{a'}^i)$; when the parking lot is full, the waiting time is determined by the turnover rate of the parking lot, which can be calculated by Eq. (23). When using Eq. (19) to calculate the impedance, different methods should be adopted for two different cases (full queue or nonfull queue); thus, Eq. (24) is introduced to represent the status. Eq. (25) represents that $\lambda_{a'}^i$ is determined by the flow on link a'.

4. Model solution

In this paper, we estimate the UM and LM and then obtain the solution of the bilevel model by iterating the solutions of the UM and LM. The reason is that the bilevel model is not a convex function, and it will be very difficult to obtain the solution of the bilevel programming model directly. However, when the LM is considered alone, the number and location of parking spaces and OD trips will be treated as given constants in the LM; thus, Eq. (22) can be a monotonically increasing function that meets the requirement of applying the F-W approach. Moreover, in the LM, $X_{ka'}^i$ is an exogenous variable when k is 1 or k is 2 (shown in Eqs. (20) and (21)). In this case, the LM can be estimated by the F-W approach (Sheffi, 1985). Then, the solution of the bilevel model can be obtained.

To estimate the UM, we first set the initial solution. When the actual supply is much lower than the optimal supply, that is, the supply of parking lots lags behind the growth in cars, we set the actual supply as the initial solution to improve the efficiency of calculation. When the actual supply is higher than the optimal supply, that is, $Z_1^i - Z_1^{i-1} > 0$ after the first round of calculation, we set a smaller initial number according to the situation of the city.

The LM is a modal split and assignment combination model that can be estimated by the F-W method (Sheffi, 1985). The UM estimation steps are as follows:

Step 1: Initialize and calculate Z_1^0 based on the initial OD trips;

Step 2: Update the objective function to obtain new Z_1^i with the output from the LM;

Step 3: If $\Delta Z_1^i = Z_1^i + Z_1^{i-1} \geq 0$, then stop the calculation; otherwise, go to step 4;

Step 4: Determine link a, where parking lots should be added, with Eqs. (3) and (4); and

Step 5: Increase the number of parking lots on link a and maintain the capacities in other lots.

5. Empirical study

5.1 Data
Using Dalian as a case study area, we perform numerical analyses. As the number of cars has been rapidly increasing in Dalian but not enough new parking lots have been built, the lack of parking spaces has become a serious problem in the CBD. The traffic zones, CBD and road network are shown in Figure 1, where the dots represent the zonal centroids, the gray solid lines represent the zonal boundaries, and the dark solid line represents the arterials in the road network. In addition, the service speeds of the parking lots for arriving and leaving cars are 3 vehicles per minute and 2.4 vehicles per minute, respectively. The parking fees for outdoor and

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indoor parking lots are 2.5 and 2 yuan per 0.5 hour, respectively. The initial OD trips and travel times and costs for buses and cars during 7:30-8:30 am are selected from personal trip survey data from Dalian collected in 2011. Our team consists of the technical leader and database manager of the survey. In the survey, Dalian City is divided into 176 traffic analysis zones, and 1.5% of households (approximately 46,500 persons) are interviewed with regard to all of their day trips on a week day. Meanwhile, the travel speeds of 30 main roads and 25 bus routes are measured. The initial OD trips and travel times and costs for buses and cars during 7:30-8:30 am for our case study are only a small part of the dataset. It is easy for us to select the data from the database using several commands.

Additionally, using the survey data, the parameters of the GM (Eq. (7)) and parking impedance function (Eq. (19)) are calibrated (Table 1), where the R-square, t-statistic, P-value show that the calibration is valid.

Table 1.   Calibration of Eqs. (7) and (19)

Parameters	Coefficients	R-square	t-statistic	P-value	Lower 95%	Upper 95%
k_1	1.58	0.826	2.457	0.034	0.313	6.412
k_2	0.206		6.417	0.000	0.809	1.669
θ_1	3.995	0.806	0.923	0.380	-3.747	8.911
θ_2	3.016		2.243	0.052	-0.009	2.022
θ_3	1.982		5.037	0.001	1.799	4.732

Currently, 850 parking spaces in the CBD are shown in Table 2; we name this case Scenario A (the actual case).

