J Syst Sci Syst Eng (Feb 2018) 27(1):24-45
DOI: 10.1007/s11518-017-5352-6

ISSN: 1004-3756 (Paper) 1861-9576 (Online)
CN11-2983/N

CHARGING STATION PLANNING FOR PLUG-IN ELECTRIC VEHICLES

Zhihong Zhu[1] Ziyou Gao[1,2] Jianfeng Zheng[3] Haoming Du[1]

[1]*Institute of Transportation System Science and Engineering, Beijing Jiaotong University, Beijing, 100044, China*
12114196@bjtu.edu.cn, zygao@bjtu.edu.cn (✉), 12114197@bjtu.edu.cn,

[2]*MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, Beijing, 100044, China*

[3]*Transportation Management College, Dalian Maritime University, Dalian, 116026, China*
jfzheng@dlmu.edu.cn

Abstract

A novel model for the charging station planning problem of plug-in electric vehicles is proposed in this paper considering the users' daily travel. With the objective of minimizing the total cost, including the charging stations' cost (including installing cost and management cost) and the users' cost (including station access cost and charging cost), the proposed model simultaneously handles the problems where to locate the charging stations and how many chargers to be established in each charging station. Considering that different users may have different perception of station access cost and charging cost, two cases (i.e., homogeneous users and heterogeneous users) are typically investigated. The impacts of different discount rates, operating period of the charging stations, number of electric vehicles and number of charging stations on the location of the charging station are also studied. The simulation results not only show that it is very important to locate the charging stations according to the traveling behavior of users, but also verify the validity of the proposed model.

Keywords: Electric vehicles, charging station, location problem

1. Introduction

1.1 Background

Electric vehicles (EVs), as a new type of alternative fuel vehicles, have received great interest during the past decades. They have become an even greater concern in recent years for their advantages of low energy consumption and emission, energy-efficient, noiseless, etc. Emerged as one of the most practical and feasible alternative fuel solutions, EVs have played an important role in solving environment pollution and saving energy.

EVs are classified into three major categories by their fuel consumption technology: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Both PHEVs and BEVs are also referred to as plug-in electric vehicles (PEVs), since they are designed to be recharged by plugging into the power grid. As EVs enter the market, the location of the charging stations for PEVs has been regarded to be one of the biggest concerns. The current insufficient of public charging infrastructures is one of the major barriers to mass household adoption of EVs. Where and how many charging stations should be built to satisfy the basic charging demand? This question is important in the sense that, as many studies have concluded, the availability of convenient and affordable recharging infrastructure will directly affect customers' decision of purchase and in turn affect the popularity of PEVs.

At present, many cities and regions have started building electric vehicle charging stations, but still have not formed a complete and sophisticated layout planning system, not to mention the large scale of the construction (Li et al. 2011). To meet the expected charging demand from the growing EV fleet, both utility and oil companies in China have recently released their EV charging infrastructure deployment plans (Liu 2012). Thus the layout planning and construction of the charging stations will enter the big scale and networking era, and the research on the planning and location of charging stations are also imminent and important.

1.2 Literature Review

Research into methods for alternative fuel infrastructure planning has received increasing attention in recent years (Sathaye and Kelley 2013). These methods have generally been aimed at determining minimum needs or optimizing the location and timing of transportation fueling station deployment on networks (e.g., Lin et al. 2008, Lim and Kuby 2010, Kim and Kuby 2012, Dagdougui 2012, Kim and Kuby 2013, Yildiz et al. 2016, Zhao and Ma 2016).

With the development of EVs, many studies have begun to investigate the location of public charging stations. Frade et al. (2011) formulated a maximum covering model to locate a certain number of charging stations to maximize the demand covered within a given distance. Andrews et al. (2013) studied how the EVs of today would perform in meeting the driving needs of vehicle owners, and proposed an optimization model to find locations for charging stations needed to support EV usage. Mak et al. (2013) developed robust optimization models that aid the planning process for deploying battery-swapping infrastructure and studied the potential impacts of battery standardization and technology advancements on the optimal infrastructure deployment strategy. Using the concepts of set- and maximum-coverage, Wang and Lin (2013) formulated the capacitated multiple-recharging-station-location models, using a mixed integer programming method, based on a vehicle-refueling logic. In order to adapt the matching and planning requirements of charging station in the EVs marketization application, with related layout theories of the gas stations, Wang et al. (2013) established a location model of charging stations based on electricity consumption along the roads among cities and presented a quantitative model of charging stations based on the conversion of oil sales in a certain area. Avci et al. (2014) built a model that highlights the key mechanisms driving adoption and use of EVs in switching-station-based EV system and contrast it with conventional EVs. Payam et al. (2014) presented a Mixed-Integer Non-Linear (MINLP) optimization approach for optimal placing and sizing of the fast charging stations. Chung et al. (2015) formulated a multi-period optimization model based on a flow-refueling location model for strategic charging station location planning and proposed two myopic methods and developed a case study based on the real traffic flow data of the Korean Expressway network in 2011. Schneider et al. (2014) and Hiermann et al. (2016) all studied the electric vehicle-routing problem with time windows and recharging stations.

Some literatures have investigated the charging infrastructure location problem based on travelers' activities or parking behaviors. Specially, Xi et al. (2013) developed a simulation-optimization model that determined where to locate electric vehicle chargers to maximize the EV service levels. It was explicitly designed to model slow charging technologies and accounts for the impact of EV driving patterns and the chargers installed on flows that can be served. Chen et al. (2013) developed a mixed integer programming problem for optimal EV-charging-station location assignments using the parking information to determine public (non-residential) parking locations and durations. Dong et al. (2014) proposed an activity-based assessment method to evaluate BEV feasibility for the heterogeneous traveling population in the real world driving context and examine the impact of different deployment levels of public charging infrastructure on reducing BEV range anxiety (i.e., the fear that the vehicle has insufficient range to reach the destination). Shahraki et al. (2015) proposed an optimization model based on vehicle travel patterns to capture public charging demand and select the locations of public charging stations to maximize the amount of vehicle-miles-traveled (VMT) being electrified.

In addition, the network equilibrium problems have also been considered in a few studies. He et al. (2013) developed an equilibrium modeling framework to determine an optimal allocation of a given number of public charging stations among metropolitan areas in the region. The modeling framework maximized social welfare associated with the coupled transportation and power transmission networks. Jiang et al. (2014) presented an equilibrium-based analytical tool for quantifying travel choice patterns in urban transportation networks to consider mixed gasoline and electric vehicular flows, and their combined choices of destination, route and parking subject to the driving range limit. Considering the limited driving range and the recharging need of EVs, He et al. (2014) investigated the network equilibrium problems with BEVs. They assumed that drivers of EVs select paths to minimize their driving times while ensuring not running out of charge. He et al. (2015) first developed a tour-based network equilibrium model to optimally locate public charging stations for EVs on a road network, considering drivers' spontaneous adjustments and interactions of travel and recharging decisions.

