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Research on Location of Electric Vehicle Charging Station Based on Voronoi Diagram and Improved Particle Swarm Algorithm

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Abstract: In order to reduce the blindness of charging station construction and improve the overall satisfaction of charging station construction and operation enterprises and electric vehicle users, this paper researches the location of electric vehicle charging station. First, the number of electric vehicles in the future is predicted by the grey model. The electric vehicle charging demand is calculated based on the road network, traffic flow and user charging behavior characteristics. Then the charging station service range is quickly divided by the Voronoi diagram. And a mathematical model is established based on the minimum total social cost. Finally, Improved particle swarm optimization algorithm and Voronoi graph are combined to solve the problem. The results of the example show that the algorithm can efficiently and accurately obtain the site selection scheme with the minimum social total cost, which is of great significance to urban development planning.

Key words: electric vehicle, charging station, location,improved PSO, voronoi diagram

1. INTRODUCTION

As a new type of energy-saving and environment-friendly car, electric vehicles have greatly changed the previous energy choice, and its popularity can effectively reduce the consumption of fossil fuels. The State Council has also identified the electric vehicle industry as one of the strategic emerging industries [1]. In order to realize the popularization of electric vehicles, the rational construction of electric vehicle charging stations will be one of the important links, and scientific and reasonable location planning is an important prerequisite for the rapid development of electric vehicles. "How to develop a healthy charging service market in China" [2] reports that the increase in the number of charging piles still cannot keep up with the growth of charging demand.

2. LITERATURE REVIEW

Holzman.D took the minimum square of the distance between charging station and charging demand point as the objective function. The location model was constructed by the network planning method and was verified by examples [3]. G.Celli analyzed the loss cost of the charging station and the user's charging cost, and studied the location and capacity of the charging station through genetic algorithm [4]. Andy Ip analyzed the factors affecting the location of electric vehicle charging stations and established a two-stage location planning model. In the first stage, the charging demand point and the demand quantity were obtained by the cluster analysis method, and the second stage was the modeling and analysis of the charging station candidate point optimization [5]. By analyzing the characteristics of the distributed power supply of the charging pile, Yang Yi considered the predicted value of the power supply load and the uncertainty of the distributed power output power. The objective function was the fuzzy expected value of annual operating expenses, and the constraints were various conditions restricting its economic and reliable operation [6]. In existing research, there have been many studies on the site selection of facilities. Most of them have conducted in-depth research on site selection

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principles, distribution network constraints, and network planning, but less consideration was given to the layout of the road network, traffic flow and user charging behavior characteristics.

3. CALCULATION OF ELECTRIC VEHICLE CHARGING DEMAND

3.1 The prediction of electric vehicle ownership

Grey model is a method to predict uncertain factors. Pingyao Wang used GM (1,1) model to predict the population of Dalian city, and the results were satisfactory[7]. By identifying the degree of divergence of development trends among system factors, correlation analysis is carried out, and the original data is generated and processed to find the change rule of the system, generate strong regular data sequence, and then establish the corresponding differential equation model, so as to predict the future development trend [8]. The prediction of electric vehicle ownership in this paper are based on GM (1,1) model. Due to the limitation of space, the theoretical derivation is not carried out here, and the prediction model is as follows:

$$\hat{x}^{(0)}(k+1)=(1-e^{a})(x^{(0)}(1)-\frac{u}{a})e^{-ak} \quad (k=1,2,\ldots) \tag{1}$$

And in this paper, the model accuracy is tested by posterior test. The procedure of posterior inspection is as follows.

(1) Calculating residuals:

$$e(k)=x^{(0)}(k)-\hat{x}^{(0)}(k), k=1,2,\cdots,n \tag{2}$$

(2) The variance of the original sequence $x^{(0)}$ and the residual sequence E are S_1^2 and S_2^2 respectively.

$$S_1^2=\frac{1}{n}\sum_{k=1}^{n}\left[x^{(0)}(k)-\bar{x}\right]^2 \tag{3}$$

$$S_2^2=\frac{1}{n}\sum_{k=1}^{n}[e(k)-\bar{e}]^2 \tag{4}$$

among them,

$$\bar{x}=\frac{1}{n}\sum_{k=1}^{n}x^{(0)}(k) \tag{5}$$

$$\bar{e}=\frac{1}{n}\sum_{k=1}^{n}e(k) \tag{6}$$

(3) The posterior difference ratio C is calculated as

$$C=S_2/S_1 \tag{7}$$

The value of C is directly related to the accuracy, and the accuracy test level is shown in Table 1.