Table 2.   Number of parking lots on links

Name	Link 1	Link 2	Link 3	Link 4
Lots	0	330	310	210

5.2 Output Analyses

The solution of the Bi-level model proposed in this paper is obtained using Matlab (CUP: Core i3, 3.4GHz). To test the efficiency of the algorithm, we use the combination of tic/toc functions. The elapsed time for estimating the LM is 4.52 seconds, and the elapsed time of the main program is 182.31 seconds.

First, to analyze the impacts of the location of the added parking spaces on the average trip time and the parking impedance of car trips ending at the CBD, we set 16 scenarios; in these scenarios, the number of parking spaces is the same as the number of parking spaces in Scenario A. The 16 scenarios are 16 cases obtained by randomly allocating the 850 parking spaces to 4 links. Figure 4 shows the differences between the 16 scenarios and Scenario A, where the horizontal axis represents the differences in the parking impedance of car trips ending at the CBD and the vertical axis represents the differences in the average travel impedance of all car trips. The dot size indicates the increasing ratio of the car mode, and the circle size indicates the decreasing ratio of the car mode. The car mode is negatively correlated with the parking impedance.

To further analyze the impacts of the location of parking spaces, we randomly select four scenarios (one from each quadrant in Figure 4) to show the advantages and disadvantages of

each scenario (Table 3). In Scenario 1, both the average travel impedance of car trips and the parking impedance of car trips that end at the CBD increase. In Scenario 2, the average impedance of car trips increases, but the parking impedance of car trips that end at the CBD decreases. In Scenario 3, in which the service level of the road network is high and the parking supply is adequate, both impedances decrease. In Scenario 4, the modal split of the car decreases, whereas the parking impedance of car trips increases; thus, Scenario 4 is acceptable. The average travel impedance and car mode of trips that end at the CBD differ because the changes in parking supply and the scenarios in Quadrant III are better than those in the other quadrants.
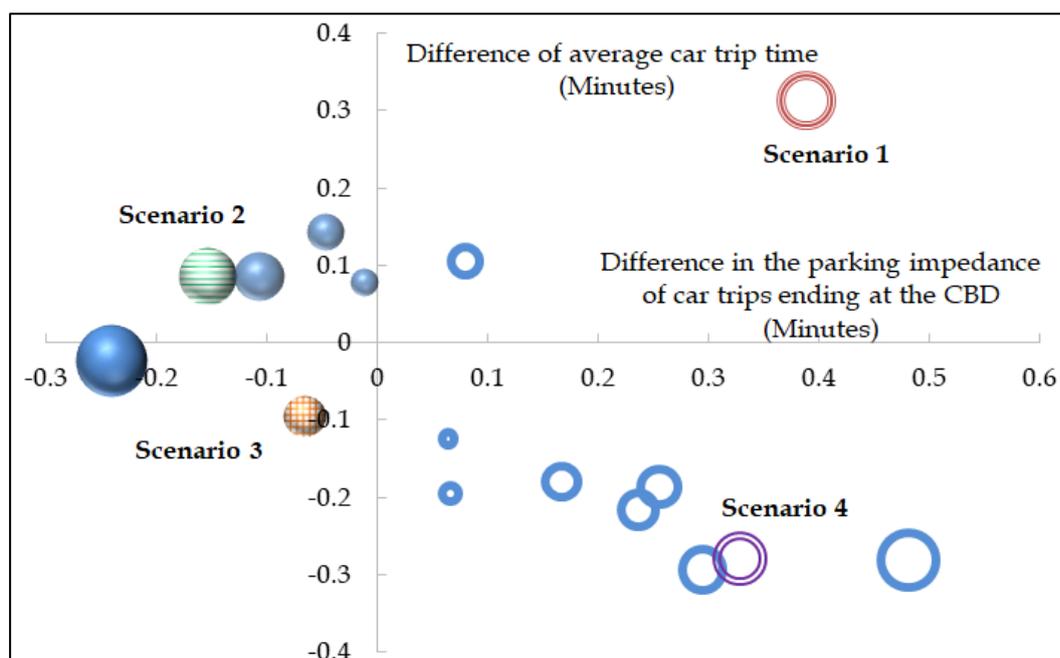