EVs, as a new travel mode of friendly environment, have attracted more and more concerns. However, because that the number of electric recharging stations is still small compared with that of conventional fuel stations, the limited range of EVs becomes a critical constraint in purchasing and operational decisions (Pelletier et al. 2016). Therefore, the planning and layout of charging stations is an urgent problem for the government. Focusing on different practical problems, the previous studies have investigated the charging infrastructure location problem taking different objectives and various constraints into account (Zhu et al. 2016). Different from the previous studies, this paper will study the charging station planning problem based on the following considerations. First, travelers may prefer to charge their EVs during the middle of the workday, most conveniently at their work locations when their vehicles would be idle for extended amounts of time for charging (Dashora et al. 2010). Second, different travelers may have different perceptions of station access cost they spend from the charging stations to their destinations and charging cost in choosing charging stations. Third, the government planning often aims to minimize the total social cost. This paper will present a minimum cost model to locate fixed number of charging stations at commuters' destinations considering their behaviors in choosing charging stations.

1.3 Objectives and Contributions

The objective of this paper is to formulate a mathematical model to optimize the location of charging stations and the number of chargers in each station to meet the charging demand and minimize the total cost.

The contribution of this paper can be summarized as follows. First, a novel model of solving the charging station location problem (CSLP) is proposed based on the users' daily travel. In the model, both the charging stations' cost (including installing cost and management cost) and the users' cost (including station access cost and charging cost) are taken into account for calculating the total cost. Second, considering that different users may have different perceptions of station access cost and charging cost, the CSLP was respectively investigated based on the homogeneous users and heterogeneous users. Particularly, for homogeneous users, the impact of the unit charging prices for different charging stations on the users' choice and the location of the charging stations is discussed. Third, the effects of different discount rates, operating periods of the charging station, number of EVs and number of charging stations on the CSLP are also discussed in the case study.

For the remainder, Section 2 describes the problem, and gives the related assumptions and notations. Section 3 proposes and analyzes the CSLP model. Section 4 gives the case study and reports the related results, and section 5 concludes the study.

2. Problem Description, Assumptions and Notations

2.1 Problem Description

Because of the characteristics of low pollution and emissions, EVs have good prospects for development. With the large-scale construction of charging facilities, how to make scientific and rational allocation of these charging infrastructures has become one of the urgent problems.

In real life, it is becoming more and more popular to use the PEVs. Every day, travelers will go to their destinations, such as workplace, school, shopping mall etc. to conduct various economic and social activities from their origins. After finishing the activities, they will return to their origins to complete a round trip. In order to ensure there is sufficient power to complete the trip, many travelers have to charge their PEVs during the trip. Then, where the charging stations should be built to meet the charging demand is the problem here we will solve. From the view of the government, it is better to reduce the budget as much as possible in the process of the charging stations' planning and implementation. Therefore, the minimization of the total cost is used to as the objective function in this paper. It is necessary to not only consider the construction cost and operation cost, but also consider the users' benefits after the planning and construction of the charging stations. Thus, both the cost of the charging stations and the cost of the users are all taken into account for calculating the total cost. Specifically, for travelers, if there are charging stations in their own destinations, they can directly charge their PEVs in the charging station as long as the charging fee is reasonable. However, if there are no charging stations in their destinations or the charging fee is beyond their affordability, travelers will first park in some other charging stations to charge their PEVs, and then walk or take other transportation modes to their destinations. Based on these considerations, Figure 1 shows the illustration of the total cost. For charging stations, the cost mainly includes installing cost and management cost. The installing cost is consisted of basic construction cost and cost of purchasing chargers. The management cost includes equipment maintenance cost, equipment depreciation cost, wage cost, etc. It can be converted into the initial installing cost. For users, the cost mainly includes the charging cost, station access cost (i.e., the cost travelers spend from the charging stations to their destinations), and waiting cost. Then, where the charging stations should be located in the destination-regions to not only meet the travelers' charging demand, but also minimize the total cost is the problem that will be investigated.

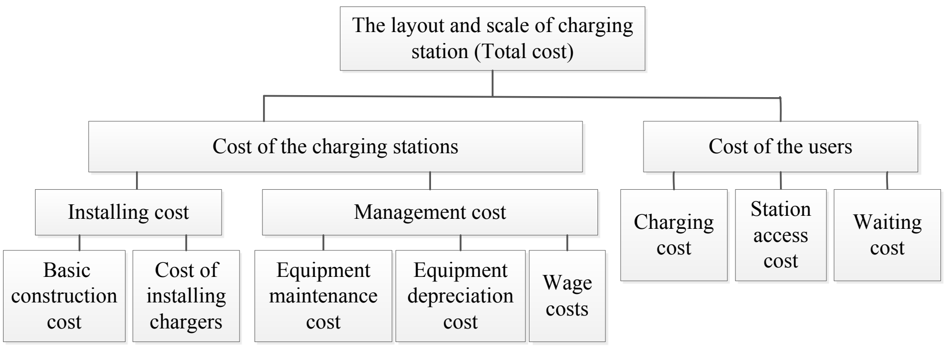

Figure 1 Illustration of the total cost

2.2 Assumptions

Suppose a study region containing several sub-regions, which can represent specific user destinations (e.g. workplace, shopping mall, university, etc.) or aggregations of such locations. The division of these sub-regions can be based on the land use or other criterions. This paper aims to determine the location of the fixed number of charging stations in the sub-regions and the number of the chargers in each charging station to meet the total charging requests over a period of time, which represents the capacity of the charging stations. For example, in the morning rush hour, if 100 BEVs come for charging, then at least 100 chargers should be installed to meet the charging demand. This is suitable for commuters, whose travel is relatively regular. Although all the BEVs cannot reach the charging stations and charge at the same time, their arrival will be relatively centralized, i.e., the charging demands are relatively centralized. Based on this consideration, the CSLP will be investigated mainly considers the traveling behavior of the commuters and the waiting time (i.e., waiting cost) will not be considered. Some other assumptions will be given as follows.

(a1) Only the BEVs rather than PHEVs are discussed in this paper.

(a2) The related data such as the number of the BEVs in every sub-region and the distance between every sub-region are available.

(a3) There is enough power for the BEVs to ensure that travelers can reach their destinations or the charging stations from their origins (e.g. residences). But the BEVs must be charged in the charging station to ensure travelers can return to their origins.

(a4) Drivers will choose the charging station within the tolerable distance.

(a5) Each vehicle can only be charged in one station, and each charger can only serve for one vehicle, i.e., once a charger is used by one vehicle, it cannot be used by the other vehicles.

(a6) Travelers' charging demands in each month are almost the same.

(a7) The number of chargers being installed in each charging station is no less than 20.

2.3 Notations

Some important model sets and parameters can be given as follows:

N : Sets of nodes, i.e., the sets of the centroids of the sub-regions;

A : Sets of the links, i.e., the set of the roads connecting the sub-regions;

S : Sets of the EVs/users, it is assumed that one vehicle corresponds to one user;

P : Number of charging stations to be constructed;

V_i : Electric vehicle i , $V_i \in S$;

D_i : Destination i , $D_i \in N$;

O_{V_i} : Origin of electric vehicle i ;

D_{V_i} : Destination of electric vehicle i , $D_{V_i} \in N$;

$C_{BC_{D_j}}$: Basic construction cost in D_j for installing one charger, including the cost of purchasing the land and the materials etc.;

P_c : Price of per charger;

P_{D_j} : Unit charging price in D_j ;

$Q_{V_i D_j}$: Electricity demand for vehicle i to charge in D_j ;

C : Access cost per kilometer;

$d_{O_{V_i} D_{V_i}}$: Distance from O_{V_i} to D_{V_i} ;

$d_{O_{V_i} D_j}$: Distance from O_{V_i} to D_j ;

$d_{D_j D_{V_i}}$: Distance from D_j to D_{V_i} ;

TD_i : Tolerable distance, i.e., the maximum distance that travelers destined to region i can accept from the charging station to their destinations;

DR : Driving range, i.e., the maximum distance that the BEVs can travel when the power is full;

e: Conversion coefficient (power consumption per unit distance traveling);

Q: Charging capacity of the BEVs, i.e., full power of the BEVs;

α_{V_i}: V_i's perception weight of the charging cost;

β_{V_i}: V_i's perception weight of the station access cost;

r: Discount rate;

T: Operating period of the charging station;

μ_0: The conversion coefficient for calculating the management cost, i.e., the proportion of management cost account for the initial installing cost;

η: The conversion coefficient for calculating the annual cost of the users.

