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Optimization of Electric Vehicle Charging Station Selection: A Complex Network Study

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Abstract: In recent years, the electric vehicle (EV) industry in China has developed rapidly with the government's series of policies. However, the construction of the basic facilities, such as the charging station, is still unable to meet the development of EV and the personalized requirements of customers. Therefore, how to plan reasonable charging station nodes for customers is particularly important. Firstly, the factors that affect the choice of customers when planning charging stations were analyzed on the basis of Complex Network theory. Secondly, the model of minimization of customer cost was built. Then, the validity of the model is verified by an example. Finally, the importance degree of each node was studied through eigenvector and approach degree. This study provides a theoretical basis for customers to decide the best charging station and avoid the risk of traffic congestion.

Keywords: electric vehicle (EV), charging station selection, complex network.

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1. INTRODUCTION

Production and sales volume of EV in China have now surpassed the United Stated, which make it the largest new energy automobile market. According to the statistics by China association of automobile manufactures [1], the cumulative production and sales in 2017 were 794 thousand and 777 thousand, representing an increase of 53.8% and 53.3% respectively. Besides, other data [2] show that by the end of 2017, China has already built 450,000 EV charging stations and 210,000 public charging piles. Compared with 2016, the numbers increased by 51%. Even though the scale and quantity of charging station have raised substantially, the number of charging station and pile still can’t meet the need of EV’s rapid development judged by industry standard- the number of EV and charging interface should not be less than 1:1. Therefore, it’s important for the government and electric vehicle charging infrastructure and the service company to provide more convenient, fast and efficient charging station.

Both Chinese and other international scholars carried on a great deal of typical studies on EV charging station node. Chen et al. [3] took carbon emission into consideration and then made a multi-objective optimization on EV charging station. Meysam et al. [4] proposed a model considering charging time and waiting time after analyzing the model of charging station location and the cognitive ability of queue. Phonrattanasak et al. [5] analyzed that technology and geographical limitations should be satisfied for the fast-charging stations optimal location in neighborhood so that it could minimize the total cost or total loss. Liu et al. [6] determined the candidate charging station sites with the minimum cost of charging station and the network loss during the planning period. Li et al. [7] applied the law of conservation which tended to the traffic flow and then proposed the minimum total annual cost model of charging station. Liu et al. [8] established the integrated optimization objective function which took geographical information, construction costs and operating costs into consideration. Huang et al. [9] took charging station service capacity into account and established an integer programming model of charging station based on the existing location model. Sadeghi-Barzani et al. [10] used the mixed integer nonlinear programming model to determine the optimal position of the electric vehicle charging station and explored the influence of different policies on the electric vehicle charging station by genetic algorithm. Wagner et al. [11] studied the optimal location of Intelligent City charging stations based on interest point method. In order to meet the needs of users, You et al. [12] set up an integer programming model for charging station location considering the total investment.

The above research mainly focused on enterprise profits, what they took into consideration was mainly minimizing the construction costs and so on, rather than the practical demand of customers. In fact, a network system with typical complex characteristics is formed through the multiple charging station nodes of EV. Therefore, in this paper, the complex network theory is applied to solve the problem of selecting the charging station network nodes, and the customer satisfaction model of charging nodes is established in the consideration of maximizing customer satisfaction so that it can provide EV customers with new idea and method to choose optimal charging station.

2. MECHANISM OF COMPLEX NETWORK MODEL

Complex network can vividly describe various models with complex relationship on the basis of computer science, mathematics and statistical physics, etc. and the goal is to analyze the complex system. Complex network [13,14,15] is characterized with complexity, small world properties, scalefree and openness, which is mainly reflected in the large scale of the network, and its network nodes are featured by dynamic complexity.

2.1 Weighted clustering coefficient

The clustering coefficient reflects the connection degree among adjacent nodes. Clustering coefficient in the weighted network is called the weighted clustering coefficient.

We define the weighted clustering coefficient C_i^w as follows:

$$C_i^w = \frac{1}{\max_j(w_{ij})\sum_{j,k} w_{ij} w_{ki}} \sum_{j,k} w_{ij}\, w_{jk} w_{ki} \tag{1}$$

Here k, j is the adjacent nodes of i. w_{ij} which connects node v_i and node v_j is the weight of edges.

2.2 Eigenvector

Eigenvector is suitable to describe the long-time influence of nodes, which is mainly used for propagation analysis, etc. The nodes with high eigenvector index usually indicates that the location of the node is very close to the source, and it's the key point that needs to prevent especially.

