Decision Model of Electric Vehicle Charging Station Configuration: A Case Study of the United States

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Abstract. This paper mainly studies the practical scientific issues of future charging station facility configuration strategies with the country as the main body. After fully considering the impact of population distribution, traffic flow, road network setting, wealth distribution, and urbanization on the optimal allocation of charging stations, the principal components analysis method is used to effectively integrate the above factors, and to use the GM (1,1) Model to predict the number of cars in the future. Further, combining the forecasting model of the total amount of cars with the weighted influence of the main factors, the constraints such as the minimum cost of charging stations and the optimal service range are established, and a decision model for the number and distribution of supercharging and destination charging stations is proposed. Taking the United States as an example, the configuration scheme for establishing the number and location of supercharging and destination charging stations for each division location in the United States is obtained through simulation, which can provide useful reference for the configuration of charging stations in various countries in the world.

1. Introduction

With the development and promotion of electric vehicles, how to configure the required charging stations for electric vehicles, so that the maximum utilization of charging stations and the widest coverage of the population has become a problem that needs to be studied today.

Zhao Mingyu (2016) used the Voronoi diagram method to optimize the layout of AC charging piles based on space-time constraints. The paper mainly considers the cost of electric vehicle charging piles and the cost of electric vehicles for charging [1]. The paper of Chen Rongjiang (2011), which used the pre-set configuration of the charging pile, mainly considered the power distribution capability of the power grid and the configuration scheme of the power verification charging pile that requires much charging [2]. This paper integrates the research methods and considerations of the two researchers and proposes a new decision-making method that considers both cost and charging capacity of charging piles, and simultaneously considers the basic national conditions of different countries such as terrain characteristics, wealth distribution, population distribution, and distribution of road traffic network.

In order to better study the configuration of the charging station, this paper takes the Tesla series as an example, assuming that the charging ports of all electric vehicles have the same type, and the types of charging posts are divided into the destination charging and supercharging. This paper selects the
United States, where electric vehicles are currently well developed, as an example for systematic analysis.

2. Model establishment
This study mainly researches the practical scientific issues of future charging station facility configuration strategies with the country as the main body.

First, the entire United States is divided into regions. Use principal component analysis to analyze the factors affecting the configuration decision, and obtain the proportion of each area and each factor in the charging pile configuration decision; second, according to utilizing the equal-dimension complementary prediction model, use the data of the 2013-2017 US Bureau of Statistics electric vehicle data to get the number of 2018-2030 electric vehicles in a certain future year. Finally, combining the principal component analysis and the number of electric vehicles, a cost and configuration optimization decision model is obtained, and then a comprehensive model for the configuration of electric vehicle charging stations is obtained.

2.1. Analysis of Influencing Factors Based on Principal Component Analysis
The main purpose is to explore the importance of national basic conditions in the deployment of electric vehicles and their supporting facilities. Assume that the factors of basic national conditions affecting the allocation scheme can be divided into above five categories.

2.1.1. Factor Analysis. Principal Component Analysis method is used to analyze the configuration decisions by selecting the main components with a large proportion of the total information of the variation in the above five categories. The greater the proportion of factors in the amount of information for degraded information, the greater its impact on configuration decisions. The variable information is represented by the sum of the squared deviations of the five index samples. The total variation after the analysis is

\[
\sum_{i=1}^{n} (x_{i1} - \bar{x}_1)^2 + \sum_{i=1}^{n} (x_{i2} - \bar{x}_2)^2 + \sum_{i=1}^{n} (x_{i3} - \bar{x}_3)^2 + \sum_{i=1}^{n} (x_{i4} - \bar{x}_4)^2 + \sum_{i=1}^{n} (x_{i5} - \bar{x}_5)^2
\]

(2-1)

When the values of \(\sum_{i=1}^{n} (x_{i1} - \bar{x}_1)^2\) 1, \(\sum_{i=1}^{n} (x_{i2} - \bar{x}_2)^2\) 2, \(\sum_{i=1}^{n} (x_{i3} - \bar{x}_3)^2\) 3, \(\sum_{i=1}^{n} (x_{i4} - \bar{x}_4)^2\) 4 and \(\sum_{i=1}^{n} (x_{i5} - \bar{x}_5)^2\) 5 are similar, it means that the five factors have similar importance for configuration decisions. When \(1:2:3:4:5=2:4:1:1:2\), it shows that township distribution occupies the most important position (about 40%) among all the factors.