Figure 4.   Comparison between 16 scenarios and Scenario A

Table 3.   Number of parking spaces supplied in the four scenarios

	Link 1 (Zhongshan Road)	Link 2 (Wuhui Road)	Link 3 (Jiefang Road)	Link 4 (Youhao Road)
Scenario 1	10	195	450	195
Scenario 2	170	390	65	225
Scenario 3	65	315	180	290
Scenario 4	60	275	60	455

Second, the parking supply is discussed. By estimating the bilevel model, the optimized parking supply is obtained; we name it Scenario B. Table 4 shows the distributions of parking lots in Scenarios A and B, which are used as base scenarios to further analyze the effectiveness of this paper's bilevel programming model. From the LM, we learn that the average impedances of car trips that end at the CBD in Scenarios A and B are 39.19 and 35.63 minutes, respectively; here, the travel impedances are 30.12 and 30.18 minutes, respectively, whereas the parking impedances are 8.98 and 5.45 minutes, respectively. The average impedances of all car trips in Scenarios A and B are 31.72 and 31.51 minutes, respectively.

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Table 4.   Number of parking spaces supplied in Scenarios A and B

	Link 1 (Zhongshan Road)	Link 2 (Wuhui Road)	Link 3 (Jiefang Road)	Link 4 (Youhao Road)	Total
Scenario A	0	330	210	310	850
Scenario B	50	345	295	360	1050

Compared with the actual case, both the travel and parking impedances in Scenario B decrease, and the number of car trips to the CBD increases from 949 vehicles/hour to 1068 vehicles/hour. On the one hand, the increase in parking supply reduces the parking impedance; on the other hand, it encourages more travelers to use cars when traveling to the CBD. Moreover, compared with Scenario A (actual case), Scenario B (optimal case) has 200 newly added parking lots, which makes the number of car trips with the CBD as the destination increase from 6551 persons/hour to 6626 persons/hour. Clearly, increasing the number of parking lots may effectively increase the accessibility of the CBD and, therefore, the number of car trips to the CBD. Although more cars will enter the CBD in this scenario, the average traffic impedance of all car trips will continue to decrease due to the decrease in the parking impedance.

Based on the analysis in Tables 3 and 4, we find that both the number and locations of parking lots in the CBD should be optimized. Inappropriate lot locations may cause more cruising and congestion because a small increment in car traffic on some saturated roadways might result in serious congestion. Locating parking lots near saturated roadways in the CBD will greatly increase the traffic environmental load. Table 4 also illustrates that in the optimal situation, although the traffic on all roadways increases, the major increments are on the unsaturated roadways, such as Jiefang Road and Youhao Road. Only a few parking lots are located along Zhongshan Road, which is a nearly saturated roadway. Zhongshan Road is the main entrance to the CBD, and the parking supply on Zhongshan Road might reduce the cruising of cars ending at the CBD.

Third, analyzing the changes in the variable values during the solution can help in understanding the impact of the parking supply in a CBD on car use. In this case, we replace "Step 3: If $\Delta Z_1^i = Z_1^i + Z_1^{i-1} \geq 0$, then stop the calculation; otherwise, go to step 4;" in "The UM solving steps" with "Step 3: If the total is 1425, then stop the calculation; otherwise, go to step 4;"; 1425 is a number larger than the optimal number 1050. Figures 5 and 6 are obtained.