3. Model Formulation

3.1 Decision Variables

The decision variables used in our model are as follows:

N_{D_j}: Number of chargers will be installed in D_j;

$Y_{V_iD_j} = 1$ if V_i choose to charge in D_j, otherwise $Y_{V_iD_j} = 0$;

$X_{D_j} = 1$ if a charging station will be located in D_j, otherwise $X_{D_j} = 0$.

3.2 The Model

In this section, the model will be proposed to solve the location problem of charging stations. As described in Section 2, the minimization of the total cost is used to as the objective function in this paper. Especially, considering the fact that travelers may have different perceptions of charging cost and station access cost, weights α_{V_i} and β_{V_i} are introduced to respectively describe user V_i's perceptions of charging cost and station access cost. We obtain the whole model as follows considering the annual cost:

$$\text{Min } \frac{r(1+r)^T}{(1+r)^T-1}\cdot\sum_{D_j\in N}\begin{pmatrix} C_{BC_{D_j}}\cdot N_{D_j} \\ +P_c\cdot N_{D_j}\end{pmatrix}+ \mu_0\cdot\sum_{D_j\in N}\left(C_{BC_{D_j}}\cdot N_{D_j}+P_c\cdot N_{D_j}\right)+ \eta\cdot\sum_{V_i\in S}\sum_{D_j\in N}\begin{pmatrix}\alpha_{V_i}\cdot Q_{V_iD_j}\cdot P_{D_j} \\ +\beta_{V_i}\cdot d_{D_jD_{V_i}}\cdot C\cdot Y_{V_iD_j}\end{pmatrix}, \tag{1}$$

$$s.t. \quad \sum_{D_j\in N} Y_{V_iD_j}=1,\ \forall V_i\in S, \tag{2}$$

$$\sum_{D_j} X_{D_j}=P,\quad \forall D_j\in N, \tag{3}$$

$$Y_{V_iD_j}\le X_{D_j},\ \forall V_i\in S, D_j\in N, \tag{4}$$

$$X_{D_j}\le N_{D_j},\ \forall D_j\in N, \tag{5}$$

$$N_{D_j}\le \mathrm{M}\cdot X_{D_j},\ \ \forall V_i\in S, D_j\in N, \tag{6}$$

$$N_{D_j}\ \ge\ 20\cdot X_{D_j},\ \forall V_i\in S, D_j\in N, \tag{7}$$

$$N_{D_j}\ge\sum_{V_i\in S} Y_{V_iD_j},\ \ \forall D_j\in N, \tag{8}$$

$$d_{O_{V_i}D_{V_j}}\le DR,\ \ \forall V_i\in S, D_{V_j}\in N, \tag{9}$$

$$\sum_{D_j\in N} d_{D_jD_{V_i}}\cdot Y_{V_iD_j}\le TD_{V_i},\ \ \forall D_{V_i}\in N, \tag{10}$$

$$\begin{aligned} &Q_{V_iD_j}\ge 2\cdot e\cdot d_{O_{V_i}D_j}\cdot Y_{V_iD_j}-Q \\ &\forall V_i\in S; D_j\in N,\end{aligned} \tag{11}$$

$$Q_{V_iD_j}\ge 0\quad \forall V_i\in S; D_j\in N, \tag{12}$$

$$Y_{V_iD_j}=\{0,1\}\qquad \forall V_i\in S, D_j\in N, \tag{13}$$

$$X_{D_j}=\{0,1\}\qquad \forall D_j\in N, \tag{14}$$

$$N_{D_j}\in Z^+\cup\{0\}\qquad \forall D_j\in N, \tag{15}$$

where M is a large positive number. The objective function (1) minimizes the total cost, in which the first part is the installing cost, the second part is the management cost and the third part is the cost of the users. Constraints (2) mean that each vehicle can only be charged in one station. Constraints (3) restrict the total number of charging stations to be constructed. Constraints (4) denote that the BEVs can be charged in D_j only when there is charging station be located in D_j. Constraints (5) ensure that a charging station will be located only when there are vehicles need to be charged in this station. Constraints (6) respect that the number of chargers installed in every charging station is finite. Constraints (7) denote that the number of chargers being installed in each charging station is no less than 20, which ensure the assumption (a7). Constraints (8) impose the number of the chargers in station D_j is not less than the number of the BEVs that choose to be charged in D_j. This condition ensures that there are enough chargers in each charging station. Constraints (9) ensure the assumption (a3). Constraints (10) mean that V_i will choose to be charged in D_j only when the distance between D_{V_i} and D_j is not larger than TD_{V_i}, which ensure the assumption (a4). Constraints (11) restrict the quantity of electricity that the vehicles should be charged. Constraints (12) are the non-negative constraint. Constraints (13) and (14) denote X_{D_j} and $Y_{V_iD_j}$ as binary variables. Constraints (15) denote N_{D_j} as a non-negative integer variable.

4. Case Study

In this section, the case study will be given to verify the validity of the proposed model. The model is a mixed integer linear program, thus it is directly solved using CPLEX (a commercially available optimization software package) to get the optimal solution in this paper.

4.1 Data Preparation

The case study is based on a small metropolitan region covers about 60 km^2 in Beijing, China. 15 sub-regions in the case study region are considered. Each sub-region represents a functional region of city such as universities, hospitals, and some transport hub stations, etc. Then, a simplified transportation network consisting of 15 nodes and 23 links will be obtained as shown in Figure 2. Four origin-regions (such as residential areas, which are not labeled in the figure) surrounding the case study region are considered to generate travel demand, because travelers in these four areas have to go to the study region to take part in various activities, such as work, study, or do other things. It is assumed that about 6400 BEVs with a 60 kilometers driving range (i.e., $DR = 60$ kilometers) are contained in these four areas. Table 1 shows the assumed number of BEVs in each origin-region. These vehicles are randomly assigned to each sub-region in the table. Generally, the basic construction costs are different at different regions, because of the differences in land use price, regional nature, degree of development, etc. Table 2 shows the assumed basic construction cost of constructing a charger in each sub-region. In addition, the assumed values of the other parameters are listed in Table 3.