Table 1. Reference table for accuracy test level

Model accuracy level	The posterior difference ratio C
Level1 (good)	$C \le 0.35$
Level2（qualified）	$C \le 0.5$ & $C > 0.35$
Level3（reluctantly）	$C \le 0.65$ & $C > 0.5$
Level4（unqualified）	$C > 0.65$

3.2 Charging demand distribution

In order to better represent the charging demands of different regions on the map, we regard all road nodes in the road network as charging demand points and allocate charging demands according to the traffic flow of each road. According to the characteristics of Voronoi diagram that the service scope can be automatically divided, this research uses it to the location process of charging stations.

A Voronoi diagram consists of a set of continuous polygons consisting of vertical bisectors connecting the lines of two adjacent points. Let R be a set of points of n elements contained in the plane. The n points in R act as growth points and expand around at the same speed until a straight line boundary is formed. Finally, except for the vertices near the boundary, they are convex polygons [9].

$R = \{R_1, R_2, \ldots, R_n\}, 3 \leq n < \infty$ is a set of a set of points in a plane, and the Voronoi diagram generated by the point set R can be defined as follows:

$$V(R_i) = \{x \in V(R_i) | d(x, R_j), j = 1,2, \ldots, n, j \neq i\} \quad (8)$$

Because Voronoi diagram can make the distribution of growing points more uniform in the network optimization and has the remarkable characteristics of partitioning according to distance, it is widely used in many fields. For example, Voronoi diagram can be used to divide distribution areas of logistics centers.

3.3 Charging demand calculation

Accurately describing the travel behavior process law can be used as a basis for analyzing the charging requirements of electric cars[10]. Therefore, in the calculation of charging demand, this article fully considers the travel behavior characteristics of electric vehicle users. And it is assumed that the maximum driving distance of an electric vehicle is 150 kilometers. Because of the "charging anxiety problem", it is assumed that when the remaining power is only 30% of the maximum power, the user must go to the charging station to charge.

The first step is to distinguish whether the electric vehicle user owns a household charging pile. If so, electric cars can be charged at home every night without having to go to a public charging station, otherwise, electric cars must go to a public charging station to charge. Xing Yan reached a survey conclusion[11].Of the 200 car owners surveyed in Beijing, 45% of the respondents said that they own private household electric vehicle charging piles. Therefore, it can be assumed that 45% of electric vehicle users can charge at home every night. It also shows that another 55% of users must use public charging piles for charging.

The second step is to analyze whether to go to a public charging station to charge according to the average daily mileage of electric vehicle users. Shiqi Ou[12] conducted a detailed investigation and analysis of the travel characteristics of Chinese electric vehicle users. In that survey, 169,296 privately-owned passenger vehicles are investigated from 82 cities in 27 provincial regions in mainland China (excluding Hong Kong, Macao, and Taiwan).It was found that the average daily mileage of electric vehicle users in China is about 34km. It can be inferred from this, considering the problem of charging anxiety, for car owners without home charging piles, they need to go to the public charging station to recharge about once every three days. That is, in one day, the probability that an electric car without a household charging pile will go to a public charging station to charge is 33.33%.

And Shiqi Ou researched and found that there is a 99% probability that the average daily driving distance in China didn’t exceed 105 kilometers. In other words, among the owners of household charging piles, there is an 1% probability that they will go to a public charging station to charge in one day[12].

In summary, at the demand point j, the formula for calculating the demand for electric vehicle charging is as follows：

$$d_j = S_j * 0.45 * 0.01 + S_j * 0.55 * 0.33 \quad (9)$$

In this formula, S_j is the number of electric vehicles at demand point j.

4. LOCATION MODEL AND SOLVING PROCESS

4.1 Objective function

This paper comprehensively considers the investment and construction cost of the charging station, the operation cost of the charging station, and the time cost of the electric vehicle user to the charging station, taking into account the overall cost of the whole society as the objective function of the charging station location planning. The objective function is as follows :

$$\min C = \sum_{i=1}^{N}(C_{i1} + C_{i2}) \tag{10}$$

In this formula, C is the annual average cost of the charging station planning scheme; N is the number of electric vehicle charging stations; C_{i1} is the annual enterprise construction operating cost corresponding to the i-th charging station; C_{i2} is the annual cost of electric vehicle users corresponding to the i-th charging station.