Figure 5 shows the changes in the modal split of car trips ending at the CBD, the parking impedance and the travel impedance of car trips with the increment in the number of parking spaces in the CBD. The modal split of cars positively relates to parking capacity. When 600-975 parking spaces are supplied, with the increment in the number of parking spaces, the modal split of cars rapidly increases; however, when more than 975 parking spaces are supplied, the modal split of cars slowly increases with the increment in parking spaces. The reason is that when the number of parking spaces increases from 600 to 975, both the parking impedance and the travel impedance rapidly decrease, while beyond 975, although the parking impedance and the travel impedance are still negatively correlated with parking supply, the influence of the increment in the number of parking spaces on the parking and travel impedances is negligible. Moreover, Figure 6 shows that the average impedances of all car trips decrease and then increase as the parking supply increases. The capacity of 1050 lots is the turning point, which may be the optimal parking supply in the CBD. The number of parking lots in each site for the optimal case is shown in Table 4.
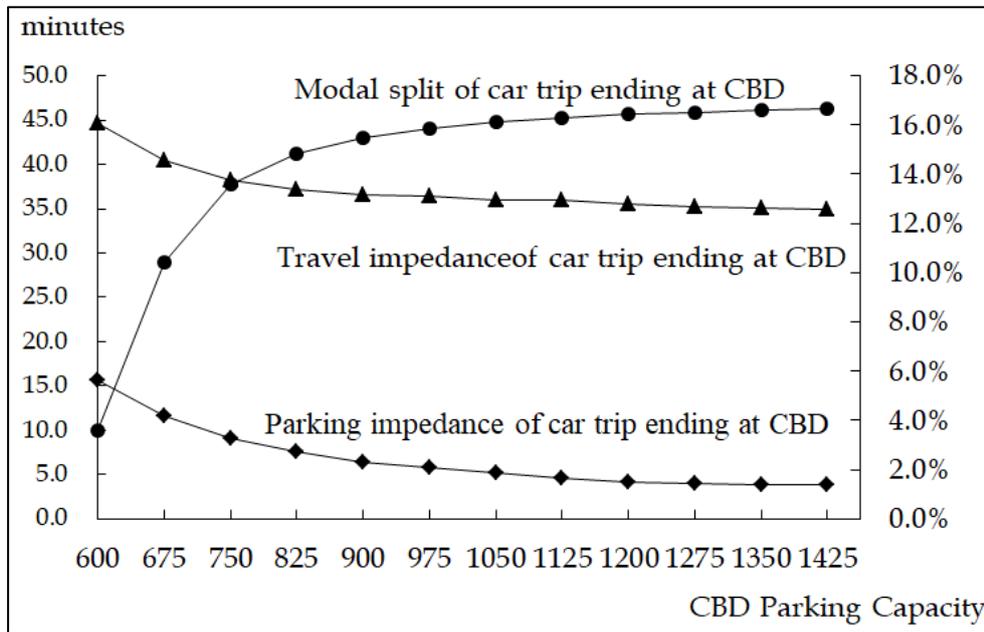
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Figure 5.   *Comparison between 16 scenarios and Scenario A*

The solution for the situation in which the impacts of parking supply in the CBD on car traffic are neglected is shown in Table 5. For comparison, we name this case Scenario C. In Scenario C, 1255 parking lots are offered in the CBD, which is 205 more than the optimal number.

Furthermore, we set Scenario C, in which the impacts of the parking supply on car trips not ending at the CBD are neglected. In this case, the objective function of the UM will be changed to Eq. (26).

$$Min: Z_1^i = \sum_o (q_{od}^i \times W_{od}) \Big/ \sum_o q_{od}^i, \forall a \in A, \quad \forall a' \in A', d = d_{CBD} \qquad (26)$$

$$W_{od} = \min \sum_k \sum_a t_a \times \delta_{aodk}^i \times \tau_k^{od}, \quad \forall o \in O, d = d_{CBD} \qquad (27)$$

τ_k^{od} - 0-1 variables; if $\tau_a^{od} = 1$, then link k is the shortest path over the set of all paths from origin to destination