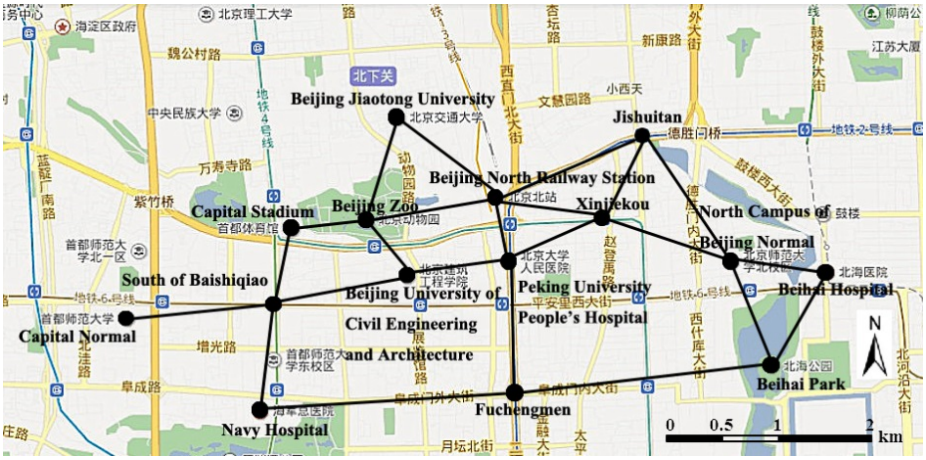

Figure 2 The case study region network (Source: 2013 Baidu-GS (2012) NO. 6003-Data)

Table 1 The assumed number of BEVs in each origin region and the assigned number of BEVs for each destination

Destination Name \ The assigned number of BEVS \ Origin Name (total number of BEVs)	Yanjiao Town (1600)	Lixian Town (1500)	Daanshan Township (2000)	Yanshou Town (1300)
Beijing North Railway Station	90	111	148	81
Peking University People's Hospital	105	95	137	78
Beijing Jiaotong University	101	89	138	92
Beijing Zoo	113	110	134	83
Beijing University of Civil Engineering and Architecture	121	99	161	90
Capital Stadium	106	97	126	91
Fuchengmen	109	90	123	92
Xinjiekou	101	99	135	68
Jishuitan	92	115	132	98
Navy Hospital	122	102	133	90
Capital Normal University	110	109	122	91
South of Baishiqiao	101	94	141	89
North Campus of Beijing Normal University	116	102	114	72
Beihai Hospital	102	96	128	83
Beihai Park	111	92	128	102

Table 2 The assumed basic construction cost of constructing a charger in different destinations

Destination Name	Basic construction cost
Beijing North Railway Station	52000
Peking University People's Hospital	57000
Beijing Jiaotong University	54600
Beijing Zoo	49000
Beijing University of Civil Engineering and Architecture	52500
Capital Stadium	49000
Fuchengmen	45400
Xinjiekou	47000
Jishuitan	44000
Navy Hospital	56000
Capital Normal University	55000
South of Baishiqiao	49000
North Campus of Beijing Normal University	53000
Beihai Hospital	53000
Beihai Park	49500

Table 3 The values of the parameters

Parameters	P_c	e	r	T	μ_0
Values	10000	0.25	0.1	10	0.2

4.2 Numerical Results

In this section, the numerical results will be discussed. It is worth noting that the value of tolerable distance for different regions may also be different, because of the difference of geographical environment or other factors. For simplicity, the tolerable distances for all the sub-regions are assumed to be an identical $TD = 2.5$ kilometers in this study.

In the proposed model, weights α_{V_i} and β_{V_i} have been introduced to respectively describe user i's perceptions of charging cost and station access cost. Therefore, we first discuss the CSLP considering the homogeneous users and the heterogeneous users, respectively. Then we will simply discuss the effects of different parameters on the CSLP.

4.2.1 For Homogeneous Users

In the following, the CSLP will first be investigated considering the homogeneous users. That is to say, for users, the weights to the charging cost are equal (i.e., $\alpha_{V_i} = \alpha_{V_j}, \forall V_i, V_j \in S$), and the weights to the station access cost are also the same (i.e., $\beta_{V_j} = \beta_{V_j}, \forall V_i, V_j \in S$). Without losing generality, it is assumed that $\alpha = \beta = 1.0$ for all the users in the simulation. In addition, the number of charging stations to be constructed in the whole area is assumed to be $P = 7$.

For charging cost, we have to pay attention to the unit charging price, due to that different charging price may affect users' choices for charging stations. Figure 3 firstly presents the numerical result for constructing charging stations under the same unit charging price $P_{D_j} = 1.0 \; \forall D_j \in N$. It can be seen that the charging stations should be constructed in the sub-regions labeled by red rectangle in the figure. The related number of chargers to be installed in each station is listed in Table 4. We can see that the charging stations tend to be constructed at the regions with low installing cost (such as Jishuitan) rather than the regions with high installing cost (such as Peking University People Hospital). This is because that the installing and management cost of charging stations will have greater effect on the total cost than the users' cost does in this case. Therefore, based on the minimizing of the total cost, the regions with low installing cost might be better choices for constructing charging stations.

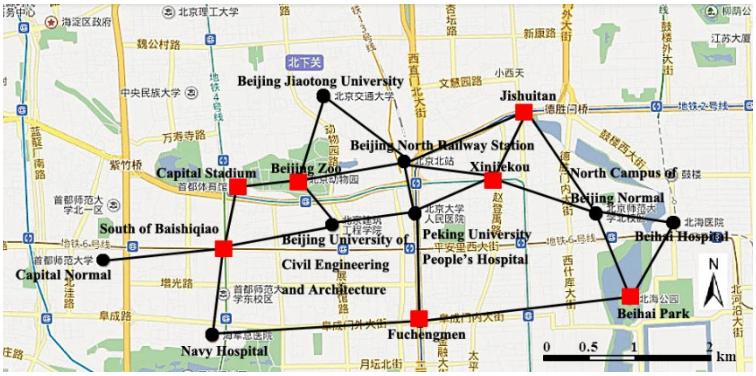

Figure 3 Location result with the same unit charging price for homogeneous users

Table 4 The expected charging stations and their related number of chargers with the same unit charging price for homogeneous users

Location of the charging station	Number of chargers
Beijing Zoo	1331
Capital Stadium	420
Fuchengmen	646
Jishuitan	1857
South of Baishiqiao	1304
Xinjiekou	211
Beihai Park	631

Furthermore, for charging stations in different regions, the unit charging price may be different, due to the different basic cost, installing cost, management cost, parking cost, regional characteristics etc. Therefore the CSLP with different unit charging price for different regions should be further discussed.

Generally, the higher the investment cost is, the higher the charging price might be. Further, in the places, which are usually important and congested, such as hospitals and railway stations, the charging price tends to be higher than that in the places which are not busy regions. Therefore, based on the basic construction cost shown in Table 2 and the characteristics of each sub-region, Table 5 lists the assumed unit charging price of charging stations in different regions.

Table 5 Unit charging price for different charging stations in different regions

Destination name	Unit charging price
Beijing North Railway Station	6
Peking University People's Hospital	10
Beijing Jiaotong University	8
Beijing Zoo	4
Beijing University of Civil Engineering and Architecture	6
Capital Stadium	3
Fuchengmen	1
Xinjiekou	2
Jishuitan	1
Navy Hospital	10
Capital Normal University	8
South of Baishiqiao	3
North Campus of Beijing Normal University	6
Beihai Hospital	6
Beihai Park	3

Through the optimization, the obtained location result is the same with that showed in Figure 3. The corresponding number of chargers in each station is shown in Table 6. It can be seen that the corresponding number of chargers in some stations have changed in Table 6 compared with those in Table 4. These changes are result from the change of the unit charging price in different regions. Table 5 shows that the assumed unit charging price in Beijing Zoo is larger than that in Capital Stadium. Many travelers originally charge in Beijing Zoo will choose to charge in Capital Stadium under the model constraints. Thus more chargers should be installed in Capital Stadium. Likewise, the number of chargers in some other stations will also change following the charging demand. As a result, more chargers are inclined to be constructed in the regions with low charging price, which is corresponds with the result we obtain above that the charging stations tend to be constructed in the regions with relatively low installing cost. Note that if the unit charging price for each station changes, the location result may be changed as well. The final result will must be the minimization of the total cost by balancing the costs of the charging stations and users.

