Research on Layout Network Optimization of Public Charging Infrastructure

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Abstract. With the gradual popularity of new energy vehicles in the world, people's demands for the construction of supporting services such as charging infrastructure are becoming increasingly urgent. The popularity of charging infrastructure also determines the upper limit of the future development of new energy vehicles. This paper starts from the research on user satisfaction of charging infrastructure, finds the key indicator that affects user satisfaction—the layout network of charging stations, establishes a multi-path trajectory node model to quantitatively solve the problem of charging station layout under complex road network conditions, and calculates Example simulations verify the feasibility of the model method.

1. Introduction
New energy vehicles are in a rapid popularization stage in the market. In 2015, "Made in China 2025" once again listed new energy vehicles as one of the ten key development areas in the next decade [1]. With the increasing number of its promotion, the charging demand for new energy vehicles has also increased accordingly. From the data point of view, the speed of charging infrastructure construction has been accelerating year by year to supplement the charging demand. However, the problem of "difficult charging" has not been fundamentally solved, and there are a lot of problems in layout construction, infrastructure operation and user experience. Waiting to be solved.

One of them is the unbalanced ratio of vehicle piles. The construction speed of charging piles is much lower than the popularization speed of electric vehicles. The demand for charging infrastructure is huge, but at the same time the construction is very difficult.

Another outstanding problem is the unreasonable layout of charging infrastructure. The current overall layout of charging facilities is concentrated in first-tier cities and concentrated in cities, with fewer expressway stations [3].

Therefore, in order to solve the above-mentioned problems, this article mainly starts with the user satisfaction of charging infrastructure. On this basis, further research will be conducted on the factors that have the greatest impact on the user satisfaction of the charging infrastructure, and the layout of the charging infrastructure under the complex road network planning conditions will be optimized, and feasible proposals for the construction of the charging infrastructure will be proposed.

2. Establishment and Analysis of User Satisfaction System of Charging Infrastructure

2.1. Establishment of User Satisfaction Evaluation Model for Electric Vehicle Charging Station
This article will use the top-down scoring method to construct a multi-level evaluation model [4]. The model can finally score the user satisfaction of a single electric vehicle charging station and rank the user satisfaction of a large number of charging stations.

First, through qualitative research (document desk research, expert interviews and field research) and analytic hierarchy process, the first and second indicators of user satisfaction evaluation of charging stations are established. Then, each indicator is quantitatively analyzed through structural equations to re-optimize the model. And finally study the weight of all levels of indicators through weight analysis [5].

In general, the factors affecting user satisfaction of electric vehicle charging stations are divided into four categories: rationality of charging station layout, charging station hardware facilities, usage cost and payment, and service experience.

In the hypothesis test of the model, this paper uses the structural model method to analyze and solve. According to the model equation, it is necessary to import the variable parameters of this study and the corresponding data matrix.

After obtaining user survey data, the validity of the questionnaire data must first be verified. Usually, the verification of the data validity uses a consistency test. This article establishes a judgment matrix for each user. This time, a total of 550 questionnaires were sent out and received. 523 valid questionnaires. Since there are a total of 523 valid survey data, we can establish 523 judgment matrices. Let $ax$ represent the $X$th indicator feedback, the general form of the judgment matrix is as follows:

$$
\begin{bmatrix}
1 & \cdots & a_{1j} \\
\vdots & \ddots & \vdots \\
a_{1j} & \cdots & 1
\end{bmatrix}
$$

(1)

Next, the maximum eigenvalue $\lambda_{\text{max}}$ (j=1, 2… 523) of these 523 sets of judgment matrices needs to be required to obtain 523 consistency indexes $CI_j$:

$$
CI_j = \frac{\lambda_{\text{max}} - n}{n - 1}
$$

(2)

Since the judgment matrix in this study is a square matrix of 15x15, looking up the table shows that the random consistency index is:

$$
RI = 1.59
$$

(3)

Therefore, we can find 523 consistency ratios:

$$
CR_j = \frac{CI_j}{RI}
$$

(4)

If the consistency ratio $CR<0.1$, we consider this set of data to pass the consistency test. If the group of data passes the consistency check, the group of data is retained; otherwise, it is deleted. According to the results, 489 sets of data passed the consistency test, and we can further solve the structural equation based on these 489 sets of data.