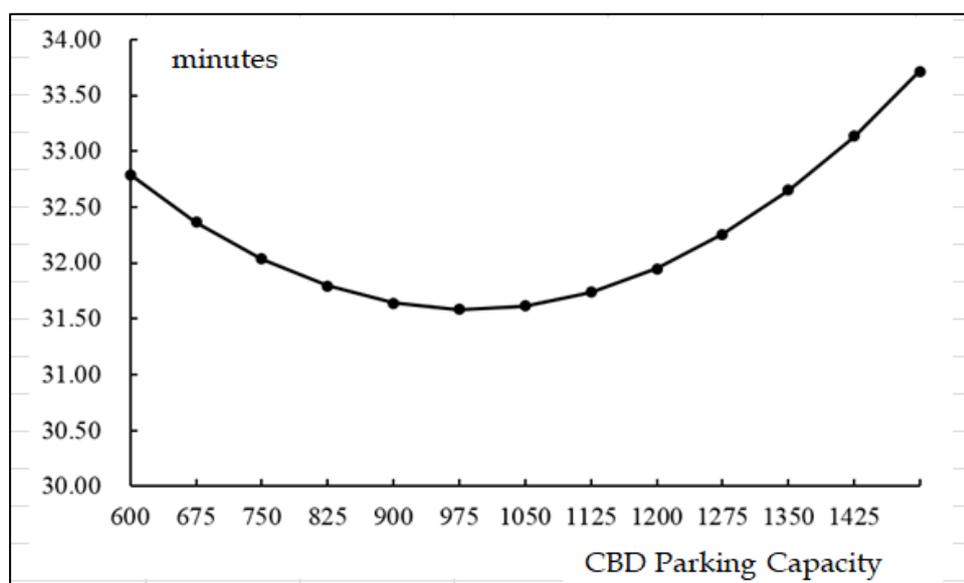The solution for Scenario C is shown in Table 5.

Figure 6.   *Impedances of car trips corresponding to different parking supplies*

Table 5.   **Parking supply in the CBD in Scenario C**

	Link 1 (Zhongshan Road)	Link 2 (Wuhui Road)	Link 3 (Jiefang Road)	Link 4 (Youhao Road)	Total
Parking Lots	320	315	345	275	1255

As the busiest area in a city, the volume of cars in a CBD is always significant. A small increase in the traffic on some roads in a CBD may induce a significant increase in the travel impedance, and the effects may spread to the entire road network and cause significant congestion. Because the parking supply in a CBD may change the modal splits of trips to the CBD, the equilibrium between the traffic flows and the service level of the road network in Scenario B (optimal case) and Scenario C (oversupply case) should be compared.

Figure 7 shows the traffic speeds on the four links in Scenarios C and B. Compared with Scenario B (optimal case), the speeds on Links 1 and 2 decrease in Scenario C, whereas the speeds on Links 3 and 4 increase. However, the decrease is smaller than the increase. For the four directions in Links 1 and 2, the average travel speeds decrease by 15.2%, whereas the average travel speeds increase by only 9.12% for the three directions in Links 3 and 4. Due to the oversupply of parking lots in Links 1 and 2, more cars may enter the CBD, and more cars (including cars that park in parking lots along Links 3 and 4 in Scenario B) will use parking lots along Links 1 and 2. Thus, the oversupply of parking lots will induce more car trips to the CBD, intensifying the near saturation of links, and congestion may spill over to the entire local network. For example, in Scenario C, because Link 1 is more congested, some travelers who used to pass through Link 1 will change their path to Link 5, which will then lead to a new equilibrium on the road network. In this case, both speeds on Links 5 and 6 decrease in Scenario C. Additionally, because there are more travelers who pass through Link 7 and then arrive at parking lots on Link 1, the travel speed on Link 7 also decreases in Scenario C.
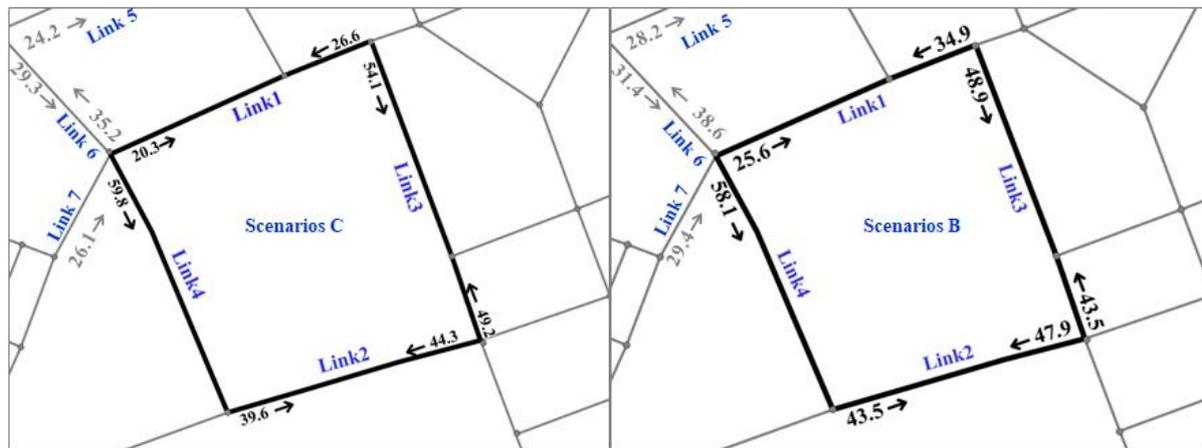
Figure 7.   Traffic speeds (m/h) in Scenarios C and B