(1) Charging station enterprise cost

The cost of the charging station enterprise mainly includes the investment construction cost and operation and maintenance cost of the charging station. Among them, the mathematical model of the total cost of the enterprise of the i-th charging station is as follows:

$$C_{i1} = C_{ci} + C_{oi} \tag{11}$$

In this formula, C_{ci} is the annual investment construction cost of charging station i; C_{oi} is the annual operation cost of charging station i.

- The annual construction investment cost of charging station i

$$C_{ci} = (w + n_i \times p) \times \frac{r_0(1+r_0)^m}{(1+r_0)^m - 1} \tag{12}$$

In this formula, w is the infrastructure cost of each charging station; n_i is the number of charging piles owned by the charging station i; p is the unit price of the charging pile; r_0 is the discount rate; m is the operating period of the charging station.

- The annual operation cost of charging station i

The operation and maintenance costs of charging stations mainly include the daily maintenance costs of charging station management labor costs. Generally considered that the cost and charging station construction cost is proportional to the number of charging piles[13], assuming that η is a scale factor, mathematical model is as follows:

$$C_{oi} = \eta * C_{ni} \tag{13}$$

(2) user cost analysis

The cost of the user is expressed as the cost of the time spent by the user on the journey from the demand point to the charging station.

$$C_{i2} = \gamma * 365 * \sum_{j=1}^{S_i} d_{ij} * \theta * w_j / v \tag{14}$$

In this formula, C_{i2} is the annual cost of the electric vehicle user served by the i-th charging station, that is, the annual road time cost of the user who goes to the charging station i; γ represents the user unit time cost; j is the charging demand point; S_i is the number of charging demand points in the service area corresponding to the charging station i; d_{ij} is the coordinate distance between the charging demand point j and the charging station i; θ is the road tortuosity coefficient between the nodes; w_j is the number of electric vehicle with charging demand at the charging demand point j ; v is the average speed of electric cars.

4.2 Constraint condition

(1) The number of charging piles of charging station i should meet the charging demands of its service area:

$$n_i = \text{ceil}(\mu * w_j / R) \tag{15}$$

In this formula, μ is the simultaneous arrival rate; ceil is the upward rounding function; R is the maximum number of queues for a single charging pile that the user can tolerate.

(2) The maximum distance constraint between the demand point and the charging station, that is, the distance between the demand point and the charging station cannot be too far:

$$\theta * d_{ij} < dmax \tag{16}$$

In this formula, $dmax$ is the maximum distance between the demand point and the charging station.

(3) The number of charging piles owned by charging stations is limited

$$nmin < n_i < nmax \tag{17}$$

In this formula, $nmin$ is the minimum number of charging piles in the charging station; $nmax$ is the maximum number of charging piles in the charging station.

4.3 Model solving

Improved particle swarm optimization (IPSO) heuristic algorithm is adopted in this paper. Improve the inertia weight in the traditional particle swarm algorithm. As the number of iterations increases, the inertia weight changes from maximum to minimum. The formula is:

$$\omega = \omega_{max} - \frac{t*(\omega_{max} - \omega_{min})}{t_{max}} \tag{18}$$

Combined with Voronoi diagram above, the model was solved jointly by Voronoi diagram and improved particle swarm optimization algorithm. The solution process is shown in figure 1 and solved by MATLAB programming.

(1) enter the coordinates of the charging demand point, the number of vehicles with charging demand at the charging demand point, and the number of charging stations N.

(2) randomly generate the position and velocity of the initial particle swarm, and each particle represents a site selection scheme.

(3) For each particle, that is, the initial charging station site, make a Voronoi diagram, divide the service area of the charging station, and calculate the number of charging piles n_i required by the charging demand in the service area. Calculate the annual total social cost of the charging station according to the number of charging piles n_i of each charging station, the distance between the demand point and the charging station in the service range, and use it as the adaptive value of the particle swarm algorithm to record the individual extremum and the total extremum, namely the local optimal solution and the global optimal solution.

(4) Update the particle swarm velocity and position, and compile it into a new charging station site, calculate the total social cost of the year, and obtain the local optimal solution and the global optimal solution. After reaching the number of iterations, the calculation result with the minimum annual social total cost is output.