2.1.2. Weights Analysis of the Same Factor in Different Regions. Studying the relationship between the importances of various factors in different regions need to divide the United States into \(jj\) regions. At the same time, the five types of graphics are divided into the same \(jj\)'s regions. Also using the principal component analysis method which described in 2.1.1, the variable information is represented by the squared deviation sum to indicate that a certain factor corresponds to \(jj\) regional index samples, then the total variation after analysis is

\[
\sum_{i=1}^{n} (x_{i1} - \bar{x}_1)^2 + \sum_{i=1}^{n} (x_{i2} - \bar{x}_2)^2 + \ldots + \sum_{i=1}^{n} (x_{i(j-1)} - \bar{x}_{(j-1)})^2 + \sum_{i=1}^{n} (x_{ij} - \bar{x}_j)^2
\]

(2-2)

The importance of the five factors and each divided area under each factor can be obtained by varying the ratio of the amount of information. The decision weights for the allocation of electric vehicles and their supporting facilities in each divided area can be expressed as:
\[ Q_i = U_i \times U_i + T_i \times T_i + TF_i \times TF_i + P_i \times P_i + W_i \times W_i \quad (2-3) \]

\( Q \) is the weight of decision-making in the allocation of regional electric vehicles and their supporting facilities configuration; \( U \) is the weight of urban distribution in five factors; \( U_i \) is the weight of urban distribution in the region \( i \); \( T \) is the weight of distribution of transportation network in five factors; \( T_i \) is the weight of distribution of transportation network in the region \( i \); \( TF \) is the weight of traffic-flow distribution in five factors; \( TF_i \) is the weight of traffic-flow distribution in the region \( i \); \( P \) is the weight of population distribution in five factors; \( P_i \) is the weight of population distribution in the region \( i \); \( W \) is the weight of the wealth distribution in five factors, and \( W_i \) is the weight of wealth distribution in the region \( i \).

2.2. Prediction of the Number of Electric Vehicles Based on the GM (1, 1) Prediction Method

Using the model to make appropriate predictions can get similar values to the future. Use the total number of electric cars collected over the calendar year to build a GM(1,1) model to predict the next year's value, and then add the new data to the known data columns, while removing the oldest time data to make the dimension of the sequence Unchanged and re-established GM(1,1) model predictions. Using the iteration of predicted grey numbers, the forecasts are rolled in turn until the prediction of the number of electric vehicles for the target year is achieved.

2.3. Charging station configuration model

The configuration of the charging station not only needs to consider above five factors, but also needs to consider the cost of installing a charging station, the amount of electricity provided by a charging station in a certain area, and the electric vehicles in a certain area. Besides, the configuration need to think over whether it is required to match and whether the charging station can meet the maximum number of charging times for electric vehicles in the area.

(1) Average daily charge per electric car

\[ \lambda = \frac{AM}{EM} \quad (2-4) \]

In the formula, \( \lambda \) is the average daily charge time of each electric vehicle; \( AM \) is the average daily mileage of each electric vehicle; \( EM \) is the cruising range of the electric vehicle. According to statistics, the average family car driving 60Km per day. The cruising range of current electric vehicles, according to the current battery technology can mileage up to 350Km. On the basis of formula (2-4), \( \lambda = 0.2 \), the average number of charging times of each electric vehicle per day is 0.2 times.

(2) The cost of installing the charging station

\[ Z = G_1n_1 + G_2n_2 \quad (2-5) \]

In formula (2-5), \( G_1 \) and \( G_2 \) are the costs for the installation of the two types of charging stations for supercharging and destination charging, respectively, and \( n_1 \) and \( n_2 \) are the number of supercharging and destination charging stations in each divided area. According to statistics, the cost of supercharging stations is 150,000 U.S. dollars, and the cost of the destination charging stations is 270,000 U.S. dollars.