The above analyses show that it is necessary to optimize the parking supply in the CBD according to the traffic flow on the entire network to make the CBD more attractive and active and to ensure fairness for traveler. Basically, the area surrounding the CBD has many arteries; thus, an oversupply of parking lots may induce congestion on these arteries, which will affect the cars passing through the CBD. For example, in Scenario C (oversupply case), although parking is easy, the service level in the entire road network is worse. Therefore, it is not a desirable scheme.

We also need to consider the external costs (Shoup, 1997) and benefits when optimizing the parking supply in the CBD because the parking capacity will directly change the traffic flows on the surrounding roadways and might indirectly affect the commercial and business activities and the land use pattern in the CBD.

Additionally, the method proposed here is useful for practitioners and policy-makers. On the one hand, in some countries such as China, mayors are encouraging an increment in the parking lots in the CBD based on the idea that more parking lots may make car parking easier and quickly realize the road space. However, they neglect the incentive of such an increment with regard to the mode choice of trips to the CBD. For example, some Chinese cities have lowered the entry criteria to let more bodies establish parking lots in the CBD[3]. Increasingly more cities in China, such as Yushan[4], Nanping[5], Leshan[6], and Liaocheng[7], have started to formulate a specific plan for parking supply with technical support from experts in transport planning or urban planning.

 On the other hand, some developed countries have adopted measures to control parking supply with the aim of alleviating congestion in the CBD. For example, in 2009, Seoul, South Korea, set the upper limit of parking supply. In 2003, London abandoned its requirement for a minimum parking supply but set an upper limitation. Recently, Copenhagen, Denmark, has reduced parking supply in the CBD by 2% annually[8].

In fact, our case study shows that there is a negative feedback between an increment in the parking supply and the traveling impedance in the initial stage of increasing the parking supply, while when the parking capacity is larger than the projected optimal capacity, the traveling impedance will start to increase with the increment in the parking supply. Additionally, based on

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[3] http://www.chezhubidu.com/detail/298331

[4] http://www.zgys.gov.cn/xwzx/gsgg/content_7210

[5] http://www.npgh.gov.cn/cms/html/npscxghj/2014-02-18/2115525077.html

[6] http://sc.sina.com.cn/news/m/2018-02-02/detail-ifyrcsrw6921743.shtml

[7] http://www.liaocheng.gov.cn/xxgk/szfbmxxgk/sghj/201809/P020180921383374855349.pdf

[8] http://www.tranbbs.com/Advisory/Evaluate/Advisory_142565.shtml

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our proposed method, the optimal scale and location of parking spaces in the CBD can be determined.