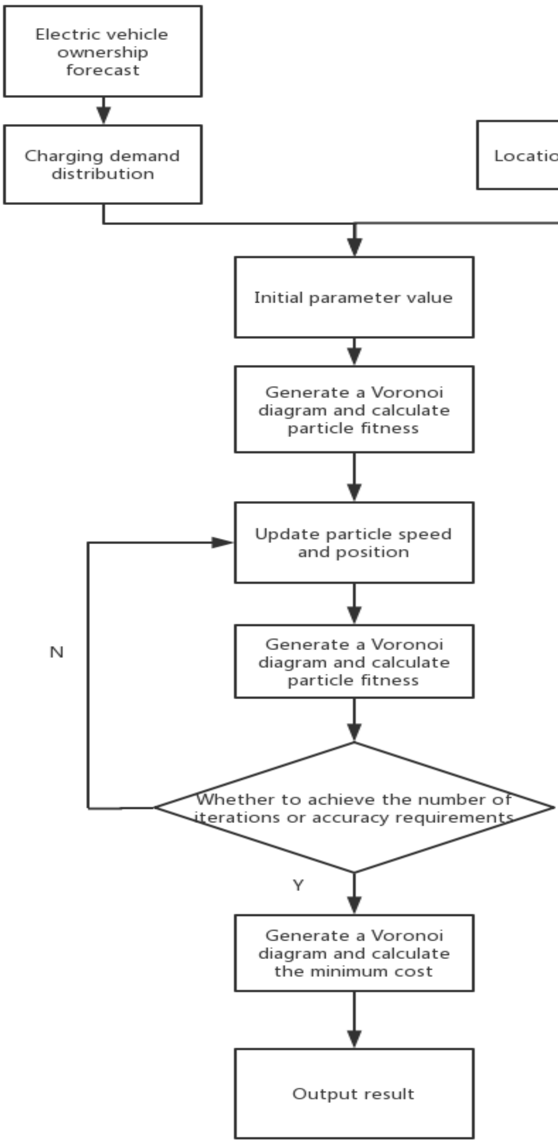

Figure 1. Vorinoi diagram and particle swarm algorithm joint solution process

5. CASE ANALYSIS

5.1 Case description

Due to the difficulty in obtaining such data as traffic flow at demand points, this paper simulates relevant data of a certain region. The simulated area covers a total area of 100 square kilometers with 36 major road nodes, approximately expressed as 36 demand points, as shown in figure 2. The planned number of charging stations ranges from 7 to 11. Electric vehicle charging station rate is 0.6 at the same time. Each station on the basis of construction cost is 500000 yuan. The price of a single charging pile is 150000 yuan. The user cost per unit time is 30yuan. The winding path coefficient is 1.2. The average speed of electric car 30 km per hour. A charging station can contain a maximum of 30 charging piles and a minimum of 4 charging piles. On a single charging station, users can accept up to 4 cars in line. The distance between the charging station and the demand point cannot exceed 5000 meters. The charging station has a life cycle of 20 years and a discount rate of 0.8.

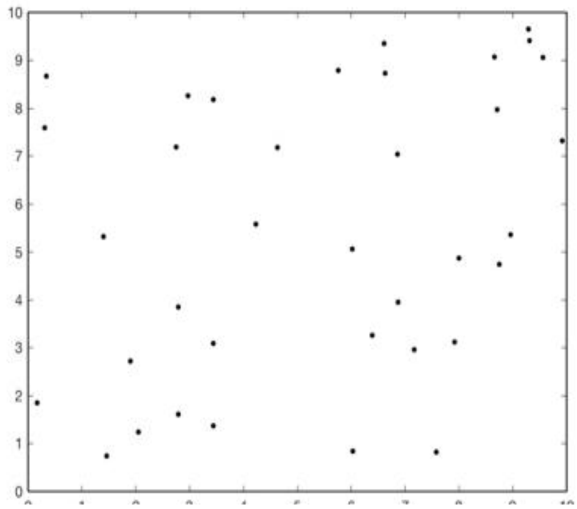

Figure 2. Location map of electric vehicle charging demand point

5.2 Prediction of electric vehicle ownership

The electric vehicles ownership in the region from 2013 to 2018 is shown in Table 2.

Table 2. Electric vehicle ownership from 2013 to 2018

Years	2013	2014	2015	2016	2017	2018
Electric vehicle ownership	103	154	227	303	417	617

Through the gray forecasting process above, it is estimated that the number of electric vehicles in the region will be approximately 6,450 in 2025. The prediction results are shown in Table 3.