Table 6 The expected charging stations and their related number of chargers with different unit charging price for homogeneous users

Location of the charging station	Number of chargers
Beijing Zoo	20
Capital Stadium	1593
Fuchengmen	646
Jishuitan	1857
South of Baishiqiao	971
Xinjiekou	880
Beihai Park	433

4.2.2 For Heterogeneous Users

Considering the actual situation that different travelers may have different perceptions of charging cost and station access cost, the CSLP for heterogeneous users (i.e., $\alpha_{V_i} \neq \alpha_{V_j}$, $\beta_{V_i} \neq \beta_{V_j}$, $\forall V_i, V_j \in S$) will be investigated in this section. The total number of the charging stations to be constructed is still $P = 7$.

It is very complex to allocate weights of the charging cost and the station access cost to each user, especially when the number of users is very large. For simplicity, in the following simulations, the users are classified according to the properties of their destinations. It is assumed that users destined to the same region or the regions with the same properties will have same weights of charging cost and same weights of station access cost, respectively. For example, for users to hospitals (V_i is used here), the distance between the origin and the destination is very important. Because that the distance can reflect the convenience of the doctors to cure the patients or the patients to be treated by the doctors. In comparison, the charging cost is not considered to be so important. Thus $\alpha_{V_i} < \beta_{V_i}$ will be hold for users destined to hospitals. On the contrary, users to park or zoo (V_j is used here) can afford relative long distance and prefer to enjoy low charging cost. In this case, $\alpha_{V_j} > \beta_{V_j}$ will be hold. Based on the above analysis, $\alpha_{V_j} > \alpha_{V_i}$ and $\beta_{V_j} < \beta_{V_i}$ will also be hold in this study. Table 7 shows the assumed α and β for users destined to different regions.

Table 7 The assumed α and β for users destined to different regions

Destination name	Weight α	Weight β
Beijing North Railway Station	2	8
Peking University People's Hospital	1	10
Beijing Jiaotong University	3	6
Beijing Zoo	4	3
Beijing University of Civil Engineering and Architecture	3	6
Capital Stadium	4	3
Fuchengmen	2	2
Xinjiekou	2	2
Jishuitan	2	2
Navy Hospital	1	10
Capital Normal University	3	6
South of Baishiqiao	2	2
North Campus of Beijing Normal University	3	6
Beihai Hospital	1	10
Beihai Park	4	3

The location result based on Table 5 and Table 7 is displayed in Figure 4. Comparing with the results in Figure 3, it can be found that Beijing Zoo is no longer selected, while Beihai Hospital is additionally selected in Figure 4. This is because that for users to Beihai Hospital, the weight β is remarkably larger than α. Namely, comparing with charging cost, users put more focus on station access cost. In this case, some users to Beihai Hospital will choose to charge there. While the other part of the users will still charge in Beihai Park comprehensively considering the distance between the origins and destinations, the charging price, the weights α and β etc. As a result, both Beihai Park and Beihai Hospital should be selected with the objective of minimizing the total cost. Analogously, users originally charge in Beijing Zoo will charge in other places. The corresponding number of chargers for each charging station is listed in Table 8. Comparing Table 6 with Table 8, we can observe that different perceptions of charging cost and station access cost largely determine the choice of the users for the charging stations, and in turn affect the location of the charging stations.

To sum up, the proposed model can effectively solve the location problem of charging stations by comprehensively considering the charging stations' cost and the users' daily travel.

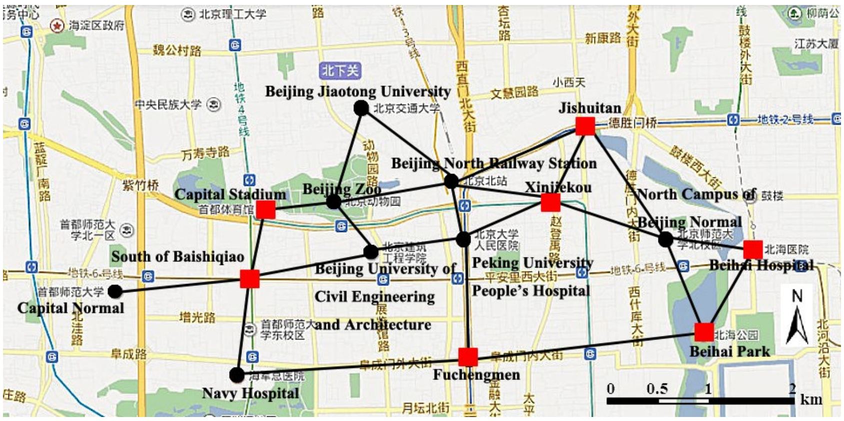

Figure 4 Location result for the different unit charging price for heterogeneous users

Table 8 The expected charging stations and their related number of chargers with different unit charging price for heterogeneous users

Location of the charging station	Number of chargers
Capital Stadium	1381
Fuchengmen	724
Jishuitan	1674
South of Baishiqiao	1203
Xinjiekou	576
Beihai Park	561
Beihai Hospital	281

4.2.3 For Different Discount Rates and Operating Period of Charging Station

In this section, the effects of discount rate and operation period of charging station on the CSLP will be simply discussed. For simplicity, we only typically show the case for homogeneous users based on the same unit charging price, and still let $P = 7$.

Firstly, given $T = 10$, the numerical results for the cases $r = 0.05, 0.2, 0.3$ are respectively studied. The location results of these three cases are all the same with that for the case $r = 0.1$ as shown in Figure 3. However, the number of chargers in some charging stations will be changed when the discount rate varies. Table 9 shows the number of chargers in each charging station. It can be seen from Table 9 that, when the discount rate is large (e.g., $r = 0.2$), more chargers will be installed in Xinjiekou station, while less chargers will be installed in Beijing Zoo station comparing with that for the cases $r = 0.05, 0.1$. When the discount rate continue to increase (e.g. $r = 0.3$), these changes are further enlarged (see column 4 and 5 in Table 9). The reason can be explained as follows. With the increase of the discount rate, the conversion coefficient $r(1+r)^T \big/ \left((1+r)^T - 1\right)$ in the model will increase. Correspondingly, the average annual installing costs for each region and the difference between these costs will all increase. Based on the conclusion in 4.2.1, more chargers will tend to be constructed in the regions with lower installing cost such as Xinjiekou to minimize the total cost. Furthermore, the relationship between the total cost (TC) and the discount rate r is plotted in Figure 5. It can be found that the total cost is nearly a linear increasing function of the discount rate.