In this case, our study can provide a theoretical basis for practitioners and policy-makers. Using our model, they can determine the optimal parking capacity in their CBD and then evaluate whether to encourage or control parking supply.

6. Empirical study

This study proposes a bilevel programming model that can be employed to optimize the parking supply in an area (i.e., a CBD) in the context of interactions between car parking and car traveling based on queuing theory and a generalized traffic impedance (parking one + travel one). The case study of Qingniwa (CBD) in Dalian illustrates that the modal split of car trips that end at a CBD and the travel impedance will increase as the parking capacity increases, whereas the parking impedance will decrease. The average impedance of all car trips decreases and then increases with an increase in the parking supply of a CBD. Therefore, additional parking capacity in a CBD may not be beneficial because an optimal parking supply in the entire city is needed. Finding the optimized scenario is crucial for parking supply planning in a CBD. When the parking supply is less than the optimal parking supply, it should be increased. Otherwise, the parking supply should be decreased, and parking efficiency should be increased.

Additionally, the method of optimizing parking supply in this paper can provide a theoretical basis for practitioners and policy-makers to determine the optimal parking capacity in their CBD and then improve the traffic situation of the city by encouraging or controlling parking supply.

Acknowledgments

References

Angel, I., Ruben, C., Luigi, O., and Jose, L.M. (2011). Modeling demand in restricted parking zones. *Transportation Research Part A*, (45): 485-498. doi:10.1016/j.tra.2011.03.004

Bifulco, G.N. (1993). A stochastic user equilibrium assignment model for the evaluation of parking policies. *European Journal of Operational Research*, 71(2): 269-287. doi:10.1016/0377-2217(93)90054-Q

Cao, J., Menendez, M., Waraich, R. (2017). Impacts of the urban parking system on cruising traffic and policy development: the case of zurich downtown area, switzerland. *Transportation*, (1), 1-26.

García, R., Marín, A. (2002). Parking capacity and pricing in park'n ride trips: a continuous equilibrium network design problem. *Annals of Operations Research*, 116(1-4), 153-178.

Cheng, T.X., Tai, M.M., Ma, Z. (2012). The model of parking demand forecast for the urban CCD. *Energy Procedia*, (16): 1393-1400. doi:10.1016/j.egypro.2012.01.221

Cutter, W.B., and Franco, S.F. (2012). Do parking requirements significantly increase the area dedicated to parking? A test of the effect of parking requirements values in Los Angeles County. *Transportation Research Part A*, (46): 901-925

Dowling, C., Fiez, T., Ratliff, L., Zhang, B. (2017). How much urban traffic is searching for parking?.

Franco, S. F. (2017). Downtown parking supply, work-trip mode choice and urban spatial structure. *Transportation Research Part B Methodological*, 101, 107-122.

EJTIR **19**(1), 2019, pp.24-42   41
Yang and Chen
A study on parking supply optimization in central business districts considering the two-way interaction between
car traveling and parking

Gallo, M., D'Acierno, L., and Montella, B. (2011). A multilayer model to simulate cruising for parking in urban areas. *Transport Policy,* (18): 735-744. doi:10.1016/j.tranpol.2011.01.009

Goulias, K., Davis, A. W., Lee, J., Lundberg, A., & Mcbride, E. (2016). Behavioural micro-dynamics of car ownership and travel in the seattle metropolitan region from 1989 to 2002. *European Journal of Transport & Infrastructure Research*, 16(4), 735-753.

Guo, H., Gao, Z., Yang, X., Zhao, X., and Wang, W. (2012). Modeling travel time under the influence of on-street parking. *Journal of Transportation Engineering*. 138(2): 229-235. doi:10.1061/(ASCE)TE.1943-5436.0000319

Guo, Z. (2013). Does residential parking supply affect household car ownership? the case of new york city. *Journal of Transport Geography*, 26(1), 18-28.