Table 3. Forecast of electric vehicle ownership from 2019 to 2025

Years	2019	2020	2021	2022	2023	2024	2025
Electric vehicle ownership	832	1170	1646	2316	3258	4584	6450

The model needs to be tested to verify its validity and availability. This paper uses the posterior difference ratio to test. In this case, the post-test difference ratio test is calculated as 0.1226. Referring to Table 1 for the accuracy test level reference table, the post-test difference is less than 0.35, so the prediction model belongs to a higher precision model and the prediction result is relatively accurate.

5.3 Charging demand calculation

It is difficult to obtain the data of electric vehicle ownership at each demand point. However, the number of electric cars is positively correlated with the traffic flow, so we calculate the electric vehicle ownership at each demand point through the following formula:

$$S_j = S * R_j \tag{19}$$

In this formula, S is the total number of electric vehicles in this region, which is 6450. R_j is the proportion of daily traffic flow of each demand point in the total traffic flow. So the number of electric vehicles in this area is shown in table 4.

Table 4. The number of electric vehicles in each demand point

Demand point number	All-day average flow of road sections (standard car)	Proportion R_j	Electric vehicle ownership s_j	Demand point number	All-day average flow of road sections (standard car)	Proportion R_j	Electric vehicle ownership s_j
1	229707	3.45%	223	19	231969	3.49%	225
2	239960	3.61%	233	20	216885	3.26%	210
3	257345	3.87%	250	21	293438	4.41%	285
4	261789	3.94%	254	22	211184	3.18%	205
5	180362	2.71%	175	23	193935	2.92%	188
6	197818	2.97%	192	24	214639	3.23%	208
7	299525	4.50%	291	25	270561	4.07%	262
8	183186	2.75%	178	26	200412	3.01%	194
9	145819	2.19%	141	27	103888	1.56%	101
10	104490	1.57%	101	28	141115	2.12%	137
11	147729	2.22%	143	29	157500	2.37%	153
12	143306	2.15%	139	30	158573	2.38%	154
13	203369	3.06%	197	31	166973	2.51%	162
14	111877	1.68%	109	32	180741	2.72%	175
15	208318	3.13%	202	33	123668	1.86%	120
16	116716	1.76%	113	34	173274	2.61%	168
17	102225	1.54%	99	35	162929	2.45%	158
18	118735	1.79%	115	36	196056	2.95%	190

We can quickly get the charging demand at each demand point using formula (9), as shown in table 5.

Table 5. Number of vehicles with daily average charging demand at each demand point

Charging demand point number	The abscissa of the charging demand point	The ordinate of the charging demand point	Electric vehicle charging demand d_j	Charging demand point number	The abscissa of the charging demand point	The ordinate of the charging demand point	electric vehicles charging demands d_j
1	0.34	8.67	41	19	5.76	8.79	42
2	7.58	0.82	43	20	1.46	0.74	39
3	8.00	4.87	47	21	8.66	9.07	53
4	9.92	7.32	47	22	0.17	1.85	38
5	6.39	3.26	33	23	2.05	1.24	35
6	1.40	5.32	36	24	6.63	8.73	39
7	7.17	2.96	54	25	2.79	1.61	49
8	0.31	7.59	33	26	6.61	9.35	36
9	8.71	7.97	26	27	3.44	1.37	19
10	4.63	7.18	19	28	3.44	3.09	25
11	8.96	5.36	27	29	6.86	7.04	28
12	6.87	3.95	26	30	2.97	8.26	29
13	2.75	7.19	37	31	9.29	9.65	30
14	8.75	4.74	20	32	4.23	5.58	33
15	1.90	2.72	38	33	6.02	5.06	22
16	6.03	0.84	21	34	9.56	9.06	31
17	9.31	9.41	18	35	2.79	3.85	29
18	7.92	3.12	21	36	3.44	8.18	35

5.4 Model solving result

According to the above example scenario, the programming solution is carried out in MATLAB software. When the number of charging stations is set as 8, the adaptation value change curve is shown in figure 3, and the optimal objective function value is 10745719. In the model, with the number of iterations increases, the adaptive value of the population decreases and becomes stable. This shows that the parameters used in this algorithm are reasonable and the independent simulation can output stable optimization results. And The specific results of charging station location are shown in table 6 and figure 4.