Table 9 The expected charging stations and their related number of chargers for different discount rates

Location of the charging station \ Number of chargers \ r	0.05	0.1	0.2	0.3
Beijing Zoo	1331	1331	1210	1210
Capital Stadium	420	420	420	420
Fuchengmen	646	646	646	646
Jishuitan	1857	1857	1857	1857
South of Baishiqiao	1304	1304	1304	1304
Xinjiekou	211	211	332	530
Beihai Park	631	631	631	433

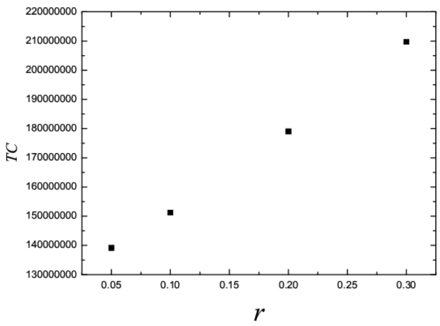

Figure 5 The relationship between the total cost TC and the discount rate r

Next, given $r = 0.1$, the numerical results for different operation periods $T = 15, 20, 25, 30$ are studied, respectively. The location results of these four cases are also same with that for the case $T = 10$ as shown in Figure 3. The number of chargers in some stations will also change as listed in Table 10. However, the changing trend is contrary to that we discussed above for different discount rates. For example, when $T = 25$, the chargers in Xinjiekou station will decrease from 211 to 83, while the chargers in Beihai Park station will increase from 631 to 759. This means that some users who originally choose to charge in Xinjiekou for $T = 10$ will choose to charge in Beihai Park when $T = 25$. In fact, it is also results from the change of the annual installing cost as discussed before. With the increase of T, $r(1+r)^T \Big/ \left((1+r)^T - 1\right)$ will decrease. Thus the average annual installing costs for each region and the difference between these costs will decrease. In this case, more chargers will be installed in Beihai Park to meet the charging demand. As a result, the total cost TC will decrease with the increase of T as shown in Figure 6. These results also mean that it is an effective means of reducing the total costs by taking some measures to prolong the operating period of the charging station.

Table 10 The expected charging stations and their related number of chargers for different operation periods

Location of the charging station \ Number of chargers \ T	10	15	20	25	30
Beijing Zoo	1331	1331	1331	1210	1210
Capital Stadium	420	420	420	420	420
Fuchengmen	646	646	646	646	646
Jishuitan	1857	1857	1857	1857	1857
South of Baishiqiao	1304	1304	1304	1304	1304
Xinjiekou	211	211	211	83	83
Beihai Park	631	631	631	759	759

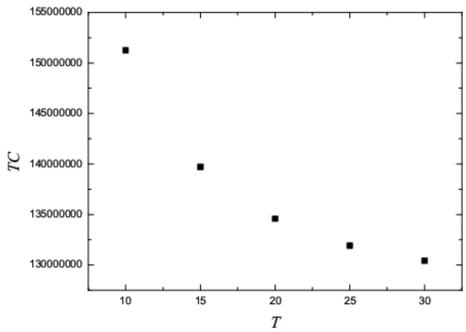

Figure 6 The relationship between the total cost TC and the operating period of the charging station T

4.2.4 For Different Number of Electric Vehicles

The total number of the BEVs is assumed to be 6400 in the above discussion. In this section, the location results for different number of BEVs will be simply discussed. For simplicity, we also only typically show the case for homogeneous users based on the same unit charging price. In addition, $T=10$, $r=0.1$ and $P=7$ are also used here.

Besides the case for 6400 BEVs that studied above, here four cases for 2000, 3000, 4000, and 5000 BEVs are discussed, respectively. The related location results are listed in Table 11. It can be seen that with the increase of the total number of BEVs, the total number of the chargers will increase to meet the increasing charging demand. Note that different assignment for the BEVs in each studied sub-region will lead the distribution of the chargers in each charging stations to be different from that in Table 11. In the actual problem, the location of the charging stations and the distribution of the chargers should be determined according to the actual BEVs assignment (i.e., the actual charging demand). Figure 7 shows the relationship between the total cost (TC) and the total number of BEVs. With the increase of the total number of the BEVs, the total cost will increase. It is easy to understand. The increase of the BEVs number means the increase of the charging demand. Then, more chargers should be installed to meet the increasing charging demand, which will increase the total cost.

Table 11 The expected charging stations and their related number of chargers for different number of BEVs

Location of the charging station \ Number of chargers \ Total number of BEVs	2000	3000	4000	5000	6400
Beijing Zoo	408	609	795	1003	1331
Capital Stadium	140	189	257	356	420
Fuchengmen	217	330	419	463	646
Jishuitan	593	878	1235	1486	1857
South of Baishiqiao	374	572	775	1016	1304
Xinjiekou	66	96	133	184	211
Beihai Park	202	326	386	492	631

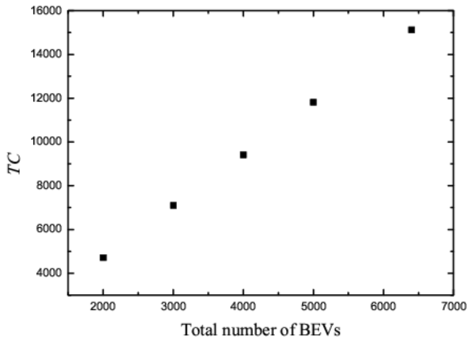

Figure 7 The relationship between the total cost (TC) and the total number of BEVs

4.2.5 For Different Number of Charging Stations

The number of charging stations is assumed to be $P=7$ in the above discussions. In this section, the results for different number of charging stations will be simply discussed. Only the results for homogeneous users based on the same unit charging price is typically discussed. $T=10$, $r=0.1$ are also used here.

By respectively solving the proposed model for $P=5,6,7,8,9,10,11,12$, it can obtained that with the increase of P, the charging stations and the corresponding chargers will spread out the entire area more continuously. Figure 8 shows the relationship between the number of the charging stations (P) and the total cost (TC). It can be seen that with the increase of P, the total cost will first decrease and then increase. It can be explained as follows. When P is small, i.e., the number of the charging stations is small, travelers' choice for charging stations will reduce. Thus, the station access cost will largely increase. With the increase of P, the location of the charging stations will be optimized, and travelers' choice for charging stations will increase. The related cost will decrease until it reaches the optimal value. As P continues to increase, the construction cost will largely increase, which lead to the increase of the total cost.

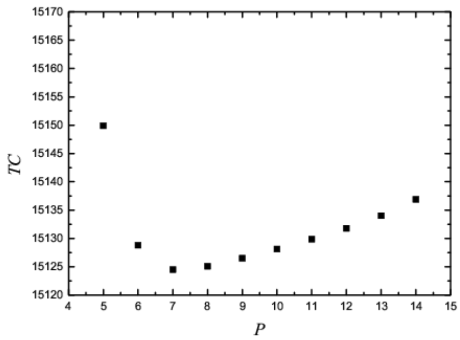

Figure 8 The relationship between the number of the charging stations (P) and the total cost (TC)

5. Conclusions and Future Work

In this paper, the commuter's daily travel is simply analyzed. Then based on the travel process, a novel model to solve the CSLP is proposed and discussed. From the view of the government planning, the minimization of the total cost is regarded as the objective function. For calculating the total cost, both the charging stations' cost (including installing cost and management cost) and the users' cost (including station access cost and charging cost) have been taken into account. The proposed model simultaneously handles the problems where to locate the charging stations and how many chargers to be established in each charging station.