Gur, Y.J., and Beimborn, E.A. (1984). Analysis of parking in urban centers: equilibrium assignment approach. *Transportation Research Record.* (957): 55-62

Habib, K.M., Morency, C., and Trépanier, M. (2012). Integrating parking behaviour in activity-based travel demand modelling: investigation of the relationship between parking type choice and activity scheduling process. *Transportation Research Part A,* (46): 154-166. doi:10.1016/j.tra.2011.09.014

Hensher, D.A., and King, J. (2001). Parking demand and responsiveness to supply, pricing and location in the Sydney central business district. *Transportation Research Part A,* (35): 177-196. doi:10.1016/S0965-8564(99)00054-3

Ibeas, Á., Cordera, R., dell'Olio, L.G., and Moura, J.L. (2011): Modelling demand in restricted parking zones. *Transportation Research Part A,* (45): 485-498. doi:10.1016/j.tra.2011.03.004

Iranpour, R., and Tung, D. (1989). Methodology for optimal design of a parking Lot. *Journal of Transportation Engeering* (115): 139-160. doi:10.1061/(ASCE)0733-947X(1989)115:2(139)

Li, Z., Huang, H., Lam, W. H. K., & Wong, S. C. (2007). Optimization of time-varying parking charges and parking supply in networks with multiple user classes and multiple parking facilities. *Tsinghua Science and Technology*, 12(2), 167-177.

Mackowski, D., Bai, Y., and Ouyang, Y. (2015). Parking space management via dynamic performance-based pricing. *Transportation Research Part C* (7): 170-191. doi:10.1016/j.trc.2015.05.021

Manville, M., and Shoup, D. (2005). Parking, people, and cities. *Journal of Planning and Development,* (131): 233-245. doi:10.1061/(ASCE)0733-9488(2005)131:4(233)

Merriman, D.(1998). How many parking spaces does it take to create one additional transit passenger? *Regional Science and Urban Economics,* (28): 565-584. doi:10.1016/S0166-0462(98)00018-0

Moradijoz, M., Moghaddam, M. P., Haghifam, M. R., Alishahi, E. (2013). A multi-objective optimization problem for allocating parking lots in a distribution network. International Journal of Electrical Power & Energy Systems, 46(46), 115-122.

Morrall, J., Bolger, D. (1996). The relationship between downtown parking supply and transit use. *Ite Journal*, 66(2), 32-34,36.

Qian, Z.S, and Rajagopal, R. (2014). Optimal occupancy-driven parking pricing under demand uncertainties and traveler heterogeneity: a stochastic control approach. *Transportation Research Part B,* (67): 144-165 (2014). doi:10.1016/j.trb.2014.03.002

Sheffi Y, (1985). Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods, USA, Prentice-Hall, Inc., Englewood Cliffs

Shoup, D.C. (1997). The high cost of free parking. *Journal of Planning Education Research,* (17): 3-20

Shoup, D.C. 1999. The trouble with minimum parking requirements. Transportation Research Part A (33): 549-574. doi:10.1016/S0965-8564(99)00007-5

Yang and Chen
A study on parking supply optimization in central business districts considering the two-way interaction between car traveling and parking

Su, P., and Park, B.B. 2015. Auction-based highway reservation system an agent-based simulation study. Transportation Research Part C Emerging. Technologies (60): 211-226. doi:10.1016/j.trc.2015.07.018

Tam, M.L., and Lam, W.H.K. 2000. Maximum car ownership under constraints of road capacity and parking space. Transportation Research Part A (34): 145-170. doi:10.1016/S0965-8564(98)00070-6

Wang, Jing, X. Zhang, and H. M. Zhang. 2018. Parking permits management and optimal parking supply considering traffic emission cost. Transportation Research Part D.

Yang, H., Liu, W., Wang, X., and Zhang, X. 2013. On the morning commute problem with bottleneck congestion and parking space constraints. Transportation Research Part B (58): 106-118. doi:10.1016/j.trb.2013.10.003

Young, W., Thompson, R.G., and Taylor, M.A.P. 1991. A review of urban car parking models. Transport Reviews (11): 63-84