In the process of continuing to solve the problem, this paper uses AMOS 18.0 software for confirmatory factor analysis, and imports the four latent variables and their corresponding indicators at the cognitive level into the AMOS software. The research and solution results of this model are shown in Table 1:
Table 1. Parameter test result.

|     | Std. | $\chi^2$ | df | $\chi^2$/df | GFI  | AGFI  | NFI  | CFI  | RMR  | RMSEA |
|-----|------|----------|----|-------------|------|-------|------|------|------|-------|
|     |      |          |    |             | GFI  | AGFI  | NFI  | CFI  | RMR  | RMSEA |
| R1.1| 187.653 | 73       | 2.643 | >0.9        | 0.934 | 0.743 | 0.919 | 0.911 | 0.048 | 0.085 |
| R1.2| 173.65  | 70       | 2.522 | >0.9        | 0.973 | 0.887 | 0.943 | 0.931 | 0.035 | 0.071 |

As shown in Table 1, R1.1 is the hypothetical model for the significant impact of indicators established in the previous section of this study. The results of AGFI and RMSEA are not ideal. By checking the function of the correction module of AMOS, it is found that HD6 and SE5 are more important to their superiors. The significant impact of the indicators HD and SE is very small, indicating that the hypothesis of the significant impact of these two indicators is not valid, that is, the conclusion can be drawn: (1) The charging pile design has no significant impact on the performance of the charging pile hardware level (2) The charging pile user The account has no significant impact on the user experience. Therefore, removing these two indicators, verifying the solution again to get R1.2, the parameter indicators of the model solution have been improved, so the optimized user satisfaction evaluation indicator model is adopted.

2.2. Calculation of Weights of User Satisfaction Evaluation Model for EV Charging Station

According to the 489 sets of data that passed the consistency test, we can find the eigenvectors corresponding to the largest eigenvalues of the 489 judgment matrices, and normalize these 489 eigenvectors to obtain 489 importance weight vectors. The result is as follows as shown in Table 2.

Table 2. Vector data of questionnaire importance.

| Num | Expense | Hardware | Latout of station | Service |
|-----|---------|----------|-------------------|---------|
| 1   | 0.062   | 0.172    | 0.623             | 0.143   |
| 2   | 0.05    | 0.177    | 0.577             | 0.196   |
| 3   | 0.222   | 0.057    | 0.615             | 0.106   |
| 4   | 0.592   | 0.089    | 0.191             | 0.128   |
| ... | ...     | ...      | ...               | ...     |
| 485 | 0.415   | 0.093    | 0.346             | 0.146   |
| 486 | 0.064   | 0.122    | 0.544             | 0.271   |
| 487 | 0.068   | 0.083    | 0.626             | 0.223   |
| 489 | 0.078   | 0.200    | 0.522             | 0.200   |

The importance weight vector of the charging infrastructure can be used as a reference for the quantitative scoring of the first-level indicator evaluation of the user satisfaction of the charging station. Assuming that the rating of a charging station is $P$, then:

$$ P = 0.212p_1 + 0.231p_2 + 0.329p_3 + 0.228p_4 $$

3. Optimized layout strategy of node charging stations for electric vehicle multi-path trajectory

3.1. Research background of charging station layout strategy

From the previous research on the user satisfaction evaluation system of charging infrastructure, it can be seen that the rationality of the layout of charging stations is one of the key influencing factors of user satisfaction. Therefore, in the following research, we will select the impact of the user satisfaction rating
system the largest indicator—the rationality indicator of the charging infrastructure layout is researched and optimized.

3.2. Overview of charging scenarios for electric vehicle multi-path trajectory nodes
The construction of the urban road network is the most important factor in the layout of the network. The condition of the urban road network affects the route planning choices of electric vehicle owners. There are often multiple route planning options for the same starting point and end point. In order to facilitate research, in the next process, the urban road network will be abstracted and become a node network model, which will be simplified by studying irrelevant factors.

In traffic planning, OD pairs are used to represent the spatial location of a trip from a certain starting point to a certain end point.

3.3. Establishment of multi-path trajectory node model
In this section, by establishing a Multipath & Nodes Charging Location Model (MNCLM) to optimize the strategy of charging station layout. In this model, the travel situation of an electric vehicle user is driving an electric vehicle with a certain remaining power (SOC) based on a certain OD line crossing multiple nodes in the urban road network.

![Figure 1. Simplified road network scenario.](image)

Here we take the 7-node model as an example for further analysis. Figure 4.2 illustrates some parameter definitions of the MNCLM model with a simplified path node model. Suppose that node A and node E are the starting nodes of the OD pair, node C and node G are the end nodes of the OD pair, and node B, node D, and node F are intermediate nodes of the network. Therefore, under this assumption, there are 4 OD pairs, A-C pair, A-G pair, E-C pair and E-G pair. At the same time, it is assumed that the distance between each node is based on the straight-line distance, and that the current electric vehicle SOC can complete a distance of 15 units.