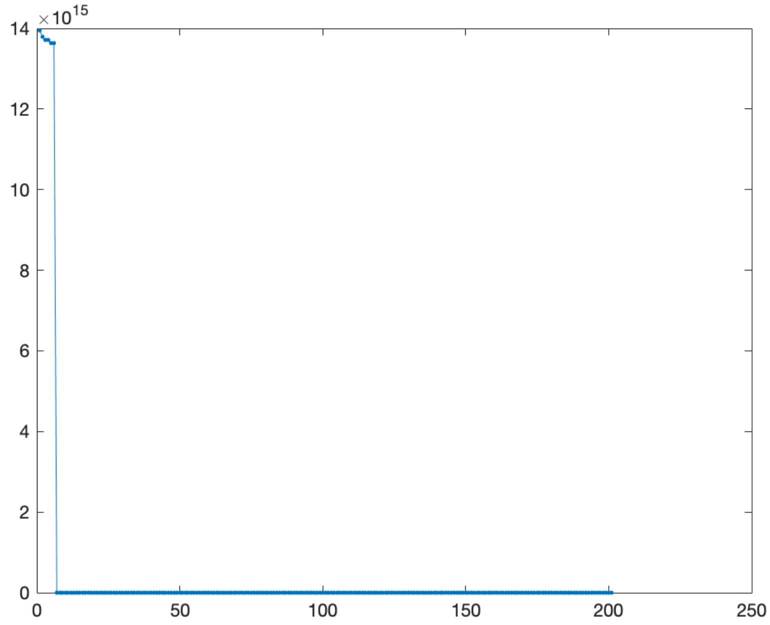

Figure 3. Adaptation value curve

Table 6. Charging station construction information table

Charging station number	The abscissa of Charging station	The ordinate of Charging station	Number of charging piles	Number of charged vehicles being served	Total social cost
1	9.9197	7.3199	11	73	
2	2.6885	7.9021	30	194	
3	9.1915	9.3235	20	132	
4	7.1699	2.9599	30	198	
5	2.7901	3.8497	25	161	10745719
6	6.5698	8.7554	22	145	
7	2.0499	1.2402	27	180	
8	8.0001	4.8700	18	116	

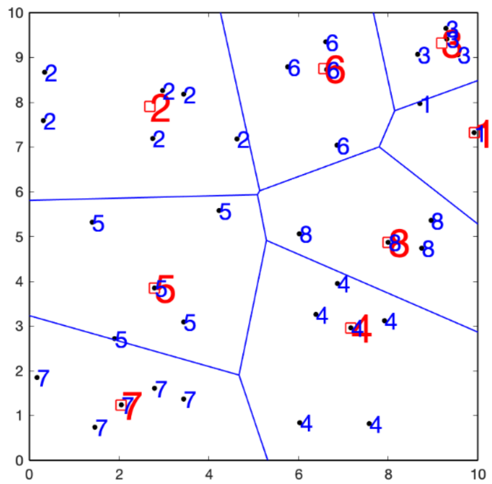

Figure 4. Location diagram of charging station

The more charging stations and charging piles there are, the shorter the distance between electric vehicle users and charging stations will be, and the smaller the time cost will be. However, the investment, construction, and operation cost of charging stations will also increase. We need to balance the user cost and the enterprise cost to get the relatively satisfactory solution with the minimum total cost. When the number of charging stations is taken as 7, 8, 9, 10 and 11 respectively, the total composition curve of social year of each scheme is shown in table 7. When the number of charging stations is 8, the total social cost is the smallest, which is 10745719 yuan, which is the optimal location solution.

Table 7. Total annual social cost corresponding to the number of different charging stations

Number of charging stations	Total annual social cost
7	26780234
8	10745719
9	11818432
10	12916324
11	14016396

6. CONCLUSION

In this paper, the optimal location of electric vehicle charging station is obtained through a simulation example, which proves the rationality and correctness of Voronoi diagram and improved particle swarm optimization in solving the location problem of charging station. This research method comprehensively considers the cost of the whole society, and combines the actual factors such as traffic flow, road network, user and charging characteristics to achieve efficient and accurate site selection of charging stations in different scenarios. It can not only provide reference for the investment and operation enterprises of charging stations and meet the needs of electric vehicle users to the greatest extent, but also promote the reasonable and orderly development of urban traffic. Due to the complexity of the location of charging stations, this paper has not considered comprehensively. For example, the security of the power grid and the environmental costs have not been considered.

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