Considering that different user may have different perception on station access cost and charging cost, the CSLP is respectively investigated based on the homogeneous users and heterogeneous users in the case study. For homogeneous users, the impact of the unit charging price for different charging stations on the users' choice and charging stations' location result is discussed. It can be found that travelers are more willing to charge in the stations with low charging price within the tolerable distance. The charging stations will be inclined to be constructed in the regions with low construction cost. For heterogeneous users, the different perceptions of charging cost and station access cost largely determine their choice for the charging stations. Therefore, some region, though with high constructions cost, will have to be selected to construct charging station. In addition, the impacts of the discount rate, the operating period of the charging station, the number of BEVs and the number of the charging stations on the CSLP are also simply discussed. The final location result will must be a tradeoff of the charging stations' cost and the users' cost to minimize the total cost. These results further demonstrate the effectiveness of the proposed model.

As we all know, any sub region is regarded as a node in our network, and the charging stations are only located at the activated nodes. Hence, the chargers serving any sub region are aggregated based on our model. For each activated sub region, the chargers can be redistributed on the sub region and then the chargers can spread out the entire area more continuously. How to redistribute the chargers is one of our research issues in the future. In addition, for general charging problem, the dwell time of the EVs in the charging stations, which represents the potential maximum charging time, is important. Therefore, we will study the location of multiple types of charging stations considering the dwell time of the EVs and the charging power of the stations in the future work.

Generally, some EVs wait at the charging station in a queue when the charging station is congested. It would be more realistic to consider EV queueing behavior for the charging station location problem. A simple charging station location problem considering EV queueing behavior is developed in Appendix A. As shown in Appendix A, the location result considering EV queueing behavior in some case is the same with that in Section 4.2.1. Moreover, each charging station can be regarded as an independent charging system. The rates λ and μ in different charging stations are usually different. Accordingly, the needed number of chargers in each station will be different. In addition, the charging times for different EVs are also various. Therefore, a more complicated and realistic mathematical programming model should be developed to further study the charging station location problem considering EV queueing behavior, which will be our future work.

Appendix A

A simple charging station location problem considering EV queueing behavior is given as follows.

Generally, the EVs independently arrive at the charging stations for charging service. When an EV arrives at the charging station with free chargers, it can charge at the station and leave the station after the charging is completed. If there is no free charger, the EVs need to wait until there is available free charger, and then the EVs can be charged in a certain order, e.g., the first-in and first-out (FIFO) order. Assume that the EVs reach the charging stations following a Poisson process with rate λ and the charging service time of the EVs follows a negative exponential distribution with rate μ. Let s be the number of the chargers that can provide charging service in each charging station. Then the charging system will be in accord with the standard $M/M/c/\infty/\infty$ queue system with the charging service intensity $\rho = \lambda / s\mu$. For simplicity, the parameters λ, μ and s are assumed to be identical for different charging stations.

Before providing the charging station location model considering EV queueing behavior, some related notations are given as follows:

N : Set of nodes, i.e., the sets of the centroids of the regions indexed by i, j;

m_i : Number of EVs in region i;

C : Access cost per kilometer;

P : Number of charging stations to be constructed;

P_c : Price of per charger;

TD : Tolerable distance, i.e., the maximum distance that travelers can accept;

C_j : Basic construction cost in region j ; n the number of EVs to accept charging service in each charging station;

P_n : Probability of there being n EVs to accept charging service in each charging station.

The decision variables are given as follows:

$Y_{ij} = 1$ if EVs in region i choose to charge in region j, otherwise $Y_{ij} = 0$;

$X_j = 1$ if a charging station will be located in region j, otherwise $X_j = 0$.

Then, the model can be formulated as follows:

$$\text{Min} \sum_{j \in N} (C_j + P_c \cdot s) \cdot X_j + \sum_{i \in N} \sum_{j \in N} C \cdot m_i \cdot d_{ij} \cdot Y_{ij}, \tag{A1}$$

$$s.t. \quad \sum_{j \in N} Y_{ij} = 1, \quad \forall i \in N, \tag{A2}$$

$$\sum_{j} X_j = P, \quad \forall j \in N, \tag{A3}$$

$$Y_{ij} \le X_j, \quad \forall i, j \in N, \tag{A4}$$

$$\sum_{j \in N} d_{ij} \cdot Y_{ij} \le TD, \quad \forall i \in N, \tag{A5}$$

$$\begin{cases} P_0 = \left[\sum_{k=0}^{s-1} \frac{1}{k!} \left(\frac{\lambda}{\mu} \right)^k + \frac{1}{s!} \frac{1}{1-\rho} \left(\frac{\lambda}{\mu} \right)^s \right]^{-1}, \\ P_n = \begin{cases} \frac{1}{n!} \left(\frac{\lambda}{\mu} \right)^n P_0 & n \le s, \\ \frac{1}{s! s^{n-s}} \left(\frac{\lambda}{\mu} \right)^n P_0 & n > s, \end{cases} \end{cases} \tag{A6}$$

$$W_j = \frac{(s\rho)^s \rho P_0}{s! (1-\rho)^2 \lambda} \cdot X_j \le 0.5, \ \forall j \in N \tag{A7}$$

$$Y_{ij} = \{0,1\}, \quad \forall i, j \in N, \tag{A8}$$

$$X_j = \{0,1\}, \quad \forall j \in N. \tag{A9}$$

The objective function (A1) minimizes the construction cost and the station access cost. Constraints (A2) mean all the vehicles should be charged in some regions. Constraints (A3) restrict the total number of charging stations to be constructed. Constraints (A4) denote that the BEVs can be charged in region j only when there is charging station be located in region j. Constraints (A5) show that the EVs in region i will choose to be charged in region j only when the distance between region i and region j is not larger than the tolerable distance TD. Constraint (A6) gives the probability of EVs to accept charging service at each charging station. Constraints (A7) restrict the queuing time W_j of the EVs waiting for charging at each charging station is no larger than 0.5 hour; Constraints (A8) and (A9) denote Y_{ij} and X_j as binary variables.

For simplicity, let $\lambda = 60$ and $\mu = 1$. Based on the objective of minimizing the construction cost, we can take λ and μ into constraints (A6) and (A7) to get the minimum number of the chargers (i.e., $s = 62$) in each charging station. Then, the resulting model (i.e., (A1)-(A5), (A8), (A9)) can be easily solved by CPLEX. Let $P = 7$, the optimal location of the charging stations are Beijing Zoo, Capital Stadium, Fuchengmen, Jishuitan, South of Baishiqiao, Xinjiekou and Beihai Park. Evidently, the location result is the same with that in Section 4.2.1.

Generally, each charging station can be regarded as an independent charging system. The rates λ and μ in different charging stations are usually different. Accordingly, the needed number of chargers in each station will be different. In addition, the charging times for different EVs are also various. Therefore, a more complicated and realistic mathematical programming model should be developed to further study the charging station location problem considering EV queueing behavior.

Acknowledgments

This work is partly supported by National Basic Research Program of China (2012CB725400), National Natural Science Foundation of China (71501021).

References

[1] Andrews, M., Dogru, M.K., Hobby, J.D., Jin, Y. & Tucci, G.H. (2013). Modeling and optimization for electric vehicle charging infrastructure. In IEEE Innovative Smart Grid Technologies Conference 2013.