The basis of the dynamic path planning problem is to solve the shortest path decision from one node to another node, that is, the shortest path distance. Through research in related fields, this paper will use Dijkstra algorithm to solve the shortest path point-to-point. After determining a single shortest path, in this model, the acceptance of the deviation of the electric vehicle's main path still needs to be considered. In the actual process, there is the possibility of choosing a detour path, so it is necessary to further solve the K shortest paths.

4. Model simulation and strategy application analysis
In this chapter we will apply the MNCLM model algorithm to two types of classic road network models: closed-loop path network model and open-loop network model.
In order to apply the algorithm, this paper simulates the urban road network planning scene, and establishes the abstract multi-node path diagrams of the multi-node closed-loop network and the multi-node open-loop network. These two path networks are user hotspot travel networks. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper.

4.1. **Closed-loop path network scenario verification**

In this experiment, the maximum path distance between nodes in the hypothetical road network model is selected as 100 as the maximum cruising range of the vehicle. In the verification example, three scenarios of path planning deviation will be considered during the calculation and solution process to illustrate the travel based on different users. The impact of behavioral path planning on the layout strategy of charging infrastructure, the three path planning deviation scenarios are: the shortest path scenario (K=1), the shortest 3 paths (K=3) and the 20% total distance deviation level scenario.

After programming in Matlab using the Dijkstra path planning algorithm and Jens algorithm, the OD pair path planning can be obtained, and then the multiple linear programming model can be solved by the AMPL_CPLEX solver. The result is shown in Figure 2:

![Figure 2. Closed loop shortest path result.](image)

By comparison, it can be clearly seen that the higher the path deviation, the fewer charging stations are needed to cover all travel needs. Through the algorithmic solution, we can get that in scenarios with different deviation degrees: the shortest path conditions K=1, K=3, and the 20% deviation degree scenarios respectively correspond to the minimum number of required charging station layouts of 12, 7, and 11. At the same time, the layout of the charging station network affects Yrs,k, and the planned path between OD pairs can be obtained through different decision variables Yrs,k.

4.2. **Open loop path network scenario verification**

An open-loop path network refers to a network in which one or more nodes exist in a multi-path node network, and the node is only connected to one node other than the node. From the example, it can be seen that node 22, node 23, node 24, both and node 25 have only one path to reach the node. The optimized MNCLM model algorithm is also used to solve the multiple linear programming in the same three deviation threshold scenarios with K=0, K=3, and 20% deviation, and the solution results are marked in the road network diagram. As shown in Figure 3:
For an electric vehicle travel scenario with a cruising range of 100 units, the minimum number of charging station layouts corresponding to \( K=1 \), \( K=3 \), and 20% deviation are 10, 8, and 9, respectively. Compared with the closed-loop path network example, the charging station layout strategy of the 25-node open-loop path network corresponding to different deviation thresholds is similar, and the degree of change is less. The main reason is that the path selection is relatively single and the number of path planning is small. For example, in the terminal node area from node 22 to node 25, in all cases, the layout of charging network points at node 14 and node 24 is required.

5. Conclusions

This topic first starts from the research on user satisfaction of charging infrastructure, collects first-hand user data through desk research, expert interviews and field investigations through qualitative research methods and quantitative methods of questionnaire surveys, and finds indicators for the rationality of the layout of charging infrastructure. It has a very important impact on user satisfaction. In order to further solve the layout problem of charging infrastructure construction, this chapter has conducted an in-depth discussion on this problem from the aspects of multi-node network and path planning. In order to verify the feasibility of MNCLM, the MNCLM model is applied to two classic multi-node path planning example models, the closed-loop path node model and the open-loop path node model, and the number of charging station network points and the selection of the layout location are solved. It has a good reference value for the early stage of charging infrastructure construction and popularization.

References

[1] Yao Yao. New Energy Vehicles: 2018, Between the Breakthroughs [J]. China Economic Information, 2017(24): 61-63.
[2] Shanghai Municipal Platform for Public Service of Charging and Swap Facilities. Monthly Statistics of Shanghai Municipal Platform for Data Collection and Monitoring of Charging and Swap Facilities [EB/OL]. https://mp.weixin.qq.com/s/I9_q8hmFSHsJDMyk2gWE-g, 2018-12-24.
[3] Jinlin Li. Re-exploration of statistical analysis of AHP method summary data[J]. Systems Engineering, 1991, 9(5): 6-8.
[4] Xinyan Liu, Yanni Liu, Zhi Yang, Houfen Wan. Constructing a new type of customer satisfaction index model——Based on the analysis of SCSB, ACSI and ECSI[J]. Nankai Management
Review, 2003(6): 52-56.

[5] Cai H, Chen Q, Guan Z, et al. Day-ahead optimal charging/discharging scheduling for electric vehicles in microgrids[J]. Protection and Control of Modern Power Systems, 2018, 3(1):9.