(3) The relationship between charging station and electric vehicle

The charging energy provided by the charging station should be greater than the energy consumed by the average daily charge of all cars. The formula can be obtained:

\[ P_s T_s N_s n_1 + P_d T_d N_d n_2 \geq \lambda Q_c N \quad (2-6) \]
In the formula, \( P_S \) and \( P_D \) respectively represent the power provided by supercharging and destination charging, and \( T_S \) and \( T_D \) respectively represent the time required to charge a car for supercharging and destination charging. \( N_S \) and \( N_D \) are respectively represent the average number of charging piles of supercharging and destination charging in each station. \( n_1 \) and \( n_2 \) are the number of supercharging stations and destination charging stations. \( N \) is the number of cars in a certain area, and \( Q_C \) is the average energy of the car.

On the basis of statistics, the power respectively provided by supercharging and destination charging is 120KW, 11KW, and the power of car is 60KW. The time required to charge a car for supercharging and destination charging is 2/3 hours and 6 hours, respectively. The average number of charging piles per station of supercharging and destination charging is 7 and 2. The formula can be expressed as:

\[
120 \times \frac{2}{3} \times 7 \times n_1 + 11 \times 6 \times 2 \times n_2 \geq 0.2 \times 60 \times N
\]

\[
560 \times n_1 + 132 \times n_2 \geq 18 \times N
\]

(2-7)

(4) Relationship between the charging station and the average daily maximum number of charges

The maximum number of chargeable charges per type of charging pile is:

\[
\frac{60T}{T_S + T_{W1}}
\]

(2-8)

\[
\frac{T}{T_S + T_{W2}}
\]

(2-9)

In the formula, \( T \) refers to working hours (24h) a day, and \( T_{W1} \) and \( T_{W2} \) are respectively expressed as the waiting time required to charge one vehicle for the supercharging pile and the destination charging pile. According as statistics, the charging time between two intervals of the supercharging pile is 10 minutes and it has 18 minutes' gap time of the destination charging pile for next charging.

In order to satisfy the charge of all cars in the entire area, the number of charging piles should be greater than the maximum number of charging times, and the formula can be expressed:

\[
\frac{\lambda N}{N_S n_1} \geq \frac{60T}{T_S + T_{W1}}
\]

(2-10)

\[
\frac{\lambda N}{N_D n_2} \geq \frac{T}{T_D + T_{W2}}
\]

(2-11)

The formula (2-10) and (2-11) are that the supercharging station and the destination charging station should meet the requirement of more than the maximum number of charging. The formula can be obtained:

\[
\frac{0.2N}{7n_1} \geq 28.8
\]

(2-12)

\[
\frac{0.2N}{2n_2} \geq 3.8
\]

(2-13)

In summary, a decision model that satisfies the aforementioned conditions can be obtained:
3. Numeric analysis

In order to explore the rationality and accuracy of the verification model, the proposed model is used to analyze the American configuration scheme for electric vehicle charging stations in 2030. In order to achieve the accuracy of the decision, the United States is divided into 50*50 sections according to the model needs. Because the regional division is too small, the accuracy of the prediction decision will be insufficient.

3.1. Weights of US Decision Factors

3.1.1. Weights among the five factors. Using formula (2-1), the weight relationships among the above five factors are as follows:

\[
\begin{aligned}
\sum_{i=1}^{n} (x_{i1} - \bar{x}_1)^2: \ldots : \sum_{i=1}^{n} (x_{i5} - \bar{x}_5)^2 = 0.1531: 0.2168: 0.2468: 0.1042: 0.2791
\end{aligned}
\]

From formula (3-1), we can see that wealth distribution is the most important one among the five factors, and the population density distribution is the lowest among the five factors. According to equation (3-1), \(U=0.1531, T=0.2168, TF=0.2468, P=0.1042, \) and \(W=0.2791\) in equation (2-3).