Suppose that there are N nodes in network; A presents the adjacency matrix of the network; $\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_N$ represents the N eigenvalues of A; λ is the maximum eigenvalue of A (the main feature value) and the corresponding feature vector is $\mathrm{e} = [e_1, e_2, e_3, \ldots, e_n]^T$, namely:

$$\lambda \mathrm{e_i} = \sum_{j=1}^{N} \mathrm{a_{ij} e_j}, \qquad \mathrm{i} = 1, \ldots, \mathrm{n} \tag{2}$$

We define the eigenvector index of node v_i as shown in Eq.3:

$$\mathrm{C_e(v_i)} = \lambda^{-1} \sum_{j=1}^{N} \mathrm{a_{ij} e_j} \tag{3}$$

2.3 Proximity

The index of proximity is used to describe the level of difficulty of one node to reach another node through network, which reflects the global structure of the network and the effect of one node on other nodes through the network.

If there are N nodes in network, the proximity index of node v_i can be defined as:

$$\mathrm{C_c(v_i)} = \left[\sum_{j=1}^{N} \mathrm{d_{ij}}\right]^{-1} \tag{4}$$

3. OPTIMIZATION MODEL OF CUSTOMER SATISFACTION OF EV CHARGING STATION

3.1 Complexity of EV charging station network

The complexity of EV charging station network is mainly reflected in the following aspects:

(1) The scale of charging station service network is huge;

(2) Complex structure and complicated nodes of charging station network;

(3) Fusions of multiplicity and complexity.

This paper abstracts the charging station network by applying the complex network theory. The charging station is abstracted as a network node, and the connection between roads as a line between nodes. The complex network theory is applied in the node selection problem of charging station network. We establish customer satisfaction model considering the maximizing customer satisfaction, so it can provide EV customer new idea and method to choose the optimal charging station.

3.2 The establishment of customer satisfaction model

In general, when EV customers choose charging station, the main considerations are:

(1) Personal preference;

(2) Charging price;

(3) Standard of service fee;

(4) The distance between EV and the selected charging station;

(5) The time of waiting in the queue;
(6) Service attitude and after-sales service.
In this paper, we ignore the customer's personal preference, service attitude of charging station and other uncertain factors, and consider the objective aspect to analyze questions quantitatively. Due to the charging price and charging pile capacity in China, it has not yet formed a unified standard, so the study of charging price, queuing time and charging time still has limitations. It assumes that (1) EV power consumption of one hundred kilometers is 15kwh; (2) 45kwh of EV battery ; (3) 2 hours of charging period; (4) the waiting time is equal to the minimum wage of non-full-time employees, namely 18.7 Yuan / hour of Beijing city; (5) The peak and valley time of electricity price is not considered here; (6) The road blocking time is not considered
Suppose $\mathrm{m_i}$ (Yuan/kWh) is the charge price of ith charging station node; $\mathrm{l_i}$ is the distance of the ith charging station node; g denotes the number of EVs waiting to charge; $\mathrm{f_i}$ (Yuan/ kWh) is the service fee standard of the ith charging station node; $\mathrm{t_i}$ is the charging time in the ith charging station node; 100 km loss of vehicle is proportional to the cube of the distance and the proportional coefficient is k.
Therefore, we build the maximum customer satisfaction model:

$$y_i = \min[\ ((2 * \mathrm{g} + t_i) * 18.7 + l_i * \frac{15}{100} * (m_i + f_i) + \mathrm{k} * ({l_i}/{100})^3] \tag{5}$$

Here $t_i = \frac{2}{45} * l_i * \frac{15}{100}$, i=2, ..., 5.
Eq.5 shows the relatively minimal model of customer cost, but it still has certain limitation for it doesn't take the degree of importance and congestion of charging station nodes into consideration. Weighted clustering coefficient reflects the degree of contact between the adjacent nodes, the greater of the coefficient C_i the more frequently the contact between the point and neighbor point.
So, we build the following relative cost minimization model:

$$Y_i = C_i * y_i \tag{6}$$

4. CASE STUDY

There is an electric vehicle infrastructure service corporation who plans to build charging stations among point $\mathrm{V_1}$ and point $\mathrm{V_6}$, supposed that the distance between each node and the remaining total battery capacity of the sites are already known. To determine the construction of charging station which can better meet customers' demand, suppose that a full load EV wants to get to $\mathrm{V_6}$ from $\mathrm{V_1}$. The charging station service network is shown in Fig. 1, which consists of 4 charging stations and 10 circuits.