[2] Avci, B., Girotra, K. & Netessine, S. (2014). Electric vehicles with a battery switching station: adoption and environmental impact. Management Science, 61(4): 772-794.

[3] Chen, T.D., Kockelman, K.M. & Khan, M. (2013). The electric vehicle charging station location problem: a parking based assignment method for Seattle. Transportation Research Board 92nd Annual Meeting, 340.

[4] Chung, S.H. & Kwon, C. (2015). Multi-period planning for electric car charging station locations: a case of Korean expressways. European Journal of Operational Research, 242(2): 677-687.

[5] Dagdougui, H. (2012). Models, methods and approaches for the planning and design of the future hydrogen supply chain. International Journal of Hydrogen Energy, 37(6): 5318-5327.

[6] Dashora, Y., Barnes, J., Combs, R.P.T., Hilliard, M. & Chinthavali, M. (2010). The PHEV charging infrastructure planning (PCIP) problem. International Journal of Emerging Electric Power System, 11(2).

[7] Dong, J., Liu, C.Z. & Lin Z.H. (2014). Charging infrastructure planning for promoting battery electric vehicles: an activity-based approach using multiday travel data. Transportation Research Part C, 38: 44-55.

[8] Frade, I., Ribeiro, A., Goncalves, G. & Antunes, A.P. (2011). An optimization model for locating electric vehicle charging stations in central urban areas. Transportation Research Record: Journal of the Transportation Research Board, 3582: 1-19..

[9] He, F., Wu, D., Yin, Y.F. & Guan, Y.P. (2013). Optimal deployment of public charging stations for plug-in hybrid electric vehicles. Transportation Research Part B, 47: 87-101.

[10] He, F., Yin, Y. & Lawphongpanich, S. (2014). Network equilibrium models with battery electric vehicles. Transportation Research Part B, 67: 306-319.

[11] He, F., Yin, Y.F. & Zhou, J. (2015). Deploying public charging stations for electric vehicles on urban road networks. Transportation Research Part C, 60: 227-240.

[12] Hiermann, G. , Puchinger, J., Ropke, S. & Hartl, R.F. (2016). The electric fleet size and mix vehicle routing problem with time windows and recharging stations. European Journal of Operational Research, 252(3): 995-1018.

[13] Jiang, N., Xie, C., Duthie, J.C. & Waller, S.T. (2014). A network equilibrium analysis on destination, route and parking choices with mixed gasoline and electric vehicular flows. European Journal on Transportation and Logistics, 3(1): 55-92.

[14] Kim, J.G. & Kuby, M. (2012). The deviation-flow refueling location model for optimizing a network of refueling stations. International Journal of Hydrogen Energy, 37(6): 5406-5420.

[15] Kim, J.G. & Kuby, M. (2013). A network transformation heuristic approach for the deviation flow refueling location model. Computer Operations Research, 40 (4): 1122-1131 .

[16] Li, Y.Q., Li, L., Yong, J., Yao, Y. & Li, Z. (2011). Layout planning of electrical vehicle charging stations based on genetic algorithm. Electrical Power Systems and Computers, Spring Berlin Heidelberg, 99: 661-668.

[17] Lim, S. & Kuby, M. (2010). Heuristic algorithms for siting alternative-fuel stations using the Flow-Refueling Location Model. European Journal of Operational Research, 204(1): 51-61.

[18] Lin, Z., Ogden, J., Fan, Y. & Chen, C.W. (2008). The fuel-travel-back approach to hydrogen station siting. International Journal of Hydrogen Energy, 33(12): 3096-3101.

[19] Liu J. (2012). Electric vehicle charging infrastructure assignment and power grid impacts assessment in Beijing. Energy Policy, 51: 544-557.

[20] Mak, H.Y., Rong, Y. & Max Shen, Z.J. (2013). Infrastructure planning for electric vehicles with battery swapping. Management Science, 59(7): 1557-1575.

[21] Payam, S.B., Abbas, R.G. & Hosein, K.K. (2014). Optimal fast charging station placing and sizing. Applied Energy, 125: 289-299.

[22] Pelletier, S., Jabali, O. & Laporte, G. (2016). 50th Anniversary invited article-goods distribution with electric vehicles: review and research perspectives. Transportation Science, 50(1): 3-22.

[23] Sathaye, N. & Kelley, S. (2013). An approach for the optimal planning of electric vehicle infrastructure for highway corridors. Transportation Research Part E, 59: 15-33.

[24] Schneider, M., Stenger, A. & Goeke. D. (2014). The electric vehicle routing problem with time windows and recharging stations. Transportation Science, 48 (4): 500-520.

[25] Shahraki, N., Cai, H., Turkay, M. & Xu, M. (2015). Optimal locations of electric public charging stations using real world vehicle

travel patterns. Transportation Research Part D, 41: 165-176.

[26] Wang, Y.W. & Lin, C.C. (2013). Locating multiple types of recharging stations for battery-powered electric vehicle transport. Transportation Research Part E, 58: 76-87.

[27] Wang, Z.P., Liu, P., Cui, J., Xi, Y. & Zhang, L. (2013). Research on quantitative models of electric vehicle charging stations based on principle of energy equivalence. Mathematical Problems in Engineering: 1-10.

[28] Xi, X. M., Ramteen, S. & Vincenzo, M. (2013). Simulation-optimization model for location of a public electric vehicle charging infrastructure. Transportation Research Part D, 22: 60-69.

[29] Yildiz, B., Arslan, O. & Karasan, O.E. (2016). A branch and price approach for routing and refueling station location model. European Journal of Operational Research, 248(3): 815-826.

[30] Zhao, J.J. & Ma, T.J. (2016). Optimizing layouts of initial AFV refueling stations targeting different drivers, and experiments with agent-based simulations. European Journal of Operational Research, 249(2): 706-716.

[31] Zhu, Z.H., Gao, Z.Y., Zheng, J.F. & Du, H.M. (2016). Charging station location problem of plug-in electric vehicles. Journal of Transport Geography, 52: 11-22.

Zhihong Zhu is currently a Ph.D. student in Institute of Transportation System Science and Engineering, Beijing Jiaotong University, Beijing, China. She completed master's degree in Shandong University of Science and Technology, China (2012). Her current research interests include the charging station location problem of EVs and complex system modelling.

Ziyou Gao is a professor in Institute of Transportation System Science and Engineering, Beijing Jiaotong University, Beijing, China. He is one of the important leaders in the RP China Complex Systems Theory and Technology. He has more than 20 years of experience in transportation planning and management. His work has been published in a range of transportation and planning journals, including Operation Research, Transportation Research A: Policy and Practice, Transportation Research B: Methodological, Transportation Research C: Emerging Technology, Transportation Research E: Logistics and Transportation Reviews, etc.

Jianfeng Zheng is a professor in Transportation Management College, Dalian Maritime University, Dalian, Liaoning province, China. During the past years, he has focus on teaching and conducting research in the areas of liner shipping, complex system modelling and logistics location. His work has been published in journals such as Transportation Science, Transportation Research part E: Logistics and Transportation Reviews, European Journal of Operational Research, etc.

Haoming Du is currently a Ph.D. student in Institute of Transportation System Science and Engineering, Beijing Jiaotong University. He completed master's degree in Shandong University of Science and Technology, China (2012). His research interests include public transportation, traffic system modeling and bus fare optimization.