3.1.2. Weights of various regions within each factor. Using formula (2-2) to get the internal relationship among the five factors, a 50*50 matrix can be obtained through simulation. Each element in the matrix represents a divided area, and the figure is the proportion of the corresponding area in the divided area. You can get \(U_i, T_i, TF_i, P_i, \) and \(W_i\) in equation (2-3).

According to formula (2-3), combined with the data obtained after analysis in 3.1.1 and 3.1.2, the weight of each divided area can be obtained through simulation.

3.2. Prediction of the Number of Electric Vehicles

According to statistics, the number of electric vehicles in the United States since 2013-2017 is shown in Table 1:

| Year       | 2013 | 2014 | 2015 | 2016 | 2017 |
|------------|------|------|------|------|------|
| Total electric vehicles | 2.5  | 3.3  | 14   | 27.3 | 36.8 |

Utilizing the equal-dimension complementary prediction model proposed in 2.2.1, the predicted value of the future number of electric vehicles in the United States can be obtained. Through simulation, the number of electric vehicles in 2018-2031 can be predicted, as shown in Table 2:
Table 2. 2018-2030 years statistics of the number of American cars (thousands)

| Year | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  | 2024  |
|------|-------|-------|-------|-------|-------|-------|-------|
| Total electric vehicles | 65.59 | 65.59 | 181.16 | 297.040 | 483.08 | 779.67 | 1249.3 |

Using the number of electric vehicles in 2030 to continue to be validated and simulated. Using equation (2-3) and combining the data obtained in 3.1, the distribution of cars can be obtained as shown in Figure 1.

Figure 1. The distribution of electric vehicles in 2030 (sample: 50*50)

3.3. Application of configuration model of charging station

Apply the proposed model (2-14) to get the configuration scheme for supercharging and destination charging stations. Through computer simulation, the configuration scheme can be obtained as shown in Figure 2.

![Figure 2](image)

Figure 2. The distribution of charging designed stations in 2030 (sample: 50*50)

4. Conclusion

This paper mainly studies the practical scientific issues of future charging station facility configuration strategy with the country as the main body. Fully consider the impact of urban distribution, traffic network, traffic flow, population density distribution, wealth distribution and other factors on the configuration, and use the GM (1, 1) to predict the trend of future changes in the total amount of
electric vehicles. After analysis of the data, using the lowest cost of building a charging station and the largest range of services to restrict the number of supercharging and destination charging stations for each block. In order to study the issue of charging facility planning, a new idea was provided, and a combination of factors including population and traffic impacts. The unit was studied by the state to study the problem of building a charging station. Compared to the configuration of a charging station based on a certain city, better solve the problem of practical building charging stations in life.

References
[1] Zhao Mingyu, Wu Jun, Zhang Weiguo, et al. Optimal layout of AC charging piles based on space-time constraints [J]. Automation of Electric Power Systems, 2016 (4): 66-70.
[2] Chen Rongjiang. Construction Design of AC Charging Piles for Electric Vehicles [J]. Electrotechnical Engineering, 2011 (6): 23-24.
[3] Li Yanshuang, Zeng Zhenxiang, Zhang Wei, et al. Application of Principal Component Analysis in Multi-index Comprehensive Evaluation Method [J]. Journal of Hebei University of Technology, 1999, 28 (1): 94-97.
[4] Wang Meng. Research on the Network Layout and Operation of Electric Vehicle Charge and Replacement Station [D]. Beijing Jiaotong University, 2017.
[5] Zhang Wei. Comprehensive Evaluation Modeling for Operation Service of Electric Vehicle Charging Station Based on Combination Evaluation Method [D]. Beijing Jiaotong University, 2017.
[6] Li Rong. Study on the planning method of charging stations for electric vehicles [D]. Tianjin University, 2015.
[7] Lei Jiyu, Fu Yuqi. Development Trend of Global Electric Vehicles in 2016 [J]. Electric Age, 2017 (5): 22-24.