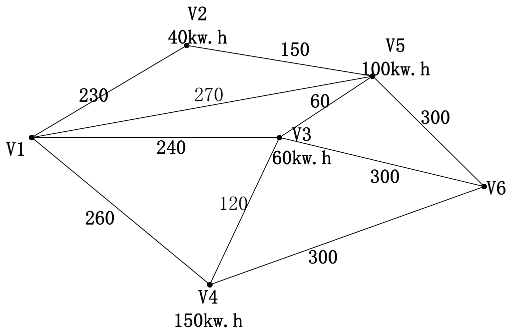

Fig. 1. The model of charge station service network

The parameters of each charging station are displayed in Table 1.

Table 1. Parameters of charging station

Site number	Electricity price(Yuan/kWh)	Service fee(Yuan/kWh)	Quantity for waiting EVs (unit)
V2	0.8745	0.8	2
V3	0.68	1.5	1
V4	1.2	0.9	0
V5	0.87	1.0	1

4.1 The calculation of weighted clustering coefficient

Taking the data in Figure 1 into equation (1) and using Matlab software, each charging station node's clustering coefficient can be calculated as listed in Table 2.

Table 2. Clustering coefficient of each site

Site number	V_2	V_3	V_4	V_5
Clustering coefficient	27/23	383/735	254/605	689/2330

4.2 Comparative analysis of typical path

The value of y_i corresponding to main path from V_1 to V_6 is listed in Table 3.

Table 3. The value of y_i about the main path

path	1-2-5-6	1-5-6	1-3-6	1-3-5-6	1-4-6	1-4-3-6
y_i	265.587	153.564	151.7195	213.4608	120.7769	212.6274

Putting in the corresponding weighted clustering coefficient of each site, the relative cost of corresponding path is listed in Table 4.

Table 4. The relative cost of main path

path	1-2-5-6	1-5-6	1-3-6	1-3-5-6	1-4-6	1-4-3-6
Y_i	220.5328	44.2524	77.0192	95.2766	49.0627	96.92493

Through analyzing Y_i in Table 4, we can see that the relative costs of paths 1-4-6 and 1-5-6 are smaller, so the constructions of charging station in the nodes V_4 and V_5 are better. For minimum charging cost and service fees, selecting the direct charging stations costs less. The relative cost added the weighted clustering coefficient reflects characters of avoiding traffic congestion risk, which provides a certain theoretical basis for location optimization.

4.3 Analysis the importance of charging station node

Research of complexity theory on transport network can determine the transportation hub and provide the prevention and control basis for easing traffic congestion in the city. Transportation hub nodes play a vital role in the overall structure of the network and system stability, etc. Traffic pressure can be relieved through controlling the hub nodes' traffic flow, which provides a basis for the overall operation of the traffic network.

The importance degree of each node must be considered when infrastructure companies construct charging stations. To reduce the waiting time, traffic congestion nodes should be avoided as far as possible when selecting charging stations. Here we use eigenvector and approach degree to analyze the importance of each node in charging station network.

According to formula (3) and (4), we can obtain the feature vector index Ce and normalized proximity index Cc of each node by Matlab calculation. Results are displayed in Table 5.

Table 5. The importance of node index

Site number	V_1	V_2	V_3	V_4	V_5	V_6
Ce	281/14	761/8384	567/3247	303/1810	689/2330	663/3355
Cc	1/308	1/274	1/186	1/238	1/192	1/378

By comparing V_2, V_3, V_4, V_5, we can see the sites V_3 and V_5 are relatively important, which easily lead to traffic congestion that we must pay attention to these two points as scheduling traffic network and avoid them when choosing charging station. Through comparing the importance of nodes, finding traffic hub nodes and controlling them can provide ideas and methods to improve traffic network transport efficiency etc.

In order to serve customers better, avoid the risk of traffic congestion and maximize customer satisfaction as far as possible, infrastructure companies should avoid V_5 and choose V_4 node to build charging station.

5. CONCLUSION

Reasonable planning of electric vehicle charging station can satisfy customers with better services and enhance the loyalty of them to a considerable extent. It becomes one of the challenges for charging stations selection in order to reduce customer queuing time and avoid traffic congestion. Due to the complexity of the selection charging stations, this paper studied the optimization of it based on complex network theory with the objective of minimizing the cost and took the traffic congestion and the key points of the node into consideration. This study can maximize customer satisfaction, provide a theoretical basis for the location of charging piles, and promote the development of electric vehicles in China to a certain extent.

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